COPING WITH MYTHS AND REALITIES OF COSMIC RADIATION

REVIEW OF THE PHENOMENA, OF REGULATIONS AND OF PRACTICAL COMPLIANCE POLICIES

By Jean-Jacques Speyer

Director Operational Evaluation,
Human Factors and Communication

1. COSMIC RADIATION BASICS

1.1. Radiation

When discussing hazards to flight, general crew and passenger health, radiation falls into 2 categories: ionizing and non-ionizing radiation.
Ionization involves the displacement of electrically charged particles (electrons) from atoms and the breakup of the nuclei of atoms and the resultant production of ions.
Ionizing radiation also includes alpha rays/particles, beta rays/particles, gamma rays, radon and X-rays and is associated with the radiation of ions.
Cosmic radiation is the collective term for the radiation of high-energy subatomic particles from space (exploding stars) and to a lesser extent, from the sun, and the secondary (ionizing) radiation produced when the high-energy subatomic particles interact with nitrogen, oxygen and other elements of earth's atmosphere.

1.1.1. Non-ionizing radiation

This includes the major part of the Electro-Magnetic Radiation (EMR) spectrum, from ultraviolet through visible, infrared and microwave. Laser light is included in this group. These EMR's, which are the most important to pilots from the perspective of health, include ultraviolet (UV) and to a lesser degree microwaves. Various portions of ultraviolet light, or radiation wavelengths, can affect the eye, specifically the cornea (UVB 200-315 nanometers), the eye lens (UVA 315-400 nm) and to an uncommon degree, the retina (UVC 400-700nm).
Most ultraviolet radiation from the sun is filtered out by the ozone layer in the atmosphere, especially UVC waves. Ultraviolet radiation damage is limited to cataracts and can be prevented by ensuring that sunglasses have a coating that filters out the full ultraviolet range (200-400nm). Exposure to ultraviolet radiation also affects the skin with UVB causing most of the damage. Despite the relationship between ultraviolet radiation and sunburn with skin cancer through melanoma, tanning is still an outdoors ritual but its risks can be mitigated through gradual exposure. Microwave radiation is of minimal danger, the worst being the generation of heat within the cells.

1.1.2. Ionizing radiation

Ionizing radiation is potentially serious and studies have recently intensified to determine its effects especially in the context of Ultra Long Range (ULR) flights, the main concern being the development of cancer in the pilot and other aircrew as they spend more time at altitude. A lot of variables are involved, including length of exposure, altitude, latitude and time of the year. The earth's atmosphere filters out most of this kind of radiation and even if cosmic radiation does not really reach the levels considered being toxic, any level of radiation that may cause hazards is considered unacceptable. Ionization that occurs in body tissues or body organs can lead to cancer and to genetic defects that can be passed on from parents to offspring. Considering that there is background radiation at ground level from the Earth itself, any suspected issues must be relative to the background level to make sense. The European Joint Aviation Authorities (JAA) in 2001 established requirements for operators to educate crewmembers of health risks, to adjust work schedules of those exposed to high levels of radiation and to measure or to sample radiation during flights above 49,000 ft. The exposure limit recommended by JAA is about eight times less than that recommended in the USA. The radiation we receive comes either from outer space (constant intensity) or from the sun (periodic solar flare activity).

1.1.3. Components of Cosmic Radiation

Cosmic radiation consists of primary ionizing particles coming from the sun and sources outside our solar system and of secondary radiation produced when these particles collide with atoms in the atmosphere. The primary ionizing particles coming from the sun together with the resultant secondary radiation are classified as solar radiation while that coming from outside our solar system and its associated secondary radiation are classified as galactic radiation.

As can be seen in figure 1, the interaction with the earth's atmosphere produces nuclear reactions that generate a cascade of secondary particles comprising protons, neutrons, mesons and nuclear fragments most of which are being absorbed before reaching the surface of earth. The geomagnetic field and the attenuating effects of the earth's atmosphere provide natural protection from cosmic radiation.

