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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 consistently reported 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 conclusive evidence for any increase in cancer mortality or cancer incidence directly attributable to ionising radiation exposure. Whilst there is no level of radiation exposure below which effects do not occur, current evidence indicates that the probability of airline crew or passengers suffering adverse health effects as a result of exposure to cosmic radiation is very low.

Introduction

The planet earth is continuously bathed in high-energy galactic cosmic ionising 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 break apart its nucleus. It is when these events occur in body tissue that potentially health effects may result if the human body's self-repair mechanism fails.

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

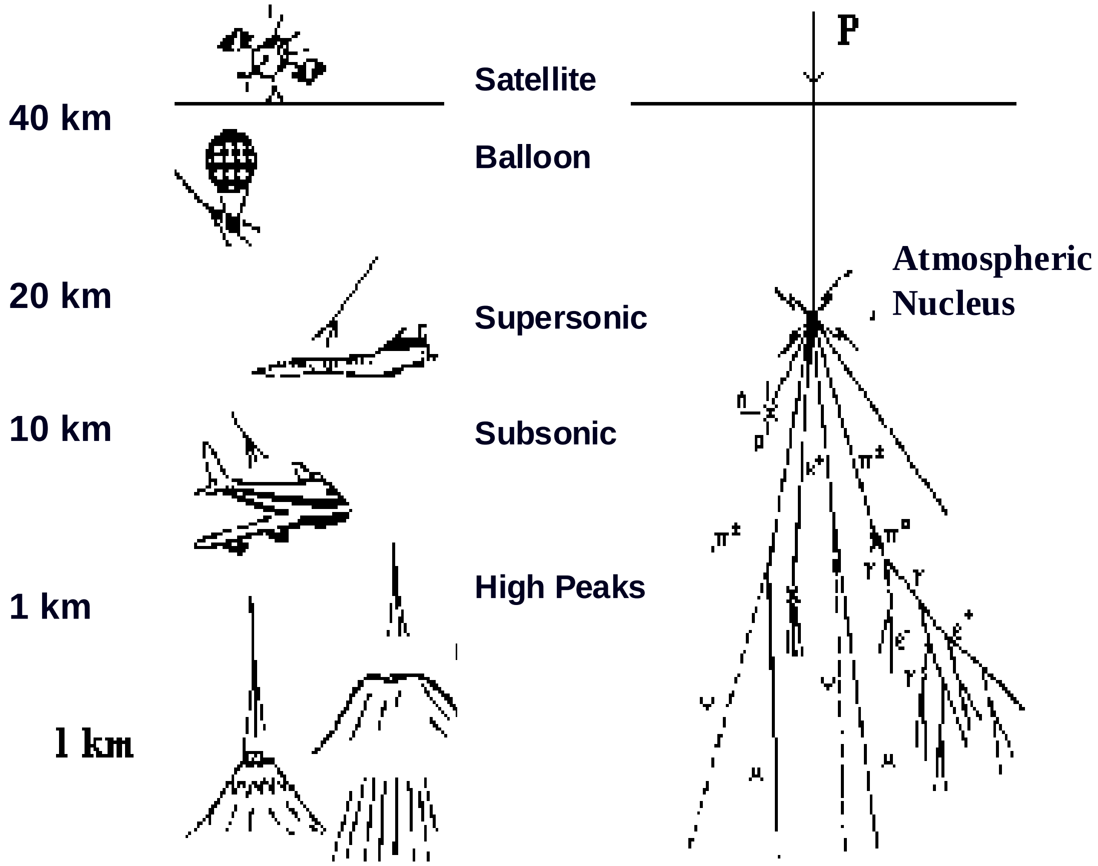
Table 1.

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 (44). Of the energetic nuclei, 87% are protons, 12% are helium ions and 1% are heavier ions.

On entering the earth's atmosphere, the particles collide with the nuclei of nitrogen, oxygen and other atmospheric atoms, generating additional ionising radiation particles. At normal commercial aircraft flight altitudes this GCR consists mainly of neutrons, protons, electrons, positrons and photons.

