

# Cosmic Radiation

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Cosmic rays were discovered in 1911 by the Austrian physicist, Victor Hess. The planet Earth is continuously bathed in high-energy galactic cosmic ionizing 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), although 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. Inhabitants of planet Earth gain protection from the effects of cosmic radiation from the Earth's magnetic field and the atmosphere, as well as from the sun's magnetic field and solar wind. These protective effects extend to the occupants of aircraft flying within the Earth's atmosphere, although the effects can be complex for aircraft flying at high altitudes and high latitudes.

Travelers in space do not have the benefit of this protection and are exposed to an ionizing radiation field very different in magnitude and quality from the exposure of individuals flying in commercial airliners. The higher amounts and distinct types of radiation qualities in space lead to a large need for understanding the biological effects of space radiation. It is recognized that although there are many overlaps between the aviation and the space environments, there are large differences in radiation dosimetry, risks and protection for airline crewmembers, passengers, and astronauts. These differences affect the application of radiation protection principles of risk justification, limitation, and the principle of as low as reasonably achievable (ALARA). This chapter accordingly is divided into three major sections, the first dealing with the basic physics and health risks, the second with the commercial airline experience, and the third with the aspects of cosmic radiation appertaining to space travel including future considerations.

## FUNDAMENTAL PHYSICS OF COSMIC RADIATION

### Ionizing Radiation

Ionizing 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 tissues of the body that health effects may result if the human body's self-repair mechanisms fail. Ionizing radiation types and their properties are shown in Table 8-1.

Outside the Earth's atmosphere, GCR consists mostly of fast-moving protons (hydrogen nuclei),  $\alpha$ -particles (helium particles), and high charge and energy (HZE) nuclei ranging from lithium to uranium. GCR is 98% atomic nuclei and 2% electrons (1). Of the energetic nuclei, 87% are protons, 12% are helium ions, and 1% are heavier ions. The energy of GCR is expressed as mega-electron volt per atomic mass unit ( $1 \text{ mMeV/u} = 9.64853336 \times 10^{13} \text{ m}^2/\text{s}^2$ ). The energies range from a few MeV/u to more than 10,000 MeV/u peaking near 1,000 MeV/u. The higher energy ions move close to the speed of light.

As charged particles pass through shielding or the atmosphere and tissue, they lose energy and undergo nuclear interactions. Energy loss is caused by electromagnetic interactions transferring energy to electrons leading to ionization and excitation. The rate of energy loss increases rapidly with increasing charge of the particle and decreasing speed (2). The distance traveled 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 result in energy losses that appear as isolated occurrences along the particle's path.

Nuclear interactions produce lower charge and mass nuclei from a primary GCR nucleus and secondary radiation from the material being hit (3). The mean free path for nuclear collision is on the order of 10 cm and after

TABLE 8 - 1

## Ionizing Radiation Types and Properties

Radiation Type	Consists of	Range in Air	Range in Human Tissue	Hazard Site <sup>a</sup>
$\beta$ Particles	An electron	Several meters	Few millimeters	Internal + external
$\gamma$ Rays	Electromagnetic ray	Many meters	Many centimeters	Internal + external
X-rays	Electromagnetic ray	Many meters	Many centimeters	External
Protons	Free proton	Few to many centimeters	Few to many centimeters	External
Neutrons	Free neutrons	Many meters	Many centimeters	External
$\alpha$ Particles	2 Protons + 2 neutrons (helium)	Few centimeters	Cannot penetrate skin	Internal
High charge and energy (HZE) nuclei	Nuclei of atoms with n-neutrons and z-protons	Few to many centimeters	Few to many centimeters	External

<sup>a</sup>The hazard site refers to whether the radiation type exerts its effect only on ingestion or inhalation (internal), or whether it can penetrate the human body (external).

several mean free paths the primary GCR heavy ions are converted largely into protons and neutrons. On entering the Earth's atmosphere, the particles collide with the nuclei of nitrogen, oxygen, and other atmospheric atoms, generating additional (secondary) ionizing radiation particles. At normal commercial aircraft flight altitudes, this GCR consists mainly of neutrons, protons, electrons, positrons, and photons.

Figure 8-1 illustrates the production of secondary particles as a primary particle penetrates the Earth's atmosphere and interacts with an atmospheric nucleus.

### Terrestrial Protection from Galactic Cosmic Radiation

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 that reverses direction approximately every 11 years. Recently solar maximum period peaked around 2000 to 2002 and the next one is expected around 2011. Near the reversal, at "solar minimum" (around 2006 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 (4).