Galactic radiation is being sent continuously towards the sun and towards the earth originating from sources outside the solar system, such as stellar flares, super-nova explosions and pulsar accelerations. The energy of galactic particles reaching the earth is extremely high (exceeding 10^{20}eV, which should be compared to the highest accelerators which reach 10^{13}eV) and consequently galactic radiation penetrates deeply into the atmosphere. Ultrahigh energy particles are however very rare with less than one per century and per square meter). In comparison, the energy of solar particles is low and, with the exception of rare solar flares, solar radiation is stopped in the upper atmosphere. Particles also stem from lighter elements than those from galactic or extra-galactic origins do. In terms of radiation doses encountered during commercial flights, we are looking at energy levels of GeV (1 GeV = 10^9 eV) whose flux is of the order of one particle per square cm and per second at the top of the atmosphere. At aviation altitudes, therefore, the cosmic radiation field is determined principally by the galactic component.

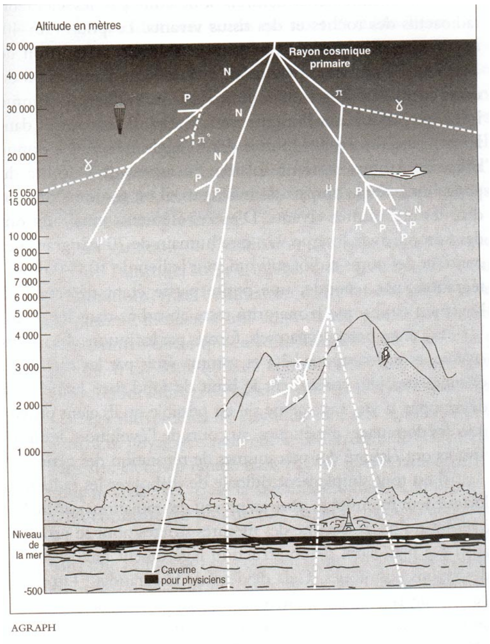

Figure 1: Cascading interactions of Cosmic Rays with the earth's atmosphere
(from "Devenez Sorciers, Devenez Savants" by Georges Charpak, Henri Broch, Odile Jacob, 2002)

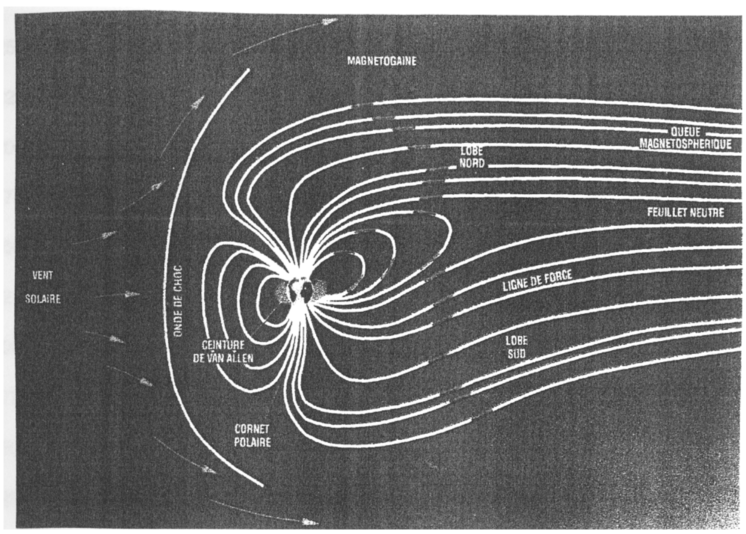

Figure 2: Interaction of Solar wind and Galactic Rays with Earth's Magnetic Field to result in Terrestrial Magnetosphere
(from "Evaluation de l'Exposition au Rayonnement Cosmique à Bord d'Avion Long Courrier" by J-F Bottolier-Depois,IPSN Feb.1997)