Diagram 1 illustrates the production of secondary particles as a primary particle penetrates the earth’s atmosphere and interacts with an atmospheric nucleus.



Terrestrial Protection from GCR

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

1. the sun's magnetic field and solar wind (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. Recently solar maximum period peaked around 2011 and the next one is expected around 2011. Near the reversal, at 'solar minimum' (around 2016 in the current cycle), 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 the geomagnetic field is almost parallel to the earth's surface. Near the magnetic poles the geomagnetic field is nearly vertical and the maximum number of primary cosmic rays can reach the atmosphere. At extremes of latitude, there is no further increase in GCR flux with increasing latitude and this is known as the polar plateau.

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 (55).

3. Life on earth is shielded from cosmic radiation by the atmosphere.

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.

The ambient radiation increases with altitude by approximately 15% for each increase of around 2,000 ft (~600 m) (dependent on latitude), with certain secondary particles reaching a maximum at around 65,000 feet (20 km) (the Pfotzer maximum). Primary heavy ions and secondary fragments become important above this point.

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 secondary components produced by 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).

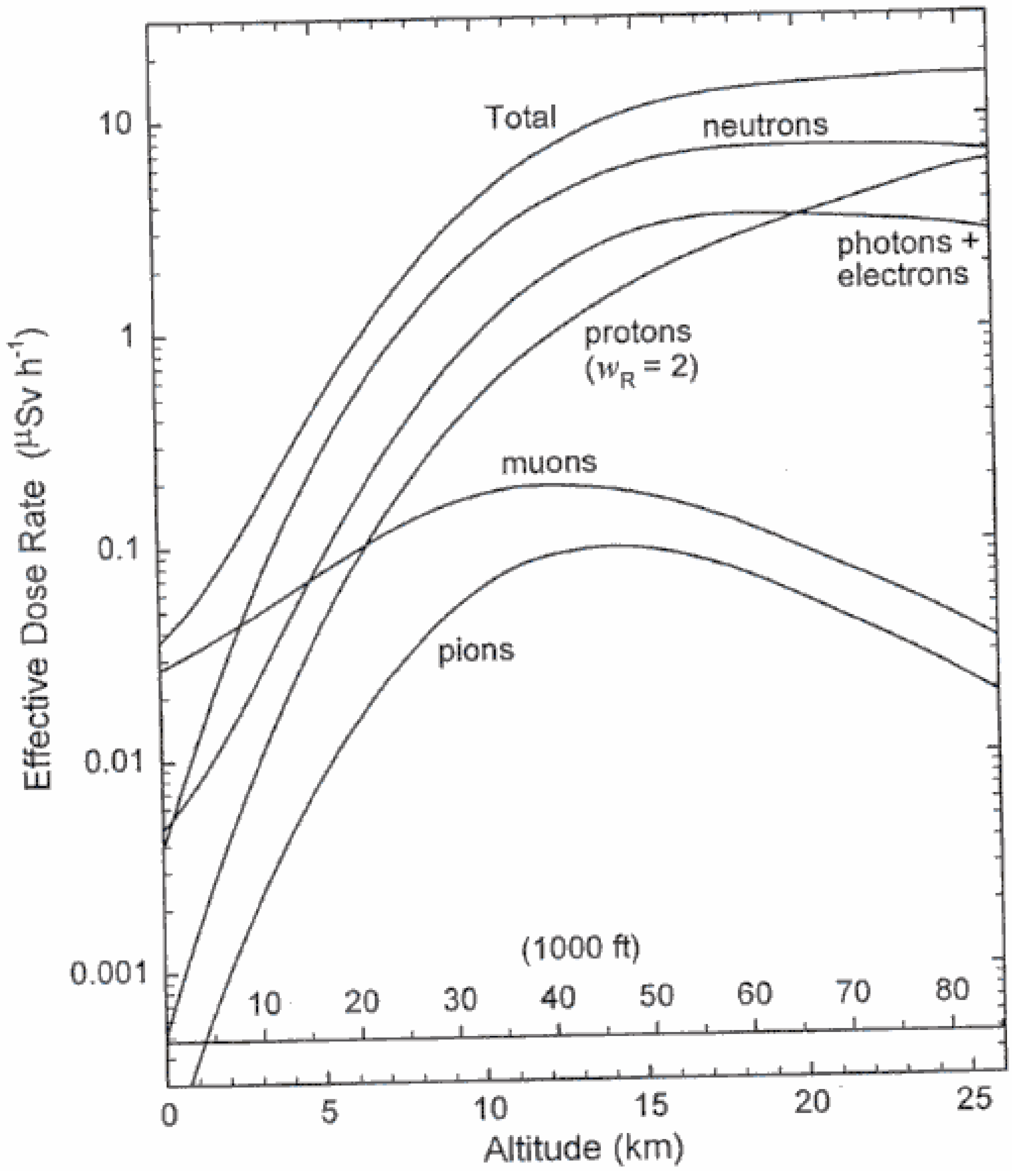


Fig. 1. Calculated effective dose rate as a function of altitude for various component particles of galactic cosmic radiation in the atmosphere near the polar plateau (cutoff = 0.8 GV) at solar minimum (June 1997). Data are courtesy of K. O'Brien, calculated using his LUIN-98F radiation transport code, 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, averaging about one per year grouped around solar maximum, 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 as a result of the enhanced solar wind (Forbush decrease). The disturbance to the geomagnetic field can allow easier access to cosmic rays and solar particles. This can give significant increases at lower latitudes particularly for SPEs. Thus the combined effect of an SPE may be a net decrease or increase in radiation dose, and further work is needed to understand the contribution of SPEs to 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 (51)

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 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. However it should be cautioned that the latitude effect exceeds the altitude effect for SPEs and Concorde did not reach very high magnetic latitudes.

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, 53).

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 (56). 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 (56).

As charged particles slow down when passing through human tissue, they lose energy. This is caused by electromagnetic interactions transferring energy to electrons leading to ionisation and excitation. The rate of energy loss increases rapidly with increasing charge of the particle and decreasing speed (56). The distance travelled depends on the energy, 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).