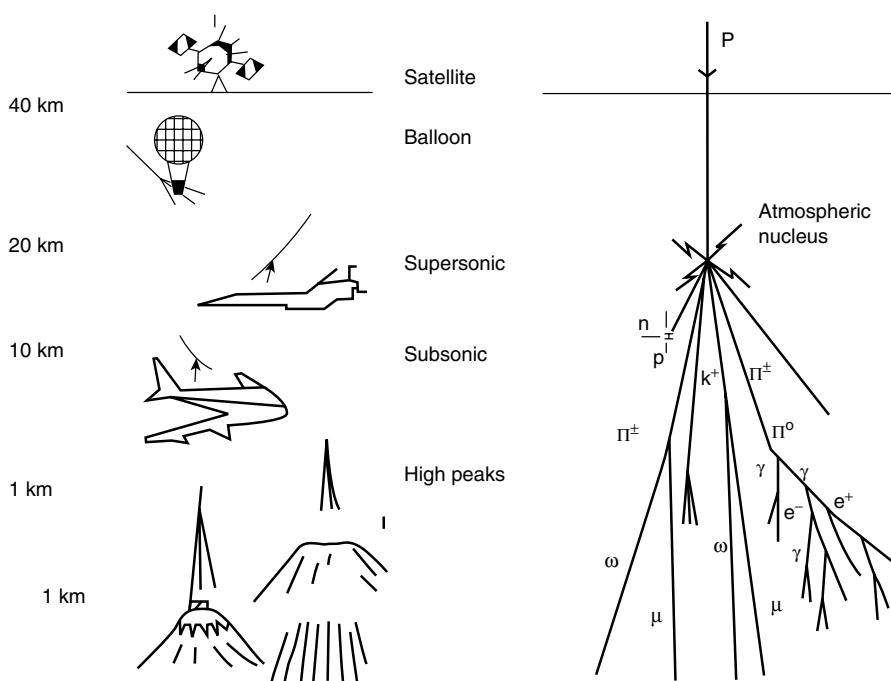


FIGURE 8-1 Production of secondary particles in the atmosphere.

When the solar magnetic field is stronger, the paths of the electrically charged ions are deflected further and less GCR reaches the Earth. Therefore, 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 (5,6).

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 toward the equator, the size of this effect being dependent 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 (7).

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

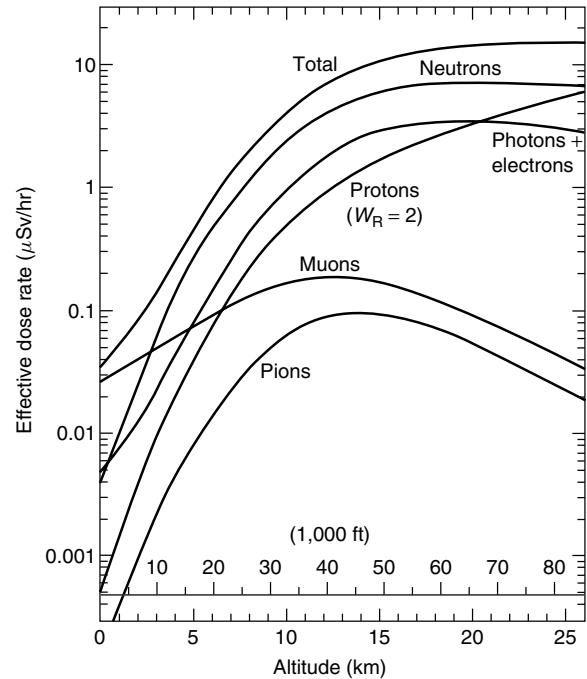
Charged cosmic radiation particles lose energy as they penetrate the atmosphere by ionizing the atoms and molecules of the air (releasing electrons). The particles also collide with the atomic nuclei of nitrogen, oxygen, and other atmospheric constituents.

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

In addition to 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. Dose rate increases with both altitude and latitude. The effect of increasing latitude at a constant altitude is greater than that of increasing altitude at a constant latitude.

Figure 8-2 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) (4).

It can be seen that the total effective dose rate at 30,000 ft is approximately 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



**FIGURE 8-2** 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 2 (NCRP 1993) rather than 5. (Reproduced from Goldhagen P. Overview of aircraft radiation exposure and recent ER-2 measurements. *Health Phys* 2000;79(5):586–591, the journal *Health Physics* with permission from the Health Physics Society and the National Council on Radiation Protection and Measurements.)

that at all altitudes from 10,000 ft to more than 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*, 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 ionization of the Earth's upper atmosphere by x-rays, protons or ultraviolet radiation from the sun. This can occur in the absence of excessive ionizing 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 ionizing 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 approximately 1/yr grouped around solar maximum, and the spectrum varies between events (8). 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. Therefore, 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 analyzed since 1942, and are numbered sequentially (9). Of the 64 GLEs observed up to 2003, with the exception of GLE5 (February 1956), none has presented any risk of attaining an annual dose of 1 mSv (the *International Commission on Radiological Protection* [ICRP] recommended public exposure limit) (10). For GLE60, which occurred in April 2001, the total contribution to radiation dose from the SPE was measured as 20  $\mu$ Sv (11).

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 approximately 1 month of GCR exposure only, which would not have given an annual dose in excess of 1 mSv (12). 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 0.5 mSv/hr. 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 (10) 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.

## RADIOBIOLOGY

### Biological Effects of Ionizing Radiation

Very high levels of ionizing radiation, such as that from a nuclear explosion, will cause severe cell damage or cell

death. Adverse health impacts include early death, within days or a few weeks, as a result of acute exposure whereas longer-term consequences include development of cancer, or genetic maldevelopment as a result of damage to the reproductive cells. It is more difficult to predict the effects of low-level doses of ionizing radiation such as cosmic radiation or medical x-rays because of the individual variability in the body's self-repair processes. Indeed, several health effects have been suggested at low doses and dose rates, including that the effect of radiation on human health is not linear, but is either a J-shaped curve with exposure being beneficial at low doses (13,14); or in contrast is increased due to nontargeted effects where cells not directly traversed by radiation tracks are responsible for malignancy (15,16).

Biological effectiveness depends on the spatial distribution of the energy imparted and the density of the ionizations per unit path length of the ionizing particles. The energy loss per unit path length of a charged particle is referred to as the *stopping power*, whereas the energy deposited is referred to as *linear energy transfer* (LET).

The ionization process in living tissues consists of atomic and molecular excitations, and ejecting bound electrons from the cellular molecules, leaving behind chemically active radicals that 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 (17). The number of ionization events per particle passage is related to the physical processes by which particle kinetic energy is transferred to the cellular bound electrons (2). The rate at which ions produce electrons in isolated cells is important because repair of a single event is relatively efficient unless many events occur within the repair period (14).