Galactic radiation is really being produced when primary photons and very high-energy particles from outside the solar system, primarily the nuclei of atoms stripped of all electrons interact with components of the earth's atmosphere. These comprise 85% protons (hydrogen nuclei), 14% alpha particles or helium nuclei, and 1% heavier covering the full range of elements, some of the more abundant being for example Carbon, Iron, Nickel, Calcium, Magnesium or Lithium nuclei.
Travelling at close to the speed of light, particles from galactic radiation not only have huge energies (>GeV) but they also have been on their way through the galaxy for tens of million years before intersecting the earth. They are partly kept out of the earth’s magnetic field and have easier access at the poles compared with the equator. Cosmic radiation is mostly absorbed by the earth’s atmosphere but it is also moderated by the magnetic fields associated with the sun and the earth.

As can be seen on Figure 2 charged particles interact with the interstellar magnetic field and with the terrestrial magnetic field to form the Magnetosphere. These particles produce a pressure on the magnetic field exposed to the sun and generate a magnetosphereic trail in the back. This perturbation is important at high altitudes but at lower altitudes the dipolar structure of the magnetic field predominates. Charged particles are hence deflected by the earth’s magnetic field resulting in the highest exposure rates at the magnetic poles and the lowest rates at the equator.

As shown on Figure 3, trapped particles constituted of electrons and protons form the so-called Van Allen radiation belts after the scientist who developed the first detector for Explorer I. A primary belt consists in electrons and a secondary, more important belt is constituted of protons. During solar flares the sun’s perturbed magnetic field influences the galactic radiation intensity reaching the earth. The influx of galactic particles is more difficult as magnetic storms contribute to reduce their injection in the Van Allen Belts close to the magnetic poles.

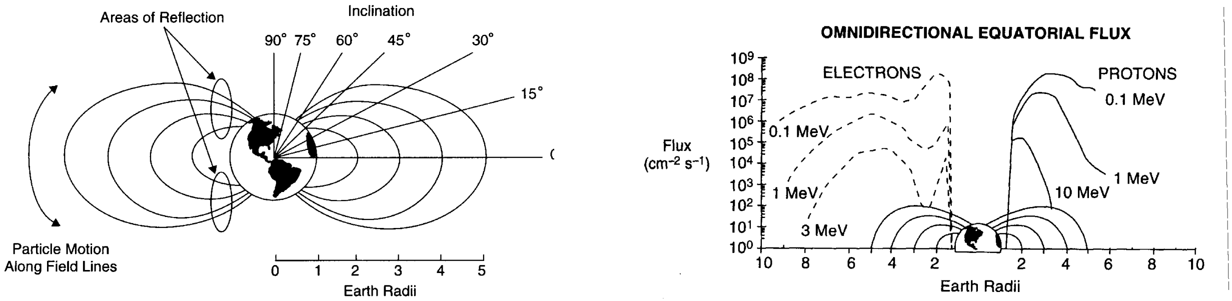

Figure 3: The earth’s magnetic field traps charged particles and reflects them along the field lines with trapped radiation belts (Van Allen) showing radiation doses for respective fluxes (from Human Spaceflight, Mission Analysis and Design, edited by W.J. Larson and L.K. Pranke, Mc Graw Hill)

Cosmic radiation hence follows an 11-year cycle, with the intensity being inversely related to solar activity. As pictured in figure 4, when solar activity is at its peak, galactic radiation is at its lowest. The converse is true when solar activity is lowest. The last solar maxima were in 1991 and 2002, maximum variation of radiation being 20 %.