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. The energy loss per unit path length of a charged particle is referred to as the ‘stopping power’, while the energy deposited is referred to as 'linear energy transfer' (LET).

The biological effect of ionising radiation depends upon whether it is high- or low-LET. Early studies of the effect of identical doses of different types of radiation on biological systems showed that they produced different amounts of damage. This led to the concept of ‘relative biological effectiveness’ (RBE), which is defined as the ratio of a dose of a particular type of radiation to the dose of gamma-rays or X-rays that yield the same biological end point.

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 the judgement of the ICRP. 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 radiation weighting factor (W_R) takes account of quality factor, 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. Electrons are the low-LET radiation of prime concern at aircraft operating altitudes.

Neutrons, 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 (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.]

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 low-energy ions, neutron radiation is more effective in inducing biological damage than gamma radiation. However, there are currently no adequate epidemiological data to evaluate to what extent 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, 46, 47). 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 currently 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). The ICRP has recommended a number of quantities based on weighting absorbed dose, to take account of the RBE of different types of radiation. Dose equivalent (Sv) is one of these.

Dose equivalent (H) is defined as

$$H(\text{LET}) = Q(\text{LET}) \times D(\text{LET})$$

where Q is the quality factor and is a function of LET, and D is the absorbed dose.

The effective dose is obtained by the use of absorbed dose, D, along with different weighting factors for organs and tissues.

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 (58). 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 (58).

Medical X-rays are delivered in a concentrated localised manner, and usual doses are of the order (58):

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).

These are all average figures with wide individual variations.

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).

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’ (ALARA) (14).

This was transformed into national law of the EU member states in 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.

Maximum mean effective dose limits are summarised in Table 3.

Table 3

	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

In 2007 the ICRP revised their recommendations and whilst the general advice governing exposures did not change, it did change the method of calculating effective dose. It also clarified its recommendation that it is not necessary to treat the exposure of frequent-flyer passengers as occupationally exposed for the purposes of control (6).