The substantive target of radiation injury is considered to be the DNA structure that may be changed or injured directly by a passing ionizing particle (2). DNA damage consists of simple types with a single base damage or break in the DNA sugar-phosphate backbone, termed a *single strand break*, to complex types where two or more damages occur in a single helical turn of DNA. The spectrum of DNA damages shifts from simple to more complex as the LET is increased (18). Double-strand breaks (DSB), defined as one or more breaks on opposing sides of the DNA sugar-phosphate backbone within 20 base pairs of each other, are expected to be the most detrimental form of DNA damage leading to various forms of mutation including gene deletion and chromosomal aberrations. For high-LET radiation, most DSB are highly complex involving base damage and other breaks near a DSB.

The ability of the cell to repair the effects of ionization depends on the class of DNA lesion (simple or complex) and 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. There are two major pathways of DSB repair in vertebrates (19): (i) nonhomologous end-joining (NHEJ) and (ii) homologous recombination (HR). NHEJ is an error-prone form of repair and is dominant in

the prereplication phase of the cell cycle and in resting cells. This process involves removal of damaged regions near the initial break and ligation of the remaining DNA ends. HR is a high-fidelity form of DNA damage repair, acting during DNA replication and mitosis, and requires a sister chromatid to act as a template for the synthesis of DNA during repair.

In recent years, there has been increased focus on non-DNA targets for harmful biological effects of radiation (15, 16). These include oxidative damage in the cytoplasm and mitochondria, and aberrant cell signaling processes that disrupt normal cellular processes such as the control of cellular growth factors, the tissue microenvironment, and DNA replication. These so-called nontargeted effects can be both mutagenic and carcinogenic.

### 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 utilizing the body's self-repair mechanisms. 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 crewmembers, and related these to cosmic radiation exposure (20–22). Nicholas et al. noted that unstable aberrations decrease with time and therefore 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 because they are relatively stable over time since exposure (23). Nicholas et al. also showed that the mean number of translocations per cell was significantly higher among the airline pilots who were studied compared to controls. However, within the radiation exposure range encountered in the study, observed values among the pilots did not correspond to the dose–response pattern expected on the basis of available models for chronic low-dose radiation exposure. In addition, this study does not determine the role of radiation in the induction of translocations and so far, no epidemiologic evidence links these aberrations with the development of cancers.

Studies of chromosome aberrations with high-LET radiation, including heavy ions, show that the complexity of chromosome aberrations also increases with LET (24). These studies are made using multicolor fluorescence *in-situ* hybridization (FISH), where chromosome-specific probes are used to label individual chromosomes, and aberrations between two or more chromosomes are observed after irradiation as illustrated in Figure 8-3. The number of chromosomes involved in chromosomal aberrations appears to increase with the LET of the radiation field. George et al. (25) reported the number and types of chromosomal aberrations in astronauts on the International Space Station (ISS).

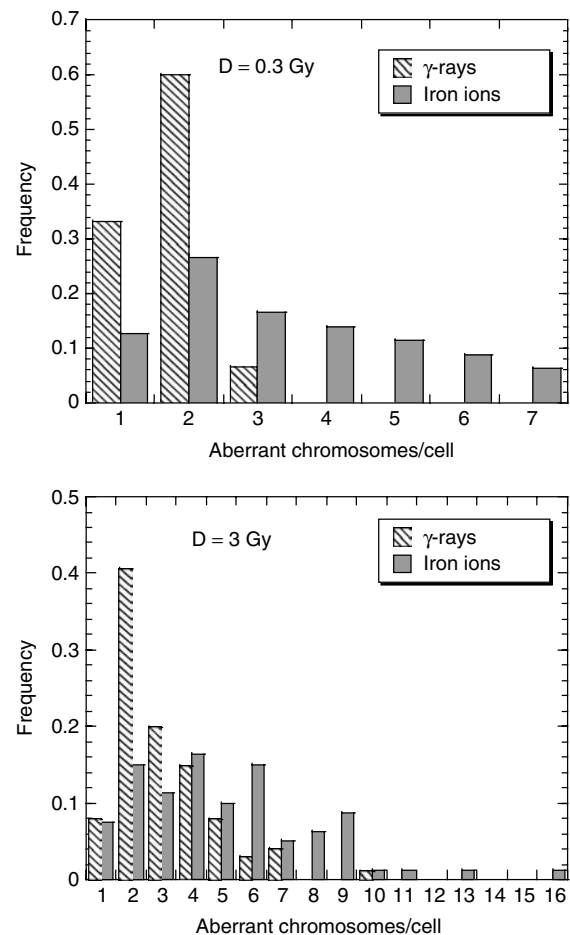
The biological effect of ionizing radiation depends upon whether it is high or low LET. Early studies of the effect of identical doses of different types of radiation on biological systems showed that different amounts of damage were

produced. 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 endpoint.

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 on appropriate biological data but also on the judgment 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 (26). The radiation weighting factor ( $W_R$ ) takes account of quality factor, and recommendations are published from time to time by the ICRP (26).

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, with neutrons providing approximately half the effective dose at high altitudes.



**FIGURE 8-3** Observation of chromosomal aberrations in human lymphocyte cells exposed to 300 mGy of  $\gamma$  rays or 1 GeV/u iron ions. (Durante M, George K, Wu H, et al. Karyotypes of human lymphocytes exposed to high-energy iron ions. *Radiat Res* 2002;158:581–590.)

