COSMIC RADIATION IN COMMERCIAL AVIATION

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This paper reviews the current knowledge of cosmic radiation and its applicability to commercial aviation. Galactic cosmic radiation emanates from outside the solar system, while occasionally a disturbance in the sun’s atmosphere leads to a surge in radiation particles. Protection is provided by the sun’s magnetic field, the earth’s magnetic field, and the earth’s atmosphere. Dose rates are dependent on the altitude, the geomagnetic latitude and the solar cycle. For occupational exposure to ionising radiation, which includes aircrew, the International Commission on Radiological Protection recommends maximum mean body effective dose limits of 20 mSv per year (averaged over 5 years, with a maximum in any one year of 50 mSv). Radiation doses can be measured during flight or may be calculated using a computer-modelling program such as CARI, EPCARD, SIEVERT or PCAIRE. Mean ambient equivalent dose rates are in the region of 4 – 5 μSv per hour for long-haul pilots and 1 – 3 μSv per hour for short-haul, giving an annual mean effective exposure of the order 2 – 3 mSv for long-haul and 1 – 2 mSv for short-haul pilots. Epidemiological studies of flight crew have not shown any increase in cancer mortality or cancer incidence that could be directly attributable to ionising radiation exposure. Whilst it is accepted that there is no level of radiation exposure below which effects do not occur, all the current evidence indicates that the probability of airline crew or passengers suffering any abnormality or disease as a result of exposure to cosmic radiation is very low.

Keywords: Galactic cosmic radiation, solar flare, coronal mass ejection, ground level enhancement (GLE), International Commission on Radiological Protection (ICRP), dose rate effectiveness (DREF), linear energy transfer (LET), relative biological effectiveness (RBE), quality factor (QF), chromosome aberrations, CARI, EPCARD, SIEVERT, PCAIRE.

Introduction

The planet earth is continuously bathed in high-energy ionising radiation known as galactic cosmic radiation (GCR), emanating from outside the solar system, and sporadically exposed to bursts of energetic particles from the sun referred to as solar particle events (SPEs).

The main source of GCR is believed to be supernovae (exploding stars), while occasionally a disturbance in the sun's atmosphere (solar flare or coronal mass ejection) leads to a surge of radiation particles with sufficient energy to penetrate the earth's magnetic field and enter the atmosphere.

Ionising Radiation

Ionising radiation refers to subatomic particles that, on interacting with an atom, can directly or indirectly cause the atom to lose an electron or even break apart its nucleus. It is when these events occur in body tissue that health effects may result if the human body's self-repair mechanism fails.

Ionising radiation is a normal part of the environment. It is emitted in all normal human tissue cells, and emanates from the ground and some building materials. It is used as a medical diagnostic and treatment tool, and is received from GCR.

Ionising radiation types and their properties are shown in Table 1.

Table 1.

Radiation Type	**Consists of**	**Range in air**	**Range in human tissue**	**Hazard site**
alpha particles	2 protons + 2 neutrons (Helium)	few cm	cannot penetrate skin	internal
beta particles	an electron	several metres	few mm	internal + external
gamma rays	electromagnetic ray	many metres	many cm	internal + external
X rays	electromagnetic ray	many metres	many cm	external
neutrons	free neutrons	many metres	many cm	external

Outside the earth's atmosphere, GCR consists mostly of fast-moving protons (hydrogen nuclei) and alpha particles (helium particles). GCR is 98% atomic nuclei and 2% electrons (43). Of the energetic nuclei, 87% are protons, 12% are helium ions and 1% are heavier ions. On average, these energetic ions approach the earth about equally from all directions, with energies up to 10^{14} MeV or more (19). Once GCR penetrates the magnetic field of the solar system, the peak of energy distribution is at a few hundred MeV to 1 GeV per nucleon, depending on solar magnetic activity.

On entering the earth's atmosphere, the particles collide with the nuclei of nitrogen, oxygen and other atmospheric atoms, generating additional ionising radiation particles. The particles entering the atmosphere and those generated are collectively referred to as galactic cosmic radiation (GCR). At normal commercial aircraft flight altitudes this GCR consists mainly of neutrons, protons, electrons, positrons and photons.

Terrestrial Protection from GCR

Protection from cosmic radiation for the earth's inhabitants is provided by three variables:

1. the sun's magnetic field (solar cycle)
2. the earth's magnetic field (latitude)
3. the earth's atmosphere (altitude).

1. The sun has a varying magnetic field with a basic dipole component which reverses direction approximately every 11 years.

Near the reversal, at 'solar minimum', there are few sunspots and the magnetic field extending throughout the solar system is relatively weak and smooth. At solar maximum there are many sunspots and other manifestations of magnetic turbulence, and the plasma of protons and electrons ejected from the sun (the solar wind) carries a relatively strong and convoluted magnetic field with it outward through the solar system (19).

When the solar magnetic field is stronger, the paths of the electrically charged ions are deflected further and less GCR reaches the earth. Thus solar maximum causes a radiation minimum and, conversely, solar minimum is the time of radiation maximum. The effect of this depends on the other two variables, altitude and geomagnetic latitude. At the altitudes flown by commercial jet aircraft and at polar latitudes, the ratio for GCR at solar minimum to that at solar maximum is in the region of 1.2 to 2 and increases with altitude (4, 5).

2. The earth's magnetic field has a larger effect than the sun's magnetic field on cosmic radiation approaching the atmosphere. Near the equator, where the geomagnetic field is almost parallel to the earth's surface, vertically incident particles with momentum per unit charge (magnetic rigidity) less than about 15 GV are reflected back into space.

Near the magnetic poles, where the geomagnetic field is nearly vertical, the vertical cut-off approaches zero and the maximum number of primary cosmic rays can reach the atmosphere.

[The term 'vertical cut-off rigidity' describes the minimum rigidity a vertically incident particle can have and still reach a given location.]

As a result, cosmic radiation levels are higher in polar regions and decline towards the equator, the size of this effect depending upon altitude and the point in the solar cycle. At the altitudes flown by commercial jet aircraft, at solar minimum, GCR is 2.5 to 5 times more intense in polar regions than near the equator, with larger latitude dependence as altitude increases (54).

Over a fairly large region near the geomagnetic poles, above about 50 degN in Canada or 70 degN in Siberia at aviation altitudes, there is no further increase in GCR with increasing latitude (19). Although the geomagnetic field would allow more low-rigidity particles to reach the atmosphere at higher latitudes, the magnetic field of the solar wind (even at solar minimum) has already deflected such low-momentum GCR. The result is a 'polar plateau' which increases in size as the sun becomes more active.

3. Life on earth is shielded from cosmic radiation by the atmosphere. The mass thickness of the air above a given altitude is called atmospheric depth, and is proportional to the air pressure at that point. This decreases approximately exponentially as altitude increases (9).

The charged cosmic radiation particles lose energy as they penetrate the atmosphere by ionising the atoms and molecules of the air (releasing electrons). The particles also collide with the atomic nuclei of nitrogen, oxygen and other atmospheric constituents. In the nuclear collisions, primary cosmic radiation heavier than protons tends to break into fragments.