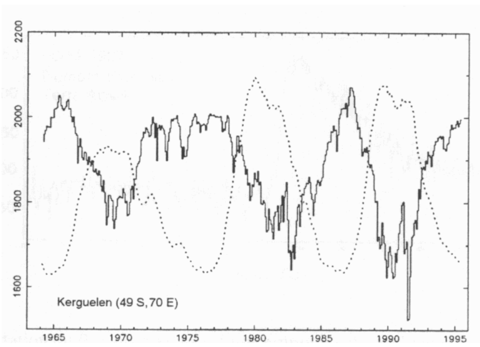

Figure 4: Cosmic radiation dependence of solar activity cycles from “Influence du Rayonnement Cosmique et des éruptions solaires sur les doses reçues par le personnel navigant” by P.Lantos and N.Fuller (Observatoire de Paris-Meudon , Mars 1999)

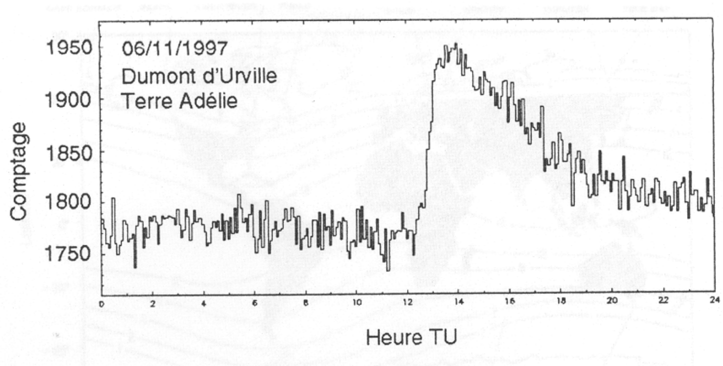

Figure 5: Increase in solar flux as observed during a solar flare by P.Lantos and N.Fuller (Observatoire de Paris-Meudon , Mars 1999)

Solar flares are sudden eruptions resulting in the emission of plasma from the surface of the sun (ejection of coronal mass on the sun). Sporadically they may result in a rapid increase in cosmic radiation intensity in the Earth's atmosphere usually lasting just a few hours. Major solar flares are rare but occasionally do particles emanate and accelerate straight from the sun to cause increased radiation at aviation altitudes. As shown in Figure 5, Ground Level Enhancement Detectors can trace these happenings which do not exceed a few tens of GeV but may involve many more particles than galactic rays.

The level of cosmic radiation depends to some extent on the geographical position, but essentially on the altitude above the ground level, the maximum radiation level occurring at about 20000 m/60000ft Polar Regions have a greater radiation intensity and exposure is more important at higher altitudes. Data on the particle flux in a given space orbit can be useful but we are more interested by the radiation dose that would result from this flux. Because of the relatively low energy of the solar particles, solar flares have only a minor effect on cosmic radiation intensity at altitudes lower than 15 000m and so are of little significance for the majority of commercial aircraft. For aircraft operating above this altitude, however, the increases in radiation associated with flares must be taken into consideration when assessing doses received by aircrew.
The magnetosphere and the earth's atmosphere both constitute strong protection shields against cosmic radiation. Without them, surface exposure on earth would well exceed a sievert per year.

1.1.4. Biological Effects

Neutrons are particles with no mass and no electric charge and can criss-cross the earth with less than one chance in a billion to interact. Mesons on the other hand are charged and interact with matter and particularly the human body. These energetic particles can deposit their energy into the crew or into a space- or aircraft's materials and subsystems, thereby degrading human and mechanical performance. The human body is on average being punctured by five mesons a second. A meson loses one hundred times more energy in our tissues than a radioactive product that we would have ingested. The overall intensity of radiation builds up to a maximum at the stratopause 20000 m and then slowly drops off to sea level. At normal cruising altitudes the radiation level is several hundred times the ground level intensity and at 20000 m a factor three higher again: at mountain altitude, there are electrons, gamma rays, i.e. energetic X-rays, mesons, at Concorde cruise altitude there are protons, neutrons and pions.

1.2. Units of Measurement

The historical unit for radiation dose is the radiation absorbed dose, or simply called the rad. It is the amount of radiation that would deposit 0.01 J/ kg of material. The official unit for radiation dose under the International System of Units (SI) is the gray (Gy), which is defined as 1J/kg. The amount of energy deposited in a material depends on the radiation itself and the material in question. Figure 3 shows typical conversions of flux to dose for silicon. Table 1 shows sensitivities to radiation doses. Structural elements are least sensitive, whereas electronics and crew are most sensitive. Grays are related to biological damage in terms of sieverts via the relative biological effectiveness (RBE) factor. As can be appreciated from the following table the crew and electronics are most sensitive to radiation damage and dominate the requirements for radiation shielding.