TABLE 8-2

## Radiation Weighting Factors

Type and Energy Range of Incident Radiation	Weighting Factor
Photons (all energies)	1
Electrons and muons (all energies)	1
Protons (incident)	5 <sup>a</sup>
Neutrons <10 keV	5
Neutrons 10–100 keV	10
Neutrons >100 keV–2 MeV	20
Neutrons >2–20 MeV	10
Neutrons >20 MeV	5
α Particles, fission fragments, heavy ions	20

<sup>a</sup>The ICRP has proposed 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.

(ICRP Publication 92: Relative Biological Effectiveness, Quality Factor, and Radiation Weighting Factor, 92. Elsevier, 2003.)

At all altitudes from 10,000 ft to more than 80,000 ft (3–25 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 no adequate epidemiologic data to evaluate to what extent neutrons are carcinogenic to humans (27).

The current weighting factors are shown in Table 8-2. The weighting factor for neutrons depends on 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 (26).

These proposals are based on current knowledge of biophysics and radiobiology, and acknowledge that judgments about 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.)

### 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 microSievert ( $\mu\text{Sv}$ ) per hour or milli-Sievert (mSv) per year (1 mSv = 1,000  $\mu\text{Sv}$ ).

The Sievert has superseded the rem as the unit of measurement of effective dose (1 Sv = 100 rem, 1 mSv = 100 mrem, 1  $\mu\text{Sv}$  = 0.1 mrem).

### Other Terrestrial Sources of Ionizing Radiation

There is a constant background flux of ionizing radiation at ground level. Terrestrial background radiation from the Earth's materials contributes 2.6 mSv/yr in the United Kingdom and 3 mSv/yr in the United States (28). This flux is dominated by the low-LET component (93%).

Inhaled radon gas contributes approximately 2 mSv/yr to the total overall background ionizing radiation level (28).

Medical x-rays are delivered in a concentrated localized manner, and usual doses are of the order (28):

Chest x-ray	0.1 mSv (100 $\mu\text{Sv}$ )
Body computed tomographic (CT) scan	10 mSv
Chest CT scan	8 mSv
Intravenous pyelogram (IVP)	1.6 mSv
Mammogram	0.7 mSv (700 $\mu\text{Sv}$ )

These are effective doses averaged over the entire body, accounting for the relative sensitivities of the different tissues exposed.

Doses received from radiotherapy for cancer treatment range from 20 to 80 Sv (29). 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 ICRP recommends maximum mean body effective dose limits of 20 mSv/yr (averaged over 5 years, with a maximum in any 1 year of 50 mSv), with an additional recommendation that the equivalent dose to the fetus should not exceed 1 mSv during the declared term of the pregnancy. This limit for the fetus is in line with the ICRP recommendation that the limit for the general public should be 1 mSv/yr (30).

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

In the United Kingdom, the National Radiological Protection Board (NRPB) recommends that a record be

TABLE 8 - 3

## Summary of Maximum Mean Effective Dose Limits

	ICRP	EU	FAA
General public	1 mSv/yr	1 mSv/yr	1 mSv/yr
Occupationally exposed	20 mSv/yr, 5-yr average, but not more than 50 mSv in 1yr	20 mSv/yr, 5-yr average, but not more than 50 mSv in 1yr	20 mSv/yr, 5-yr average, but not more than 50 mSv in 1yr
Fetus equivalent dose	1 mSv/yr	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

ICRP, International Commission for Radiological Protection; EU, European Union; FAA, Federal Aviation Administration; ALARA, as low as reasonably achievable.

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 6 mSv/yr, this being referred to as the *control level*. This value is a cautious arbitrary figure, representing three tenths of the annual maximum for classified workers and has no radiobiological significance (31).

In 1991, the ICRP recommended that exposure of flight crewmembers to cosmic radiation in jet aircraft should be considered part of occupational exposure to ionizing radiation (30).

In 1994, the United States Federal Aviation Administration (FAA) formally recognized that air carrier aircrews are occupationally exposed to ionizing radiation, and recommended that they be informed about their radiation exposure, associated health risks, and that they be assisted in making informed decisions with regard to their work environment (32). The FAA subsequently issued a technical report in October 2003 advising aircrew about their occupational exposure to ionizing radiation (33). The FAA recommends the limit for an aircrew member of a 5-year average effective dose of 20 mSv/yr, with no more than 50 mSv in a single year (34). For a pregnant aircrew member starting when she reports her pregnancy to management, the recommended limit for the conceptus is an equivalent dose of 1 mSv, with no more than 0.5 mSv in any month (34).

Following the ICRP recommendation, 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 ionizing radiation (35). 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/yr appropriate measures must be taken. In particular, the employer must perform the following functions:

- Assess the exposure of the crew concerned.
- Take into account the assessed exposure when organizing 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

The European Directive applies the ICRP limits for occupational exposure (20 mSv/yr) and the 1-mSv exposure limit to the fetus for the duration of declared pregnancy. In addition, the European Directive indicates that radiation exposure to a pregnant crewmember should be “as low as reasonably achievable” (ALARA) (35). 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 ALARA, with an absolute maximum of 1 mSv. However, the FAA recommends a maximum dose to the fetus of 1 mSv but allows 0.5 mSv in any month, making no reference to ALARA. Maximum mean effective dose limits are summarized in Table 8-3.

## 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/yr over a career span of 20 years (a typical prediction for a long-haul crewmember), the likelihood of developing cancer will be 0.4% (33,36). 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% (33,36). 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 ionizing radiation is at risk of inheriting radiation-induced genetic defects. These may take the form of anatomic or functional abnormalities apparent at birth or later in life. The risk following an accumulated dose of 5 mSv/yr over a career span of 20 years will be 1 in 2,510 (33). 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% to 3% of liveborn children having one or more severe abnormalities at birth (33).