The ambient radiation increases with altitude by approximately 15% for each increase of around 2,000 ft (~600 m) (dependent on latitude).

At an atmospheric depth of 58 g cm^{-2} (65,000 ft, 19.8 km), the primary proton flux is reduced to about half of the incident flux, the alpha particle (helium ion) flux to about a quarter, and the heavy ion flux to about 3% or less, depending on the mass of the ion (43). The target air nuclei also fragment, both processes resulting in a spray of secondary particles including lighter nuclei, nucleons (protons and neutrons), and charged and neutral pions. Except for the neutral pions, all these hadrons (particles with strong nuclear interactions) can undergo further collisions with air nuclei, creating a cascade of secondary particles. The neutral pions decay almost immediately into high-energy gamma rays. These interact with air nuclei to produce electron-positron pairs, giving rise to an electromagnetic cascade of electrons (negative and positive) and photons. Charged pions decay into muons, which do not interact strongly with air nuclei and can penetrate all the way to the ground before they decay into electrons (19).

From this it can be seen that as well as providing shielding from GCR, the atmosphere contributes different components to the radiation flux as a function of atmospheric depth. Accordingly the potential biological effects of cosmic radiation on aircraft occupants are directly altitude dependent.

Figure 1 is taken from Goldhagen (2000) (19), reproduced from the journal Health Physics with permission from the Health Physics Society and the National Council on Radiation Protection and Measurements. It shows the calculated effective dose rate from each of the components of GCR (and the total effective dose) as a function of altitude for a location at the edge of the polar plateau during solar minimum (radiation maximum).

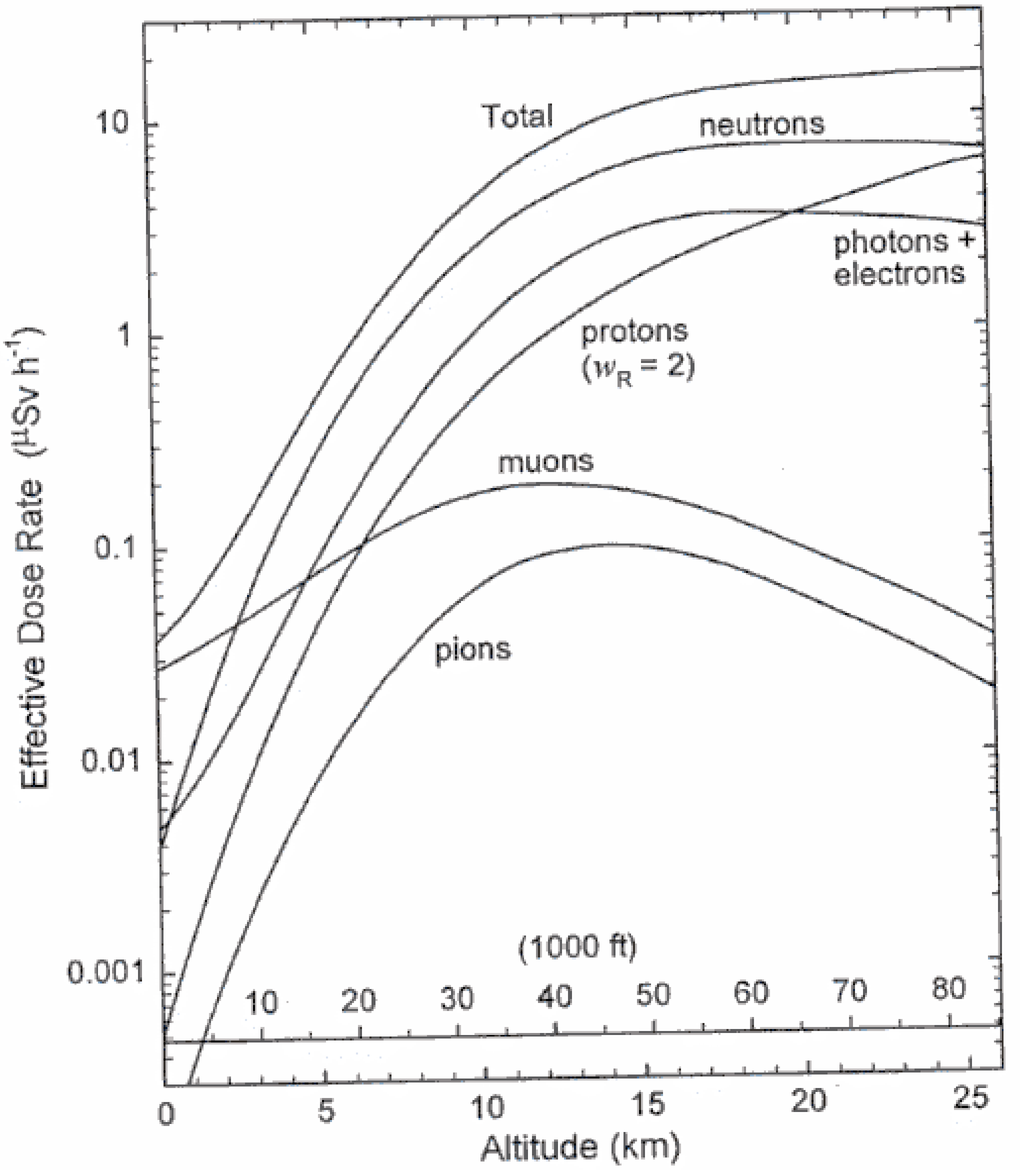

Fig. 1. Calculated effective dose rate as a function of altitude for various component particles of galactic cosmic radiation in the atmosphere near the polar plateau (cutoff = 0.8 GV) at solar minimum (June 1997). Data are courtesy of K. O'Brien, calculated using his LUIN-98F radiation transport code, but with w_R for protons set equal to two (NCRP 1993) rather than five.

It can be seen that the total effective dose rate at 30,000 ft is about 90 times the rate at sea level. It increases by a factor of 2 between 30,000 ft and 40,000 ft, and by another factor of 2 between 40,000 ft and 65,000 ft. It should be noted that at all altitudes from 10,000 ft to over 80,000 ft (3 to 25 km) neutrons are the dominant component. They are less dominant at lower latitudes, but still contribute 40 to 65% of the total dose equivalent rate.

Solar Flares

Occasionally a disturbance in the sun's atmosphere, known as a solar particle event (SPE), leads to a surge of radiation particles. These are produced by sudden sporadic releases of energy in the solar atmosphere (solar flares) and by coronal mass ejections (CMEs), and are usually of insufficient energy to contribute to the radiation field at aviation altitudes. However, on occasions proton particles are produced with sufficient energy to penetrate the earth's magnetic field and enter the atmosphere. These particles interact with air atoms in the same way as GCR particles. Such events are comparatively short lived and vary with the 11-year solar cycle, being more frequent at solar maximum.