In 2010 ICRP set up a task group to clarify the application of the ICRP recommendations for the protection of aircrew against cosmic rays; publication is awaited (2014).

Health Risks of Cosmic Radiation

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 2,510 (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 51 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 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 and 2007 recommendations require that cosmic radiation exposure for flight crew members should be assessed and recorded (6, 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.

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 60,000 ft (18km). Accordingly, ionising radiation monitoring equipment was permanently installed in all Concordes and much data were derived (1, 2, 9, 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, to a lesser extent, 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.

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, 43, 48, 50, 51).

Effective dose is not directly measurable, but measured operational quantity ambient dose equivalent can be a good estimator of the effective dose received from cosmic radiation. (See 'Radiation Units of Measurement', above) 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. Based on data derived from these measurements, cost-benefit analysis makes it difficult to justify the cost of installation, calibration and maintenance for such equipment in the worldwide fleet of subsonic aircraft.

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, taking 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). However, other workers question this accuracy because of uncertainty of the contribution of solar particles. 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 (European Programme Package for the Calculation of Aviation Route Doses), has been developed on behalf of the European Commission (49). This is based on the FLUKA transport code (45) 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 similar validated 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, 43, 48-51), 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 depends 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, gaining 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, the ICRP recommends that it is not necessary to treat the exposure of frequent-flyer passengers as occupationally exposed for the purpose of control and that only aircrew should be considered (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 (57), together with a large cancer incidence study amongst Nordic pilots (39) have been 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 591,584 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. Blettner concluded that the excess melanoma incidence may be attributable to ultraviolet radiation, perhaps due to leisure-time sun exposure, but more work is required.

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 (57), 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, 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 (57) examined data from eight European countries. Mortality patterns among more than 51,000 airline cabin crew members were investigated, yielding approximately 659,000 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 authors concluded that ionising radiation could contribute in a small way 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, such as circadian rhythm disruption.

A study by Raffnson et al in 2003 based on 35 cases of breast cancer (42), for which more detailed information on reproductive history is available, attempted to further identify the relative contribution of occupation to the excess seen in their earlier cohort study (40).

When the results are examined the risk is seen to be significantly increased only during the period prior to 1971, when cosmic radiation doses would have been lower due to altitude considerations. No excess is seen in the period after 1971 showing the difficulty of disentangling the contribution of cosmic radiation to the aetiology of breast cancer

Overall the conclusion from Zeeb et al (57) 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.

A study of Air New Zealand pilot morbidity published in 2012 showed that pilots have a lower prevalence of most medical conditions, with the exception of a small increase in kidney disease and malignant melanoma (59). In common with other studies, there was no excess of cancer apart from melanoma.

A population-based case-controlled study from Iceland published by Raffnson et al in 2005 (41) concluded that the association between the cosmic radiation exposure of pilots and the risk of developing eye nuclear cataracts, adjusted for age, smoking status, and sunbathing habits, indicates that cosmic radiation may be a causative factor in nuclear cataracts among commercial airline pilots. However the study fails to address the variability in objective assessment of cataracts and the possibility of observer bias.

A report by Stern from the German Center of Aerospace in 2006 (52) concluded that the occurrence of cataract surgery amongst their pilot population is smaller than in the normal population, with no cases of pilots having to undergo cataract surgery during their career (other than one case of traumatic cataract). Similar findings are reported by the UK CAA (personal communication, 2007).

Any association between exposure of airline pilots to cosmic radiation and the development of cataracts would appear to be weak.

Conclusion

Whilst it is known that there is no level of ionising radiation exposure below which effects do not occur, the evidence so far 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 so far 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.

Similarly when considering the reported association between cosmic radiation and eye cataracts, it is difficult to exclude observer bias and the influence of sunlight, smoking, dehydration and diet associated with the protein structure changes in the lens associated with age.

The European Union has in place a legislative framework for assessing the cosmic radiation exposure for airline crew members, which appears to be effective. Other jurisdictions, such as the USA, rely on advisory material and educational programmes. There is a need to improve worldwide consistency, accuracy of calculations, measurements and allowance for, and avoidance of, solar particle events.

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