3. **Risk to the health of the fetus.** The risks to the fetus from ionizing radiation are cancer and mental retardation. There is a background rate of approximately 1 in 39,000 for neonatal lymphoblastic leukemia and 1 in 170 for childhood mental retardation within the general population. It is estimated that exposure of the fetus to cosmic radiation for 80 block hours/mo 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%) (33).
4. **Noncancer effects (degenerative tissue risks).** The most important of the noncancer risks due to radiation exposure are degenerative diseases including heart and digestive diseases, early and late effects in the central nervous system, and cataracts. Noncancer effects are thought to be deterministic in nature, occurring only above a dose threshold well above aviation doses and most space missions, except for a Mars mission or extraterrestrial exposure to a large SPE. However, recent epidemiologic studies (37,38) indicate threshold concepts do not seem to hold, indicating these risks are a concern for spaceflight.

## COSMIC RADIATION IN COMMERCIAL AVIATION

### Measurement of Cosmic Radiation Doses in Aviation

The ICRP 1991 recommendations require that cosmic radiation exposure for flight crewmembers should be assessed and recorded (30). It has been seen that the GCR 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 approximately 60,000 ft (18 km). Accordingly, ionizing radiation monitoring equipment was permanently installed in all Concorde and much data were derived (39–43).

The introduction of aircraft such as the Boeing 747-400 and the Airbus A330 and A340 has led to the development of ultralong haul 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.

GCR 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 subsonic flights, measured both actively and passively (5,11,36,39,40,44–51). These values are discussed in the next section.

Effective dose cannot be measured directly, but ambient dose equivalent, which is a measured operational quantity, can be a good estimator of the effective dose received from cosmic radiation. (See section **Radiation Units of Measurement**) 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. On the basis of 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 crewmembers. 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. reported that during an experiment involving crew members voluntarily wearing personal dosimeters, 8% of the badges were lost or not used and 2% had received additional x-rays during baggage security screening (12). The logistics and 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 GCR, taking account of the following factors:

- 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
- Helicentric 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 U.S. FAA based on the LUIN transport code (52). 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  $\pm 7\%$  (12). However, other workers question this accuracy because of the uncertainty associated with the contribution of solar particles. There is a freely available interactive version of CARI-6, which runs on the Internet and is publicly accessible (<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, European Programme Package for the Calculation of Aviation Route Doses (EPCARD), has been developed on behalf of the European Commission (53). This is based on the FLUKA transport code (54) and is again limited to the galactic cosmic ray component, which is isotropic and of constant spectrum outside of the heliosphere. The Systeme d'Information et d'Evaluation par Vol de l'Exposition au Rayonnement cosmique dans les Transport aeriens (SIEVERT) system which has been developed on behalf of the French Aviation Administration (DGAC) (12) is freely available (<http://www.sievert-system.org>). A similar validated Canadian program is known as PCAIRE and is also freely available ([www.pcaire.com](http://www.pcaire.com)) (46).

These computer programs allow airline companies and their employees to comply with the ICRP recommendations to monitor radiation exposure. European airlines have a statutory duty to comply with the ICRP recommendations as a result of the EU Directive (see the preceding text). However, elsewhere in the world there is no legal requirement for airlines to follow the ICRP recommendation.

### Cosmic Radiation Doses Received by Aircraft Occupants

There have been many studies of cosmic radiation dose rates in both Concorde and subsonic aircraft (5,11,36,39,40,44–51,53,55), 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 computer programs discussed in the preceding text 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 ( $\mu\text{Sv}$ ) 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  $\mu\text{Sv/hr}$
- Long haul: 4–5  $\mu\text{Sv/hr}$
- Short haul: 1–3  $\mu\text{Sv/hr}$

In general, for UK-based crewmembers operating to the maximum flight time limitations of 900 hr/yr, it is calculated that:

- Long-haul crew have an annual mean effective exposure of 2 to 4 mSv/yr, less than one fifth of the ICRP recommended dose limit

- Short-haul crew have an annual mean effective exposure of 1 to 2 mSv/yr, less than one tenth of the recommended dose limit

On the worst-case U.K. high-latitude polar routes, such as London Heathrow to Tokyo Narita, the mean ambient equivalent dose rate has been measured at 6  $\mu\text{Sv/hr}$  (5). For a crewmember flying 900 hr/yr only on this route, the annual exposure would be in the region of 5.4 mSv, less than three tenths of the ICRP recommended dose limit of 20 mSv. For ultra-long range airline operations (arbitrarily defined as sector lengths in excess of 18 hours), recent studies (55) have shown a mean effective sector exposure of 80  $\mu\text{Sv}$  on the Dubai to Los Angeles route. A crew member flying three return trips per month would accrue an annual exposure of 5.76 mSv. The FAA has calculated the worst-case U.S. high altitude, high-latitude long-haul flight to be New York to Athens, with an equivalent dose of 6.3  $\mu\text{Sv/hr}$  (33)

For a pregnant crewmember 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 crewmembers to cease flying on declaration of pregnancy, in conformity with the European Directive requirement for the radiation exposure to the fetus to be as low as reasonably achievable (56). The policy of the FAA is that crewmembers must be provided with information about cosmic radiation, but there is no statutory requirement for them to stop flying.

For passengers, the ICRP limit for the general public of 1 mSv/yr would have equated to approximately 100 hours of flying per year on Concorde, and equates to approximately 200 hr/yr on trans-Equatorial subsonic routes (42).

There are essentially two types of airline passenger—the occasional social traveler and the frequent business traveler. The public limit of 1 mSv/yr will be of no consequence to the former, but could be of significance to the frequent business traveler who would exceed the 1 mSv limit if flying more than eight transatlantic or five UK-Antipodean return subsonic journeys per year (42). However, business travelers 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 (57). Although business travellers may exceed the doses for aircrew, there is no mechanism in place to monitor or control their exposure.