Long distance radio communications are sometimes disrupted because of increased ionisation of the earth’s upper atmosphere by X-rays, protons or ultra-violet radiation from the sun. This can occur in the absence of excessive ionising radiation levels at commercial flight altitudes. Similarly the Aurorae Borealis and Australis (northern and southern lights), while resulting from the interaction of charged particles with air in the upper atmosphere, are not an indication of increased ionising radiation levels at flight altitudes.

When primary solar particle energies are sufficient to produce secondary particles detected at ground level by neutron monitors, this is known as ground level enhancement (GLE). GLEs are rare, occurring about one per year, and the spectrum varies between events (34). Any rise in dose rates associated with an event is rapid, usually taking place in minutes. The duration may be hours to several days.

The strong magnetic disturbance associated with SPEs can lead to significant decreases in GCR dose rate over many hours (Forbush decrease). Thus the combined effect of an SPE may be a net decrease or increase in radiation dose. Prediction of which SPEs will give rise to significant increases in radiation dose rates at commercial aircraft operating altitudes is not currently possible, and work continues with this aspect of space weather.

GLEs have been recorded and analysed since 1942, and are numbered sequentially (12). With the exception of GLE5 (February 1956), of the 64 GLEs observed up to 2003, none has presented any risk of attaining an annual dose of 1 mSv (the ICRP recommended public exposure limit) (29). For GLE60, which occurred in April 2001, the total contribution to radiation dose from the SPE was measured as 20 μSv (50)

GLE42, which occurred in September 1989, was the most intense observed since that of 1956 (GLE5) with a recorded magnitude of 252%. However this represented about one month of GCR exposure only, which would not have given an annual dose in excess of 1mSv (30). Concorde supersonic transport aircraft of British Airways and Air France were flying during this solar event and the on-board monitoring equipment did not activate a radiation warning alert, which is triggered at 0.5mSv per hour.

It has been reported (29) that a number of airlines have changed flight plans to avoid high geomagnetic latitudes during periods of predicted solar flare ground level events, with significant cost and delays to service. Data indicate that these actions were unnecessary in terms of radiation dose protection.

Biological Effects of Ionising Radiation

Very high levels of ionising radiation, such as that from a nuclear explosion, will cause severe cell damage or cell death. This may lead to the immediate death of the individual as a result of acute exposure, or to longer-term consequences such as the development of cancer, or to genetic mal-development as a result of damage to the reproductive cells. It is more difficult to predict the effects of low-level doses of ionising radiation such as cosmic radiation or medical X-rays because of the individual variability in the body's self-repair process. Indeed, it has even been suggested that the effect of radiation on human health is not linear, but is a J-shaped curve with exposure being beneficial at low doses (27, 52).

The ionisation process in living tissues consists of ejecting bound electrons from the cellular molecules, leaving behind chemically active radicals which are the source of adverse changes. Many of the radicals resulting from radiation injury are similar to those produced in normal metabolic processes, for which the cell has developed recovery mechanisms needed for long term survival (7). The substantive target of radiation injury is considered to be the DNA structure which may be changed or injured directly by a passing ionising particle (55). The ability of the cell to repair the effects of ionisation depends in part on the number of such events occurring within the cell from the passage of a single particle, and the rate at which such passages occur. The number of ionisation events per particle passage is related to the physical processes by which particle kinetic energy is transferred to the cellular bound electrons (55).

As charged particles slow down when passing through a viscous medium such as human tissue, they lose energy. The rate of energy loss increases rapidly with increasing charge of the particle and decreasing speed (55). From basic physics, the distance travelled depends on the inertia, and massive particles are more penetrating than lighter particles of the same charge and speed. Uncharged particles have longer free paths and, for neutrons, larger energy transfers per event resulting in energy losses which appear as isolated occurrences along the particle's path. The rate at which ions produce electrons in isolated cells is important, since repair of a single event is relatively efficient unless many events occur within the repair period (53).

The dose rate effectiveness factor (DREF) of ionising radiation is influenced by the dose, dose rate and quality of the radiation, leading to the concept of relative biological effectiveness (RBE). However, because biological effectiveness depends on the spatial distribution of the energy imparted and the density of the ionisations per unit path length of the ionising particles, other factors need to be considered. The most important is the energy loss per unit path length of a charged particle, or the stopping power; this is referred to as 'linear energy transfer' (LET).

The biological effect of ionising radiation depends upon whether it is high- or low-LET. The dose equivalent to the tissue (DE) is the product of the absorbed dose (D) and the quality factor (Q or QF), Q being dependent upon LET. The numerical value of Q depends not only upon appropriate biological data, but also on judgement. It establishes the value of the absorbed dose of any radiation that engenders the same risk as a given absorbed dose of a reference radiation (24). The quality factor is numerically the same as the radiation weighting factor (W_R), and recommendations are published from time to time by the ICRP (24).

Low-LET radiation, all with a weighting factor of 1, includes photons, X and gamma rays, as well as electrons and muons. Gamma rays are the low-LET radiation of prime concern at aircraft operating altitudes.

Neutrons, protons, alpha particles, fission fragments and heavy nuclei are classified as high-LET, neutrons providing about half the effective dose at high altitudes. The current weighting factors are shown in Table 2.

Type & energy range of incident radiation	**Weighting factor**
Photons (all energies)	1
Electrons and muons (all energies)	1
Protons (incident)	5 (but see text)
Neutrons <10 keV	5
Neutrons 10 keV - 100 keV	10
Neutrons >100 keV - 2 MeV	20
Neutrons >2 MeV - 20 MeV	10
Neutrons >20 MeV	5
Alpha particles, fission fragments, heavy ions	20

The ICRP has proposed (24) that the weighting factor for protons should be reduced from a value of 5 (as recommended in ICRP Publication 60, 1991) to a value of 2.

The weighting factor for neutrons depends upon the energy of the incident neutrons. ICRP Publication 92 proposes that the means of computation of the factor should be a continuous function of energy rather than the step function given in Publication 60. [For further detail, refer to ICRP Publication 92 pp 2-3 (24).]

These proposals are based on current knowledge of biophysics and radiobiology, and acknowledge that judgements on these factors may change from time to time.

[ICRP recommends that no attempt be made to retrospectively correct individual historical estimates of effective dose or equivalent dose in a single tissue or organ. Rather the revised weighting factor should be applied from the date of adoption.]

As previously noted, at all altitudes from 10,000 ft to over 80,000 ft (3 to 25 km) neutrons are the dominant component of the cosmic radiation field. They are less dominant at lower latitudes, but still contribute 40 to 65% of the total dose equivalent rate. Because neutron interactions produce massive low-energy ions, neutron radiation is more effective in inducing biological damage than gamma radiation. However, there are no adequate epidemiological data to evaluate whether neutrons are carcinogenic to humans (23).

Chromosome Aberrations

Tissue cells may be damaged by physical agents such as heat, cold, vibration and radiation. Throughout life there is a continuous ongoing cycle of cell damage and repair utilising the body’s self-repair mechanism. During the repair process, gene translocation and other chromosome aberrations may occur.