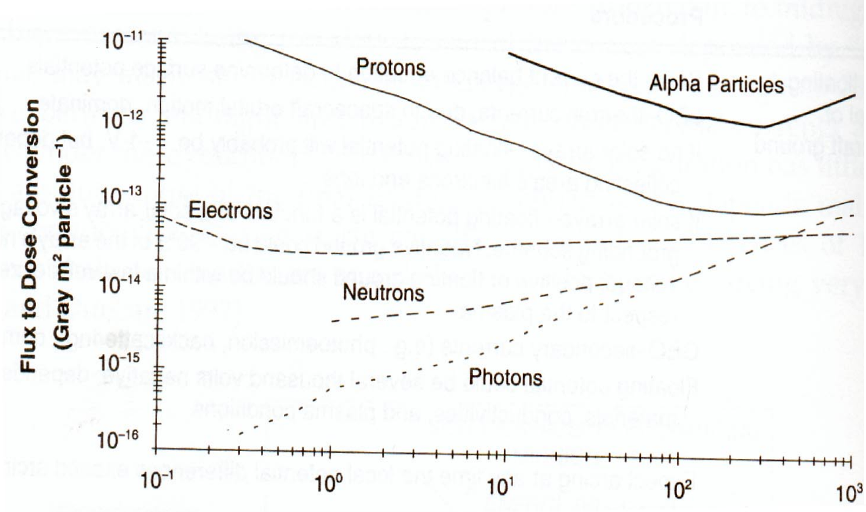

Figure 3: Converting radiation doses for Silicon Radiation depends on the nature of the radiation, its energy, and the material absorbing the energy. To calculate doses for a flux of energetic particles, simply multiply the flux by the appropriate conversion factor
(from Human Spaceflight, Mission Analysis and Design, edited by W.J. Larson and L.K. Pranke, Mc Graw Hill)

Material	*Damage Threshold (gray)*
Humans and animals	$10^{-1} - 10°$
Electronics	$10^{0} - 10^{4}$
Lubricants, Hydraulic Fluid	$10^{3} - 10^{5}$
Ceramics, glasses	$10^{4} - 10^{6}$
Polymeric material	$10^{5} - 10^{7}$
Structural metals	$10^{7} - 10^{9}$

Table 1: Typical sensitivities to Radiation doses

As cited earlier sources of ionizing radiation include:

- galactic cosmic rays (protons, alpha particles and heavy nuclei),
- particles within the trapped radiation belts (protons, electrons, and other ions),
- solar particle events (protons plus some alpha particles and heavy nuclei),
- Neutrons that are being generated as other radiation interact with shielding.

Radiations have different effects even if the absorbed dose is the same. The International Commission of Radiological Protection has studied the relative biological effectiveness (RBE) of radiations and assigned them a "quality" factor, Q.
Q can be related to the linear energy transfer, or rate of energy deposition in keV/μm of radiation track in tissue. If we multiply absorbed dose in gray (Gy) units (1 Gy = 100 rads= 1J/kg) times Q, the result is a dose-equivalent expressed in rem or in sieverts (Sv) where 1 Sv = 100 rem.

Radiation	*Q*	*Radiation*	*Q*	*Radiation*	*Q*
X rays and γ rays	1	Heavy nuclei	20	Protons, 0.1 MeV	10
β particles, electrons 0.1 and 1.0 MeV	1	Neutrons; thermal to 10 KeV	2-3	Protons, 1.0 MeV	8.5
α particles , 1 MeV	20	Neutrons, 20 KeV	5	Protons,>100MeV	8.5
α particles , 1 MeV	15	Neutrons, 0.1MeV-20MeV	7-11		

Table 2: Approximate Quality Factors (Q) for Radiation

Typically, Q values are based on serious, chronic effects for continuous low-dose exposures. Q values for acute doses at high exposure rates may be lower, and several Q values may be revised.