### Epidemiology of Commercial Aircraft Crew Members

The annual aircrew dose of cosmic radiation is a relatively low level of overall exposure, with the maximum being no more than two or three times the annual level of exposure to background radiation at ground level. There have been a number of epidemiologic surveys of cancer

mortality and incidence in commercial flight crewmembers over the years, which have reported small excesses of a variety of cancers (58,59). 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 (60) and one amongst cabin crew (61), together with a large cancer-incidence study amongst Nordic pilots (62) 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 (60), which looked at 28,000 flight deck crew with 591,584 person-years at risk, and the Pukkala et al. paper (62), 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. (62) concluded that although the risk of melanoma increased with estimated dose of ionizing radiation, the excess might well be attributable to solar ultraviolet radiation.

In the study by Zeeb et al. (61), the excess mortality from malignant melanoma was restricted to male cabin crewmembers.

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. (61) examined data from eight European countries. Mortality patterns among more than 51,000 airline cabin crewmembers were investigated, yielding approximately 659,000 person-years of follow-up. Among female cabin crew, overall mortality and all-cancer mortality were slightly reduced, whereas breast cancer mortality was slightly but nonsignificantly increased. The authors concluded that ionizing radiation may 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 (63), 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 (64). When the results are examined, the risk is seen to be significantly increased only

during the period before 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 etiology of breast cancer. Overall, the conclusion from Zeeb et al. (61) 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 population-based case-controlled study from Iceland by Raffnson et al. in 2005 (65) 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. Additionally, a report by Stern from the German Center of Aerospace in 2006 (66) concluded that the occurrence of cataract surgery amongst the German 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 U.K. Civil Aviation Authority (CAA) (Johnston, *RV personal communication*, 2007). Therefore, any association between exposure of airline pilots to cosmic radiation and the development of cataracts would appear to be weak.

## Conclusion for Commercial Aircraft Travellers

While it is known that there is no level of ionizing radiation exposure below which effects do not occur, the evidence so far indicates that the probability of airline crewmembers or passengers suffering any abnormality or disease as a result of exposure to cosmic radiation is very low. Epidemiologic 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 ionizing 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 that the findings can be explained by exposure to ultraviolet light. 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 nonflying 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 EU has in place a legislative framework for assessing the cosmic radiation exposure for airline crewmembers, which appears to be effective. Other jurisdictions, such as the United States, rely on advisory material and educational programs. There is a need to improve worldwide consistency, accuracy of calculations, measurements and allowance for, and avoidance of, SPEs.

## COSMIC RADIATION IN SPACE FLIGHT

In considering dose limits for astronauts, it is useful to consider historical recommendations that National Aeronautics and Space Administration (NASA) has received from external advisory committees that have formed the basis for dose limits. Recommendations by the National Academy of Sciences (NAS) in 1967 (67) noted that radiation protection in manned space flight is philosophically distinct from protection practices of terrestrial workers because of the high-risk nature of space missions. The report of the NAS from 1967 did not recommend “permissible doses” for space operations, noting the possibility that such limits may place the mission in jeopardy and instead made estimates of what the likely effects would be for a given dose of radiation. In 1970, the NAS Space Science Board (68) made recommendations of guidelines for career doses to be used by NASA for long-term mission design and manned operations. At that time, NASA employed only male astronauts and the typical age of astronauts was 30 to 40 years. A “primary reference risk” was proposed to be equal to the natural probability of cancer over a period of 20 years following the radiation exposure (using the period from 35–55 years of age) and was essentially a doubling dose. The estimated doubling dose of 382 rem (3.82 Sv), which ignored a dose–rate reduction factor, was rounded to 400 rem (4 Sv). The NAS panel noted that the recommendation was not a risk limit, but rather a reference risk and that higher risk could be considered for planetary missions or a lower level of risk for a possible space station (68). Ancillary reference risks were described to consider monthly, annual, and career exposure patterns. However, the NAS recommendations were implemented by NASA as dose limits used operationally for all missions until 1989.

At the time of the 1970 NAS report the major risk from radiation was believed to be leukemia. Since then, the data from the Japanese atomic bomb (AB) survivors has led to estimates of higher levels of cancer risk for a given dose of radiation including the observation that the risk of solid tumors following radiation exposure occurs with a higher probability than leukemias, although with a longer latency period before expression. Along with the maturation of the AB data and reevaluation of the dosimetry of the AB survivors, scientific assessments of the dose–response models, and dose–rate dependencies have contributed to the large increase in the risk estimate over this time period (1970–1997).

The possibility of future changes in risk estimates cannot of course be safely predicted now. Therefore, protection against uncertainties is an ancillary condition to the ALARA principle, suggesting conservatism as workers approach dose limits.

By the early 1980s several major changes had occurred leading to the need for a new approach to define dose limits for astronauts. At that time, NASA requested the National Council on Radiation Protection and Measurements (NCRP) to reevaluate dose limits to be used for low Earth orbit (LEO) operations. Considerations included increases in estimates of radiation-induced cancer risks, the criteria for risk limits, and the role of the evolving makeup of the astronaut population from male test pilots to a larger diverse population composed of approximately 100 astronauts including mission specialists, female astronauts, and higher aged career astronauts who often participate in several missions. In 1989, the NCRP Report No. 98 (69) recommended age- and gender-dependent career dose limits using a 3% increase in cancer mortality as a common risk limit. The 3% excess cancer fatality risk was based on several criteria including comparison to dose limits for ground radiation workers and to rates of occupational death in less-safe industries. It was noted that astronauts face many other risks, and adding an overly large radiation risk was not justified. It was also noted that the average years of life loss from radiation-induced cancer death, approximately 15 years for workers older than 40 years and 20 years for workers aged between 20 and 40, is less than that of other occupational injuries. A comparison of radiation-induced cancer deaths to cancer fatalities in the U.S. population is complex because of the smaller years of life loss in the general population due to most cancer deaths occurring above age 70.