A number of studies have identified an increased rate of unstable chromosome aberrations such as dicentrics and rings in flight crew members, and related these to cosmic radiation exposure (21, 45, 46). Nicholas et al note that unstable aberrations decrease with time and thus do not serve as good indicators of cumulative exposure to GCR. They postulate that structural chromosome aberrations such as translocations may be a better marker since they are relatively stable with time since exposure (35).

The Nicholas et al study showed that the mean number of translocations per cell was significantly higher amongst the airline pilots studied than among the controls. However, within the radiation exposure range encountered in the study, observed values among the pilots did not follow the dose-response pattern expected based on available models for chronic low dose radiation exposure.

This study fails to determine the role of radiation in the induction of translocations. There is no epidemiological evidence to link these aberrations with the development of cancers.

Radiation Units of Measurement

The standard unit of radioactivity is the Becquerel (Bq), which is defined as the decay of one nucleus per second.

When considering cosmic radiation the practical interest is in the biological effect of a radiation dose, the dose equivalent being measured in Sievert (Sv). Doses of cosmic radiation are of such a level that values are usually quoted in micro-Sievert (µSv) per hour or milli-Sievert (mSv) per year (1mSv = 1000µSv).

The Sievert has superseded the rem as the unit of measurement of effective dose [1Sv = 100rem, 1mSv = 100mrem, 1µSv = 0.1mrem].

Other Sources of Ionising Radiation

There is a constant background flux of ionising radiation at ground level. Terrestrial background radiation from the earth's materials contributes 2.6 mSv per annum in the United Kingdom and 3 mSv per annum in the USA (57). This flux is dominated by the low-LET component (93%).

Inhaled radon gas contributes around 2 mSv per annum to the total overall background ionising radiation level (57).

Medical X-rays are delivered in a concentrated localised manner, and usual doses are of the order (57):

Chest X-ray	0.1 mSv (100 µSv)
Body CT scan	10 mSv
Chest CT scan	8 mSv
IVP	1.6 mSv
Mammogram	0.7 mSv (700 µSv)

Doses received from radiotherapy for cancer treatment range from 20 to 80 Sv (31).

Radiological Protection

Workers in the nuclear industry and those who work with medical X-rays may be designated as 'classified workers' and have their occupational radiation exposure monitored and recorded. For classified workers, the International Commission on Radiological Protection (ICRP) recommends maximum mean body effective dose limits of 20mSv per year (averaged over 5 years, with a maximum in any one year of 50mSv), with an additional recommendation that the equivalent dose to the foetus should not exceed 1mSv during the declared term of the pregnancy. This limit for the foetus is in line with the

ICRP recommendation that the limit for the general public should be 1mSv per year (25).

Workers in the nuclear industry and in medical physics are at potential risk of accidental high exposure, and radiological protection regulations require that they be educated to take every effort to avoid such accidents. The situation differs in the aviation environment where exposure to radiation is not the result of an accident.

In the UK, the National Radiological Protection Board (NRPB) recommends that a record should be kept of exposure rates and there should be a systematic assessment of the individual dose of any worker considered likely to receive an effective dose of more than 6mSv per year, this being referred to as the control level. This value is a cautious arbitrary figure, representing 3/10 of the annual maximum for classified workers and has no radiobiological significance (10).

In 1991 the ICRP recommended that exposure of flight crew members to cosmic radiation in jet aircraft should be considered part of occupational exposure to ionising radiation (25).

In 1994 the Federal Aviation Administration (FAA) of the USA formally recognised that air carrier aircrews are occupationally exposed to ionising radiation, and recommended that they be informed about their radiation exposure and associated health risks and that they be assisted in making informed decisions with regard to their work environment (15). The FAA subsequently issued a technical report in October 2003 advising aircrew about their occupational exposure to ionising radiation (16).

The FAA recommends the limit for an aircrew member of a 5-year average effective dose of 20mSv per year, with no more than 50mSv in a single year (17). For a pregnant aircrew member starting when she reports her pregnancy to management, the recommended limit for the conceptus is an equivalent dose of 1mSv, with no more than 0.5mSv in any month (17). [Dose equivalence essentially takes account of the dose absorbed by the tissue and the quality factor of the radiation.]

Following the ICRP recommendation, the Council of the European Union adopted a directive laying down safety standards for the protection of the health of workers and the general public against the effects of ionising radiation (14). Article 42, which deals with protection of aircrew, states that for aircrew who are liable to be subject to exposure of more than 1 mSv per annum appropriate measures must be taken. In particular the employer must:

- assess the exposure of the crew concerned;
- take into account the assessed exposure when organising working schedules with a view to reducing the doses of highly exposed aircrew;
- inform the workers concerned of the health risks their work involves; and
- apply special protection for female aircrew during declared pregnancy.

The European Directive applies the ICRP limits for occupational exposure (20mSv per year) and the 1mSv exposure limit to the foetus for the duration of declared pregnancy. In addition, the European Directive indicates that radiation exposure to a pregnant crew member should be ‘as low as reasonably achievable’ (14).

This was transformed into national law of the EU member states by 13 May 2000.

Both the European Directive and the FAA Technical Report follow the ICRP recommended limits for occupational exposure, but there are differences for pregnancy. The European Directive uses the ‘ALARA’ principle in recommending that radiation exposure to the pregnant worker should be as low as reasonably achievable, with an absolute maximum of 1mSv. However, the FAA recommends a maximum dose to the foetus of 1mSV but allows 0.5mSv in any month, making no reference to ALARA.

Health Risks of Cosmic Radiation

The biological effects of radiation are classified as probabilistic (stochastic) or deterministic (non-stochastic).

- In a stochastic effect, the probability of an effect occurring rather than its severity is a function of dose, without threshold (eg cancer or genetic damage), and can arise from damage to a single cell.
- For a non-stochastic effect, the severity of an effect is a function of dose and there may be a threshold (eg skin erythema or development of cataracts).

1. Development of cancer.

   A cell may become cancerous as a result of being irradiated, the likelihood being dependent upon the energy and the dose received. For an accumulated cosmic radiation dose of 5 mSv per year over a career span of 20 years (a typical prediction for a long haul crew member), the likelihood of developing cancer will be 0.4% (16, 18). The overall risk of cancer death in the western population is 23%, so the cosmic radiation exposure increases the risk of cancer death from 23% to 23.4% (16, 18). For a career span of 30 years, the cancer risk increases from 23% to 23.6%.

2. Genetic risk.

   A child conceived after exposure of a parent to ionising radiation is at risk of inheriting radiation-induced genetic defects. These may take the form of anatomical or functional abnormalities apparent at birth or later in life. The risk following an accumulated dose of 5 mSv per year over a career span of 20 years will be 1 in 2,500 (16). For a 30-year career, the risk increases to 1 in 1,700. Again this needs to be considered against a background incidence in the general western population of approximately 1 in 50 for genetic abnormalities, with 2 – 3% of liveborn children having one or more severe abnormalities at birth (16).