The standard unit of radioactivity is the ***Becquerel***, which is defined as ***the decay of one nucleus per second***. The practical interest is in the biological effect of a radiation dose, and the dose equivalent is measured in ***Sieverts (μSv) per hour*** or ***millisieverts (mSv) per year*** (1 mSv = 1000 μSv = 10^{-3} J/kg). The biological effect evidently also depends upon the length of time of exposure. Obviously, the effect on biological tissue, or body cells depends not only on the total dose but also on the components of the radiation field.

Summary Units of Measurement for Radiation
(from "Feux follets et champigons nucléaires" by G. Charpak, R.L.Garwin, Odile Jacob, August 2000)

1 Bq: the Becquerel is the activity of a radioactive source disintegrating once per second,
1 Ci: the Curie is the activity of a radioactive source disintegrating 3.72 x 10^{10} per second, it is the radioactivity of 1 gram of radium. The physical effect of radiation from ionizing substances can be measured through the quantity of energy deposited in one kilogram of living tissue,
1 Sv: the Sievert corresponds to 1 Joule per kilogram; 1mSv = 1 thousandth of a Sievert
With 1 Joule the temperature of 1 gram of water is elevated by 0,24°C;
The biological effect of irradiation is linked to the relative biological effectiveness factor Q.
The former irradiation unit was the Roentgen, the physical dosis received at 1m from the source of 1 Curie of Radium in 1 hour.
1 dari: annual irradiation undergone by a human being through the natural radioactivity emitted by its own body substances and in total independence of professional activities.

The biological dosis (the rem, Roentgen equivalent man) was linked to the rad through:

1 rem = 1 rad x Q	1 Gv = 1 gray = 100 rad	1 Sv = 1 Gy x Q
1 rem = 10 mSv	1dari = 0,17 mSv	1mSv = 5,88 dari

Dose flux is the dose per unit of surface and time; dose debit is the dose per unit of time.

1.3. Biological Risks

In contrast to high levels of radiation such as that from a nuclear explosion, it is more difficult to predict the effects of low level doses of radiation from cosmic radiation or medical x-rays. In most cases any cell damage is repaired satisfactorily by the body's own mechanism. It is also not possible to predict a maximum safe threshold of exposure as individuals do vary in their biological response. Consequently, a minimum safe threshold of exposure is proposed. When ionizing radiation passes through the body, energy is transmitted to the tissues, which affects the atoms within the individual cells. This may result in:

(i) Development of cancer.

In theory, small exposures to radiation can start off chains of events that may lead to cancer many years later. The body's repair mechanisms are usually able to fix the damage that is done before a cancer develops. While no level of exposure to radiation can be described as safe, at the same time, no level is uniformly dangerous. The chance of a cancer occurring is generally believed to be proportional to the level of radiation exposure: the lower the exposure, the lower the risk. A cell may be altered as a result of being irradiated and subsequently become cancerous. The likelihood of this happening will depend on the dose received.

For an accumulated dose of 5 mSv per year over a career span of 20 years (more than the anticipated annual exposure for long haul crew) the likelihood of developing cancer due to the radiation will be 0.4%. This though needs to be put in perspective, as we know from national mortality data that approximately 23% of the population will die from some type of cancer and so the additional exposure will increase the risk from 23% to 23.4%. Compared with all other risks encountered during the working life, this is very low. The only effect that is known to be possible at this level of exposure is a very slight increase in the chance of a cancer occurring many years, even decades after the exposure. Other studies quote the chance of a fatal cancer occurring to be approximately 1% following 30 years of flying, at 1000 hours a year. Most people fly much less and the chance of a fatal cancer occurring would also be much less. As we all have more or less a 25% chance of getting a fatal cancer, cosmic radiation represents a very small addition to the underlying cancer risk from all causes.