In the 1990s, the additional follow-up and evaluation of the AB survivor data has led to further reductions in the estimated cancer risk for a given dose of radiation. The 2000 recommendations from NCRP (70), while keeping the basic philosophy of risk limitation in the earlier report, advocate significantly lower limits than those recommended in 1989 (69). Table 8-4 lists examples of radiation limits for

**TABLE 8 - 4**

**Career Dose Limits (in Sv) Corresponding to 3% Excess Cancer Mortality for 10-Year Careers As a Function of Age and Sex as Recommended by the National Council on Radiation Protection and Measurements (NCRP, 1989 and NCRP, 2000)**

Age, yr	NCRP Report No. 98		NCRP Report No.132	
	Male	Female	Male	Female
25	1.5 Sv	1.0 Sv	0.7 Sv	0.4 Sv
35	2.5	1.75	1.0	0.6
45	3.2	2.5	1.5	0.9
55	4.0	3.0	3.0	1.7

a career duration of 10 years with the doses assumed to be spread evenly over a career. The values from the previous report are also listed for comparison. Both of these reports specify that these limits do not apply to exploration missions because of the large uncertainties in predicting the risks of late effects from heavy ions.

The NCRP Report No. 132 (70) notes that the use of comparisons to fatalities in the less-safe industries advocated by the NCRP in 1989 is no longer viable because of the large improvements made in ground-based occupational safety. The decreased rate of fatalities in the so-called less-safe industries, such as mining and agriculture, would suggest a limit below the 3% fatality level currently compared to that in 1989. The most recent reviews of the acceptable levels of radiation risk for LEO (70) instead advocate that comparisons to career dose limits for ground-based workers be used. It is also widely held that the social and scientific benefits of space flight continue to provide justification for the 3% risk level for astronauts participating in LEO missions.

Risk projection models serve several roles (71,72); these roles include setting dose-to-risk conversion factors needed to define dose limits, projecting mission risks, and evaluating the effectiveness of shielding or other countermeasures. For mission planning and operations, NASA uses the model recommended in the NCRP Report No. 132 for estimating cancer risks from space (70). This model, which is similar to approaches described by other radiation risk assessment committees and in the scientific literature, employs a life-table formalism. This method consists of epidemiologic assessments of excess risk in exposed cohorts such as the AB survivors, and estimates of dose and dose-rate reduction factors (DDREFs) and LET-dependent radiation quality factors.

Recently, NASA recognized that projecting uncertainties in cancer risk estimates along with point estimates should be a requirement for ensuring mission safety. This is because point estimates alone have limited value when the uncertainties in the factors that enter into risk calculations are large. Estimates of 95% confidence intervals (CI) for various radiation protection scenarios are meaningful additions to the traditional point estimates, and can be used to explore the value of mitigation approaches and of research that could narrow the various factors that enter into risk calculations.

Uncertainties for low-LET radiation, such as  $\gamma$  rays, have been reviewed several times in recent years, and indicate that the major uncertainty is the extrapolation of data on cancer effects from high to low doses and dose rates (73,74). Other uncertainties include the transfer of risk across populations and sources of error in epidemiology data including dosimetry, bias, and statistical limitations. For low-LET radiation, probability distribution functions (PDFs) were described previously (72) and indicate upper 95% CI approximately two times higher than the median risk estimate used in ground-based radiation protection.

In estimating cancer risks for space radiation, additional uncertainties occur related to estimating the biological effectiveness of protons and heavy ions, and to predicting LET spectra at tissue sites (70,71). The limited understanding of heavy ion radiobiology has been estimated to be the largest contributor to the uncertainty for space radiation effects (72), and radiation quality factors are found to contribute the major portion of the uncertainties. For space radiation, upper 95% confidence levels are estimated to be approximately four times higher than the median estimate for GCR, and three times higher for proton exposures from an SPE.