3. Risk to the health of the foetus.

   The risks to the foetus from ionising radiation are cancer and mental retardation. There is a background rate for both these conditions within the general population. It is estimated that exposure of the foetus to cosmic radiation for 80 block hours per month for a period of 4 weeks will increase the risk by between 1 in 6,000 and 1 in 30,000 depending on the routes flown. The increased lifetime risk of fatal cancer from 1 mSv received during prenatal development is 1 in 10,000 (0.01%) (16).

Measurement of Cosmic Radiation Doses

The ICRP 1991 recommendations require that cosmic radiation exposure for flight crew members should be assessed and recorded (25).

It has been seen that the galactic cosmic radiation field at aircraft operating altitudes is complex, with a large energy range and the presence of all particle types. Despite much development work, there is still no one single device, active or passive, which can satisfactorily measure the whole range of energies and particle types (5). A large number of passive and active devices have been used to measure the dose in aircraft and a summary was published by the European Radiation Dosimetry Group in 1996 (13). More recent work (32) indicates that the tissue equivalent proportional counter (TEPC) may be the most appropriate device, although it is not calibrated across the complete energy spectrum.

The Concorde supersonic transport aircraft first flew in 1969 and entered service with Air France and British Airways in 1976, retiring in 2003. From the outset it was appreciated that cosmic radiation (both galactic and solar) could present a hazard at the operating altitude of around 18km (59,000 ft). Accordingly, ionising radiation monitoring equipment was permanently installed in all Concordes and much data were derived (1, 2, 11, 38).

The introduction of aircraft such as the Boeing 747-400 and the Airbus A330 and A340, has led to the development of ultra-longhaul flights of up to 18 hours duration with the potential for even longer flight times. Many of the routes flown are trans-Polar or trans-Siberian, where geomagnetic and atmospheric shielding from GCR are less than for routes at lower latitudes.

Galactic cosmic radiation can be measured actively or passively. Many detectors measure only one type of radiation accurately and usually for only a limited energy range, but they may show some sensitivity to other types of radiation.

An active direct reading instrument displays the appropriate values immediately or after a short delay, whereas passive integrating instruments need to be evaluated in a laboratory after the flight.

Active dosimetry can be based on Geiger-Muller counters (gamma radiation), ionisation chambers (gamma radiation), moderated boron trifluoride counters (neutrons), scintillation counters (gamma radiation or neutrons), or tissue equivalent proportional counters (mixed radiation fields) which can be set up to indicate both actual dose and dose equivalent.

Passive dosimeters have the advantage of being small, light, and robust and are readily available. However, compared with active dosimeters they are much less sensitive, although this can be overcome by increasing the exposure time and the number of dosimeters used. Thermoluminescence dosimeters (TLDs) respond to X and gamma radiation and to charged particles (electrons, protons, muons, etc), and are used in the ‘film badges’ worn by radiation workers in the nuclear and medical industries . The neutron component can be measured using a polyallyldiglycol carbonate dosimeter (PADC, or CR39) which responds to neutron energies above 100 keV.

A number of studies have been published giving effective dose rates for sub-sonic flights, measured both actively and passively (1, 2, 4, 18, 28, 32, 33, 42, 47, 49, 50, 51).

Effective dose is not directly measurable, the operational quantity of interest being ambient dose equivalent. In the same way that operational quantity personal dose equivalent is used to estimate effective dose for radiation workers, so operational quantity ambient dose equivalent can be a good estimator of effective dose and equivalent dose received from cosmic radiation. Calculations of ambient dose equivalent rate or route doses can be validated by direct measurement.

Concorde was the only commercial aircraft to be equipped with radiation dosimeters measuring data for the duration of every flight. The cost of installation, calibration and maintenance for such equipment in the worldwide fleet of subsonic aircraft is not justified by cost-benefit analysis.

It is frequently suggested that individual dosimeters in the form of film badges should be worn by crew members. However, the sensitivity of such passive dosimeters is very low and the badges would have to be worn for several sectors for meaningful data to become available. Lantos et al report that during an experiment involving voluntary crew members wearing personal dosimeters, 8% of the badges were lost or not used and 2% had received additional X-rays during baggage security screening (30). The logistical costs of issuing, tracking and processing many thousands of film badges within a commercial airline operation are prohibitive.

Computer programs have been developed for the calculation of effective dose from galactic cosmic radiation. To compute the dose, it is necessary for the program to take account of

- geographic coordinates of origin and destination airports
- longitude and latitude of all points of the aircraft’s track
- altitude at all times of the flight
- helicocentric potential, to account for solar activity
- date and time of flight
- quality of the radiation field through which the aircraft flies.

The most widely used program is CARI-6, developed by the US FAA based on the LUIN transport code (36). It is limited to the galactic cosmic ray component, which is isotropic and of constant spectrum outside of the heliosphere. The CARI program has been validated by in-flight measurement and found to be accurate to within about 7% (30), although earlier studies suggest accuracy in the region of 20% (4).

There is a freely available interactive version of CARI-6, which runs on the Internet and is accessed via <http://www.cami.jccbi.gov/radiation.html>. There is also a more sophisticated downloadable version, which allows the user to store and process multiple flight profiles and to calculate dose rates at user-specified locations in the atmosphere.

Another package, EPCARD, has been developed on behalf of the European Commission (48). This is based on the FLUKA transport code (44) and again is limited to the galactic cosmic ray component, which is isotropic and of constant spectrum outside of the heliosphere.

A further program is the SIEVERT system (Systeme d'Information et d'Evaluation par Vol de l'Exposition au Rayonnement cosmique dans les Transport aeriens) which has been developed on behalf of the French Aviation Administration (DGAC) (30). This program is freely available via <http://sievert-system.org>.

A Canadian program is known as PCAIRE and is freely available from www.pcaire.com (32)

These computer programs allow airline companies and their employees to comply with the ICRP recommendations to monitor radiation exposure.

Cosmic Radiation Doses Received

There have been many studies of cosmic radiation dose rates both in Concorde and subsonic aircraft (1, 2, 4, 18, 22, 28, 32, 33, 42, 47-51), all giving similar results. European airlines have been required to monitor and record occupational exposure since May 2000 to comply with the European Directive. This is achieved using a computer program such as CARI, EPCARD, SIEVERT or PCAIRE, periodically validated by on-board measurement of the radiation field.

Exposure will depend on the route, altitude and aircraft type (which influences rate of climb and descent) and is usually quoted as microSievert (µSv) per block hour (block hours are based on the time from when the aircraft first moves under its own power to the time of engine shut-down at the end of the flight). Short haul operations tend to fly at lower altitudes than long haul, giving the benefit of atmospheric shielding as well as a shorter duration of exposure. Conversely, many long-haul routes are flown at higher latitudes as well as at higher altitudes.

For operations in the northern hemisphere, mean ambient equivalent dose rates have been measured in the region of:

- Concorde: 12 -15 µSv per hour
- Long-haul: 4 – 5 µSv per hour
- Short-haul: 1 – 3 µSv per hour.

In general, for UK-based crew members operating to the maximum flight time limitations, it is calculated that:

- Long-haul crew have an annual mean effective exposure of 2 – 3 mSv per year, ie less than one fifth of the ICRP recommended dose limit;
- Short-haul crew have an annual mean effective exposure of 1 – 2 mSv per year, ie less than one tenth of the recommended dose limit.

On the worst-case UK high latitude polar routes, such as London Heathrow to Tokyo Narita, the mean ambient equivalent dose rate has been measured at 6 µSv per hour (4). For a crew member flying 900 hours per year only on this route, the annual exposure would be in the region of 5.4 mSv, ie less than three tenths of the ICRP recommended dose limit.

For ultra-long range airline operations (arbitrarily defined as sector lengths in excess of 18 hours), recent studies (22) have shown a mean effective sector exposure of 80 µSv on the Dubai to Los Angeles route. A crew member flying 3 return trips per month would accrue an annual exposure of 5.76 mSv.

The FAA has calculated the worst case USA high altitude, high latitude long-haul flight to be New York to Athens, with an equivalent dose of 6.3 µSv per hour (16)

For a pregnant crew member working on this worst-case route, she could work 79 block hours each month without the dose to the conceptus exceeding the FAA monthly-recommended limit of 0.5 mSv (0.5/0.0063 = 79).

She could work 2 months without the dose to the conceptus exceeding the recommended pregnancy limit of 1 mSv (1/0.5 = 2).

A number of airlines require crew members to cease flying on declaration of pregnancy, in conformity with the European Directive requirement for the radiation exposure to the foetus to be as low as reasonably achievable (3).

For passengers, the ICRP limit for the general public of 1 mSv per year would have equated to about 100 hours flying per year on Concorde, and equates to about 200 hours per year on trans-Equatorial subsonic routes (11).

There are essentially two types of airline passenger – the occasional social traveller and the frequent business traveller. The public limit of 1 mSv per year will be of no consequence to the former, but could be of significance to the frequent business traveller who would exceed the 1 mSv limit if flying more than 8 transatlantic or 5 UK-Antipodean return subsonic journeys per year (11). However, business travellers are exposed to radiation as an essential part of their occupation and it is logical to apply the occupational limit of 20 mSv to this group. This view has the support of the ICRP (6).

Epidemiology

The annual aircrew dose of cosmic radiation is a relatively low level of overall exposure, with the maximum being no more than 2 or 3 times the annual level of exposure to background radiation at ground level. There have been a number of epidemiological surveys of cancer mortality and incidence in commercial flight crew members over the years, which have reported small excesses of a variety of cancers. However the results have lacked consistency.

This lack of consistency mainly derives from the small size of cohorts examined and the lack of data on exposure and confounding factors that might explain the findings.

In Europe two large mortality cohort studies, one amongst flight deck crew (8) and one amongst cabin crew (56), together with a large cancer incidence study amongst Nordic pilots (39) have been recently published. They are based on data from many of the individual studies in the literature but contain additional data, providing increased statistical power in looking at small excesses, allow measures of consistency between studies to be determined, and provide the basis for dose-response assessments.

Both the Blettner et al paper (8), which looked at 28,000 flight deck crew with 547,564 person years at risk, and the Pukkala et al paper (39), comprising 177,000 person years at risk from 10,211 pilots, concluded that occupational risk factors were of limited influence on the findings. There was consistency though in the mortality study showing an excess of malignant melanoma. In the incidence study, this excess referred to both malignant melanoma and other forms of skin cancer as well.

In the Blettner paper, the discussion states "*Both incidence and mortality from malignant melanoma have been increased in previous cockpit crew studies most of which are also included in our analysis. It is difficult to demonstrate an excess of melanoma in mortality studies because of the high survival rate for this disease. The 1.8 fold mortality increase among cockpit crew in our study was based on 25 melanoma deaths, with high risks reported mainly from Northern European countries (except Finland). Occupational UV exposure is unlikely as shielding of aircraft windows against ultraviolet radiation is effective. More frequent leisure–time sunlight exposure has been suggested as a probable explanation, but more information on this issue is clearly required. An association between ionizing radiation and incidence of melanoma remains under debate. Supporting a possible melanoma-ionizing radiation link, slight increases in melanoma risk among radiologic technologists were reported recently. Among Nordic pilots a positive dose response relationship between estimated radiation exposure and melanoma incidence was observed although the authors concluded that the excess* *melanoma incidence may well be attributable to ultraviolet radiation. Possible interactions between ionizing and UV-radiation also require further study.”*

Pukkala et al (39) concluded that although the risk of melanoma increased with estimated dose of ionizing radiation, the excess may well be attributable to solar ultra-violet radiation.

In the study by Zeeb et al (56), the excess mortality from malignant melanoma was restricted to male cabin crew members.

Several studies in the last decade have suggested a small excess of breast cancer amongst female flight attendants (cabin crew). However, as previously noted, the interpretation has been hampered by sample size and lack of detailed information on confounding factors.

In an attempt to unify the findings, the study by Zeeb et al (56) examined data from eight European countries. Mortality patterns among more than 44,000 airline cabin crew members were investigated, yielding approximately 655,000 person-years of follow-up. Among female cabin crew, overall mortality and all-cancer mortality were slightly reduced, while breast cancer mortality was slightly but non-significantly increased.

The discussion states “*Breast cancer incidence among female cabin crew has previously been studied in Finland, Denmark, Iceland, Norway and the United States. Several studies have shown an increased risk of breast cancer among women with a long duration of employment, but the results have not been consistent. All of the above Northern European countries also contributed to the current analysis, which did not show significantly increased mortality from breast cancer in the overall cohort. SMR elevations were not confined to Nordic countries, as indicated by the absence of heterogeneity. However, increased incidence of breast cancer does not necessarily result in mortality increases, partly because women from higher social classes tend to have their cancers diagnosed in early stages, and their stage-adjusted survival rates are higher than those of women from lower social strata. In general, the potential insensitivity of mortality studies for relatively nonfatal cancers such as breast cancer should be kept in mind. However, our results are consistent with both the 40 percent increase in breast cancer risk reported from the Nordic countries and no excess.*
Ionizing radiation could contribute to an excess risk of breast cancer among cabin crew, but the association may be confounded by differences in reproductive factors or other lifestyle factors. Retired personnel in our study had worked for a relatively short time (the mean duration of employment was 7.5 years among women). The corresponding cumulative radiation dose probably did not exceed 20 – 30 mSv. Therefore, any effect of ionizing radiation on breast cancer mortality in our cohort is likely to have been very small and not detectable in an epidemiologic study, even a study of this size.
Disruption of circadian rhythms has been cited as a further possible breast cancer risk factor. An alteration in melatonin metabolism decreasing the oncostatic function of this hormone has been hypothesized to be a potential biologic mechanism. Studies carried out among blind and visually impaired

persons, in whom melatonin production is not suppressed by light, and among shift working women support a possible role for melatonin in breast cancer development. Beyond showing the absence of any substantial breast cancer mortality increase among female cabin crew, our study did not contribute new data to the ongoing discussion on melatonin. Reproductive factors and social class as potential confounders could not be directly assessed in most cohorts contributing to our study. Previous studies have reported conflicting findings regarding reproductive history among cabin crew relative to the general population. No differences were found in an Icelandic study, while a lower number of children and a higher age at first birth were reported in the Finnish cabin crew cohort. A major effort would be required to further disentangle the relative contributions of occupational, reproductive, and other factors associated with breast cancer mortality."