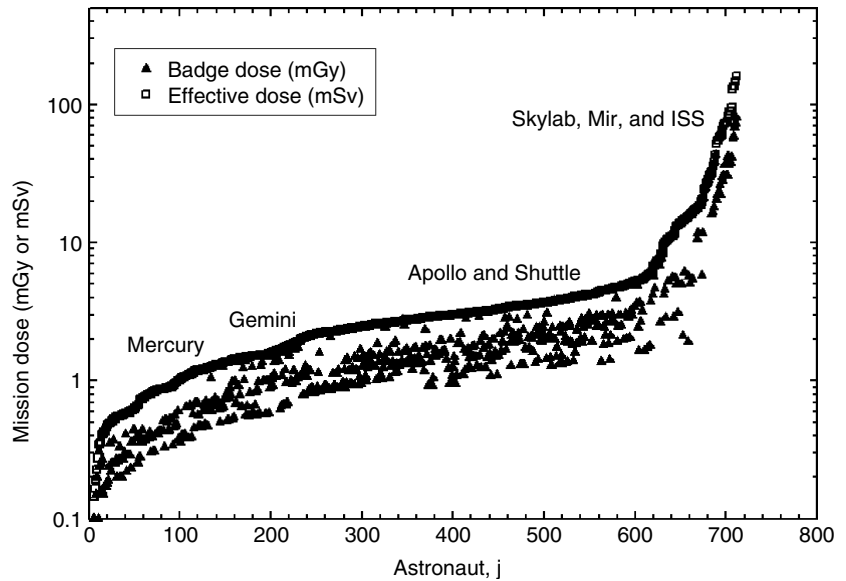
## Space Dosimetry

The use of  $W_R$  is not used directly at NASA, and instead individual organ dose and dose equivalents are estimated for each astronaut using an approach that relies on available flight dosimetry and transport models of space vehicles and the human body. In this approach  $W_R$  are replaced by LET-dependent radiation quality factors and the attenuation of space radiation by the tissue is described (70). The main source of passive dosimetry data are thermoluminescence dosimeters (TLDs) that are worn by each astronaut during his or her mission. In some cases, CR-39 plastic track detectors have been included in the passive dosimetry packages (75). Additional information is obtained by TLDs that are mounted throughout space vehicles such as the space shuttle, space station Mir, and the ISS to survey the variation of point dose dependencies from shielding variations (75).

Tissue equivalent proportional counters (TEPCs) have been flown on some space shuttle missions (76), on the Mir and the ISS. TEPCs (shown in Figure 8-4) are relatively small devices weighing less than 1 kg, providing time-dependent data and a method to estimate the individual contributions from the GCR and trapped proton doses because of the strong geographic dependence of the trapped protons (76,77) in LEO. TEPC data can be used to validate models predicting organ dose equivalents when the models of TEPC response



**FIGURE 8-4** The Tissue Equivalent Proportional Counter (TEPC) is an automatic microdosimetry system, which consists of a spectrometer unit and a detector unit. The spectrometer unit contains a computer that allows real-time analysis of the data and provides data on the dose equivalent rate as a function of lineal energy ( $y$ ) and time for space radiation. The TEPC is filled with a low-pressure gas. TEPCs are also used in aviation.



**FIGURE 8-5** The badge doses and effective doses versus calendar year from all astronauts on all National Aeronautics and Space Administration (NASA) space missions [Mercury, Gemini, Apollo, Skylab, Apollo-Soyuz, Shuttle, Mir, and ISS (Expedition 1–10)]. (Updated from Cucinotta FA, Wu H, Shavers MR, et al. Radiation dosimetry and biophysical models of space radiation effects. *Gravit Space Biol Bul* 2003;16(2):11–18.)

functions are coupled to space transport models, although not for a direct measurement of mission quality factors. It is estimated that a combined approach using crew dosimetry, worn on the surface of the body, and radiation transport codes to estimate individual organ doses are capable of describing organ dose equivalents with standard errors of less than 10%. Results of this approach for past space missions are shown in Figure 8-5 (78).

Long-term missions on the ISS or the Russian Mir space station have led to crew exposures that exceed 100 mSv. For future missions to Mars, exposures approaching 1,000 mSv or more can be expected. Table 8-5 shows projections for effective doses, risk of exposure-induced death (REID) due to fatal cancer, and 95% confidence levels for 40-year-old men and women for several deep space mission scenarios. Because these risks will be much higher levels than past space

missions or ground-based exposures, studies to improve the understanding of the biological effects of space radiation and to develop successful mitigation measures are a primary focus of NASA and other space agencies.

Radiation shielding can be shown to be cost effective for protection against SPEs. In deep space or on the surface of the moon approximately 20 g/cm<sup>2</sup> of aluminium-equivalent material will reduce effective doses from most of the SPE to well below radiation limits. Materials with high hydrogen content such as polyethylene are the most effective in reducing effective doses leading to a significantly reduced mass allotment for radiation shielding compared to traditional spacecraft materials such as aluminum (2,79). The higher energies of GCR compared to solar protons makes shielding an inadequate mitigation approach. Effective doses attenuate quite slowly and the amount of shielding needed

**TABLE 8 - 5**

**Calculations of Effective Doses, Percentage of Risk of Exposure-Induced Death (REID) from Fatal Cancer, and 95% Confidence Intervals (CI) for Lunar or Mars Missions**

<i>Exploration Mission (Length of Mission)</i>	<i>D (Gy)</i>	<i>E (Sv)</i>	<i>REID (%)</i>	<i>95% CI</i>
<b>Males (40 yr)</b>				
Lunar (180 d)	0.06	0.17	0.68	[0.20, 2.4]
Mars swingby (600 d)	0.37	1.03	4.0	[1.0, 13.5]
Mars exploration (1,000 d)	0.42	1.07	4.2	[1.3, 13.6]
<b>Females (40 yr)</b>				
Lunar (180 d)	0.06	0.17	0.82	[0.24, 3.0]
Mars swingby (600 d)	0.37	1.03	4.9	[1.4, 16.2]
Mars exploration (1,000 d)	0.42	1.07	5.1	[1.6, 16.4]

Calculations are at solar minimum where GCR dose is the highest behind a 5-g/cm aluminum shield. The absorbed dose (*D*) and effective dose (*E*) are averaged over tissues prominent for cancer risks. Competing causes of death are considered in the calculation because for high values of risk they compress the risk probabilities (>5%). (Cucinotta FA, Durante M. Cancer Risk from exposure to galactic cosmic rays: implications for space exploration by human beings. *Lancet Oncol* 2006;7:431–435.)

can be prohibitive. At present, reducing the uncertainties in models of radiation health risk such as carcinogenesis is a focus and is expected to lead to viable biological countermeasure approaches. By elucidating the biological mechanisms underlying radiation-induced cancer, including different mechanisms of action between terrestrial and space radiation types, approaches to intervene and reduce risk are expected to emerge. These studies should be of value for aviation radiation protection as well.

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