Increasing the size of the cohorts studied will still have limited influence on interpretation if the information on explanatory variables is unavailable. Even when more detailed information is to hand, data anomalies, possibly related to sample size, come into play.

For example, a study by Raffnson et al in 2003 based on 35 cases of breast cancer (41), for which more detailed information on reproductive history is available, attempts to further identify the relative contribution of occupation to the excess seen in their earlier cohort study (40).

The authors' conclusion that length of employment during specific time periods may be an important cause of breast cancer among cabin attendants, adds to the debate on the relative contribution of occupation, but also raises some further questions on interpretation.

In the analysis, a cut-off date of 1971 when jet aircraft were introduced to service was selected and employments examined pre and post this date. An arbitrary length of employment of 5 years was selected to dichotomize the data. When the results are examined the risk is seen to be only significantly increased during this early period, when cosmic radiation doses would have been lower due to altitude considerations. To counter the potential anomaly regarding higher doses after this period, when no excess is seen, the authors suggest that sufficient time must be allowed for latency considerations, (in the order of thirty years). It will be difficult on this basis to disentangle cosmic radiation effects from those of years of employment, if on the basis of the pre 1971 results it is thought that both contribute to the aetiology.

The study did use detailed information on reproductive history, but possibly affected by the small dataset involved, produced findings that were contrary to the accepted role of nulliparity and age at first childbirth (breast cancer being associated with nulliparity, late age for first pregnancy, cigarette smoking and strong family history).

Overall the conclusion from Zeeb et al (56) was that among airline cabin crew in Europe, there was no increase in mortality that could be attributed to cosmic radiation or other occupational exposures to any substantial extent.

Conclusion

Whilst it is accepted that there is no level of ionising radiation exposure below which effects do not occur, all the current evidence indicates that the probability of airline crew members or passengers suffering any abnormality or disease as a result of exposure to cosmic radiation is very low.

Epidemiological studies of flight deck crew and cabin crew have not shown any increase in cancer mortality or cancer incidence that could be directly attributable to ionising radiation exposure.

However, individual mortality studies and combined analyses have shown an excess of malignant melanoma. Separate and combined analyses of cancer incidence have shown an excess for malignant melanoma and for other skin cancers. Many authors believe the findings can be explained by exposure to ultraviolet light. Some others believe that the influence of cosmic radiation cannot be entirely excluded, although no plausible pathological mechanism has been identified

With respect to the suggestion that cabin crew may be at a higher risk of contracting breast cancer than those females in a non-flying occupation, it is very difficult to effectively disentangle the relative contributions of occupational, reproductive and other factors associated with breast cancer using the data currently available.

Current programmes in place for assessing the cosmic radiation exposure for crew members and passengers in commercial aircraft appear to be adequate.

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Figure 1 is reproduced from the journal Health Physics with permission from the Health Physics Society and the National Council on Radiological Protection and Measurements.

Summary

Aircraft occupants are exposed to elevated levels of cosmic radiation of galactic and solar origin. The intensity of the different particles making up atmospheric cosmic radiation, their energy distribution, and their potential biological effects vary with altitude, geomagnetic latitude, and the point of time in the sun's magnetic activity cycle.

The sun has a varying magnetic field, which reverses direction approximately every 11 years. Near the reversal, at 'solar minimum', there are few sunspots and the sun's magnetic field extending throughout the solar system is relatively weak. At solar maximum there are many sunspots and other manifestations of magnetic turbulence.

When the solar magnetic field is stronger, less galactic cosmic radiation reaches the earth. Thus solar maximum causes a radiation minimum and, conversely, solar minimum is at the time of radiation maximum. At commercial jet aircraft operating altitudes, the ratio for galactic cosmic radiation at solar minimum to that at solar maximum is about 1.2 to 2 and increases with altitude.

The earth's magnetic field has a larger effect than the sun's magnetic field on cosmic radiation approaching the atmosphere. The protective effect is greatest at the equator and least at the magnetic poles. At jet aircraft operating altitudes, galactic cosmic radiation is 2.5 to 5 times more intense in Polar regions than near the equator.

The earth's surface is shielded from cosmic radiation by the atmosphere, the ambient radiation decreasing with altitude by approximately 15% for each increase of around 2,000 ft (dependent on latitude).

As well as providing shielding from galactic cosmic radiation, the atmosphere contributes different components to the radiation flux as a function of atmospheric depth. The total effective dose rate at 30,000 ft is about 90 times the rate at sea level, with neutrons being the dominant component above 10,000 ft.

About once per year a solar particle event (SPE) occurs causing an observable increase in the intensity of the cosmic radiation field at commercial jet aircraft operating altitudes. Since 1956, no event has presented any risk of attaining an annual dose of 1 mSv (the recommended public exposure limit).

Disruption of long distance radio communications and activity of the Aurorae Borealis and Australis are not an indication of increased ionising radiation levels at flight altitudes.

The International Commission on Radiological Protection (ICRP) recommended in 1991 that exposure of flight crew members to cosmic radiation in jet aircraft should be considered part of occupational exposure to ionising radiation.

In 1994, the Federal Aviation Administration (FAA) recommended that air carrier aircrews should be informed about their radiation exposure and associated health risks, and that they be assisted in making informed decisions with regard to their work environment.

In Europe, the Council of the European Union (EU) adopted a directive laying down safety standards for the protection of the health of workers and the general public against the effects of ionising radiation, and this was applied to aircrew with effect from May 2000. For aircrew who are likely to receive exposures in excess of 1 mSv per annum, the employer must:

- Assess the exposure of the crew concerned;
- Take into account the assessed exposure when organising working schedules with a view to reducing the doses of highly exposed aircrew;
- Inform the workers concerned of the health risks their work involves;
- Apply special protection for female aircrew during declared pregnancy. This limits the exposure to the foetus to 1 mSv for the duration of the pregnancy and indicates that the dose should be as low as reasonably achievable.

Both the FAA and the EU apply the ICRP limits for occupational exposure of a 5-year average effective dose of 20 mSv per year, with no more than 50 mSv in a single year.

The recommended exposure limits are summarised in Table 3.

Table 3 Maximum mean effective dose limits.

	ICRP	EU	FAA
General Public	1 mSv y^{-1}	1 mSv y^{-1}	1 mSv y^{-1}
Occupationally exposed	20 mSv y^{-1}, 5 yr average, but not more than 50 mSv in 1y	20 mSv y^{-1}, 5 yr average, but not more than 50 mSv in 1y	20 mSv y^{-1}, 5 yr average, but not more than 50 mSv in 1y
Foetus equivalent dose	1 mSv y^{-1}	1 mSv for declared term of pregnancy and ALARA	1 mSV maximum, but 0.5 mSv in any month
Control level	N/a	6 mSv	N/a

The Concorde supersonic transport aircraft, in service between 1976 and 2003, had ionising radiation monitoring equipment permanently installed and much data were derived. A large number of studies have been published giving effective dose rates for sub-sonic flights, validating the available computer modelling programs (such as CARI, EPCARD, SIEVERT and PCAIRE).

Mean ambient equivalent dose rates have been calculated and measured in the region of:

- Concorde: 12 – 15 μSv per hour
- Long-haul: 4 – 6 μSv per hour
- Short-haul: 1 – 3 μSv per hour.

[It has been suggested that these doses can be compared with the radiation dose received from a chest X-ray (2 trans-Atlantic crossings being equivalent to a chest X-ray). This is not the case – a chest X-ray is delivered in a short space of time to a concentrated area of the body, while the cosmic radiation dose is diluted over a period of many hours. Also the quality of the radiation is not directly comparable.]

For European crew members operating to the maximum flight time limitations, annual mean effective exposures are calculated to be:

- Long-haul: 2 – 3 mSv (< 1/5 ICRP recommended dose limit)
- Short-haul: 1 – 2 mSV (< 1/10 ICRP recommended dose limit).

A number of airlines have changed flight plans to avoid high geomagnetic latitudes during periods of predicted solar flare ground level events, with significant cost and delays to service. Data indicate that these actions were unnecessary in terms of radiation dose protection.

In considering the health risks, for an accumulated cosmic radiation dose of 5 mSv per year over a career span of 20 years the likelihood of developing cancer due to the radiation will be 0.4%, and over 30 years 0.6%. In the western population, 23% will die from some type of cancer so the overall risk increases from 23% to 23.4 – 23.6%. Compared with all the other risks encountered during the working life, this is very low.

The risk of a child inheriting radiation-induced genetic defects after exposure of a parent to ionising radiation is 1 in 2,500 following an accumulated dose of 5 mSv over 20 years. This risk is very low against a background incidence in the general population of approximately 1 in 50 for genetic abnormalities.

When compared with the other risks during pregnancy, the risks to the foetus from cosmic radiation are insignificant. The possible effects are cancer and mental retardation and there is a background rate for both these conditions in the normal population. Exposure to cosmic radiation for 80 block hours per month for a period of 4 weeks increases the risk by between 1 in 6,000 and 1 in 30,000 depending on the routes flown.

Whilst it is accepted that there is no level of ionising radiation exposure below which effects do not occur, all the current evidence indicates that the probability of airline crew members or passengers suffering any abnormality or disease as a result of exposure to cosmic radiation is very low.

Abbreviations

ALARA	As low as reasonably achievable
Bq	Becquerel
CARI	FAA computer program for effective dose calculation
CME	Coronal mass ejection
D	Absorbed dose
DE	Dose equivalent
DREF	Dose rate effectiveness factor
EPCARD	EU computer program for effective dose calculation
EU	European Union
FAA	Federal Aviation Administration (USA)
FLUKA	Transport code used in EPCARD program
GCR	Galactic cosmic radiation
GLE	Ground level enhancement
GV	Gigaelectron volts
Gy	Gray, unit of absorbed dose
H_E	Effective dose equivalent
H_T	Dose equivalent
ICRP	International Commission on Radiological Protection
JAA	Joint Aviation Authorities (Europe)
keV	Kiloelectron volts
LET	Linear energy transfer
LUIN	Transport code used in CARI program
MeV	Megaelectron volts
µSv	micro-Sievert
mSv	milli-Sievert (1 mSv = 1000 µSv)
NCRP	National Council on Radiation Protection and Measurement (USA)
NRPB	National Radiological Protection Board (UK)
PADC	Polyallyldiglycol carbonate
PCAIRE	Canadian computer program for effective dose calculation
PMR	Proportional mortality ratio – examines proportionate mortality patterns, used to generate hypotheses for follow up
Q or QF	Quality factor
RBE	Relative biological effectiveness

RR	Relative risk – examines relative risks between subgroups within a study population, independent of any external population
SIEVERT	System d’Information et d’Evaluation par Vol de l’Exposition au Rayonnement cosmique dans les Transport aeriens – French computer program for effective dose calculation
SMR	Standardised mortality ratio – examines absolute mortality experience standardised against a comparison population
SPE	Solar particle event
Sv	Sievert
TEPC	Tissue equivalent proportional counter
TLD	Thermoluminescence dosimeter
UV	Ultra violet radiation (non ionising)
W_R	Radiation weighting factor

Definitions

Absorbed dose

The energy absorbed per unit mass of tissue (joules per kilogram) when exposed to ionising radiation. The unit was originally the rad, replaced with the gray (Gy) in 1975. 100 rad = 1 Gy. Takes no account of the differing effects of different types of ionising radiation.

Alpha particle

A particle consisting of two protons and two neutrons, which may result from a specific type of radioactive decay.

Annual effective dose equivalent

The total effective dose equivalent received over a 12-month period, being the sum of the annual individual route doses.

ALARA

A principle of radiological protection requiring that all exposure should be as low as reasonably achievable, taking account of economic and social factors.

Deterministic (non-stochastic) effects

Those effects for which the severity is a function of the dose received and for which there may be a threshold, eg cataract.

Dose equivalent

The product of the absorbed dose in tissue and quality factor, taking account of the radiobiological effectiveness of the various types of ionising radiation. The unit is the Sievert (Sv), formerly the rem (1 Sv = 100 rem).

Effective dose equivalent

The sum of the products of the dose equivalents to the organs or tissue and the weighting factor appropriate to each. The unit is the Sievert (Sv).

Genetic effects

Irradiation of the ovaries and testes may cause damage to the genes in the chromosomes.

Gray

The SI unit of absorbed dose. One gray is equal to an absorbed dose of 1 joule per kilogram (100 rads).

Ionising radiation

Radiation that has sufficient energy to dislodge an orbiting electron from an atom.

Probabalistic (stochastic) effects

Those effects for which the probability of an effect occurring rather than its severity is a function of dose, without threshold eg cancer.

Proton

A particle with both mass and a positive electrical charge found in the nucleus of an atom.

Quality factor

The modifying factor used to derive dose equivalent from absorbed dose. Recommended from time to time by the ICRP.

Rad

Formerly the unit of absorbed dose. Superseded by the gray in 1975.

Radiation weighting factor

See quality factor.

Radiological protection

The science and practice aimed at preventing detrimental deterministic effects and limiting the probability of stochastic effects to acceptable levels.

Rem

Formerly the unit of dose equivalence. Superseded by the Sievert (1 rem = 0.01 Sv)

Route dose

The effective dose equivalent received by a flight crew member or airline passenger during one flight. The value is dependent upon flight profile, flight time and solar activity.

Sievert

The SI unit of dose equivalence, equal to the absorbed dose in grays multiplied by the quality factor

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