With regard to flight crew mortality independent analysis of the British Airways pension scheme data and of British Airways own data for the period between 1950 and 1992 shows an increased life expectancy for pilots of between 3 and 5 years when compared to the general population. Death rates from heart disease and all cancers combined were considerably less than for the population of England and Wales. Although rare, death from melanoma (which is directly associated with sun exposure) was the only cause of cancer in excess. Cancers such a leukemia, which may be linked to radiation exposure, was lower within the British Airways pilot population.

(ii) Genetic risk.

A child conceived after exposure of the mother or father to ionizing 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 1,000. Again this needs to be considered against a background incidence in the general population of approximately 1 in 50 for genetic abnormalities.

(iii) Risk to the health of the foetus.

With regard to pregnancy, although the risks to the unborn child from cosmic radiation are minimal when compared with other risks during pregnancy, radiation exposure should be kept to a level 'as low as reasonably achievable'. Individual passengers will therefore need to make their own assessment of risk taking into account the likely exposure. The major risks to an unborn child from exposure to cosmic radiation are structural abnormalities, mental retardation and an increased lifetime risk of cancer.

1.4. Exposure levels encountered during space flight

As a matter of reference for exposure at very high altitudes, NASA limits radiation exposure based on mission duration and age at first exposure. But because astronauts are workers with occupational hazards, NASA recognises these standards may still allow an increase of 3% in lifetime risk of cancer mortality as shown in the following table. The table gives maximum allowable doses in sieverts (Sv) and blood-forming organs set the most restrictive standard. Career doses are more restrictive for all younger astronauts and for women versus men.

Exposure Period	To Lens of Eye (0.3 cm depth)	To skin (0.01 cm depth)	To blood-forming Organs (5 cm depth)	
30 days	1.0	1.5	0.25	
1 year	2.0	3.0	0.50	
Career, from age 25	4.0	6.0	1.5(Male)	1.0 (Female)
Career, from age 35	4.0	6.0	2.5(Male)	1.75(Female)
Career, from age 45	4.0	6.0	3.2(Male)	2.5 (Female)
Career, from age 55	4.0	6.0	4.0(Male)	3.0 (Female)

Table 3: NASA's limits in Sieverts Exposure for a Nominal Low-Earth Orbit (from Human Spaceflight, Mission Analysis and Design, edited by W.J. Larson and L.K. Pranke, Mc Graw Hill)

Whatever the normal mission dose rates, crews need special protection at times, such as during solar particle events. In particular, this danger leads to concepts of heavily shielded "safe havens" within spacecraft or other facilities. If a crew had been hit by a particle event in August 1972, for example they could have received more than 1.3 Sv to their deep organs, which would have seriously harmed them. One estimate of what it would take to provide a "safe haven" from such an event yields a spherical aluminium enclosure 7.5 mm thick (20 g/CM2) and 2m in diameter, with a mass of 2.5 metric tons! This mass highlights the value of using the spacecraft's structure, lighter weight options (such as polyethylenes) and supplies (such as water or propellant) as shielding. Astronauts on the ISS receive about 1 unit ('millisievert') of cosmic radiation per day.

On a short lunar mission, solar particle events are of greatest danger. An 8g/cm2 shield might reduce galactic cosmic rays to 0.25 Sv/yr and 50 g/cm2 to half that, while stopping many heavier nuclei with RBEs. Lunar soil has a density of 1 g/cm3 - 2g/cm3 and could serve as shielding. As applied to one severe historical solar particle event, aluminium shielding of 8 g/cm2 would have limited the dose at the deeper organs to only 0.25 Sv (the 30-day mission limit) and about 18g/cm2 would have reduced the dose to 0.1 Sv. Recommendations of 50g/cm2 shielding from lunar soil seem feasible and desirable. Based on conservative regolith density of 1g/cm3, this would yield shielding of about 0.5m. Some suggest up to 3-5m shielding for some missions, depending on risk assessments, especially with longer exposures having increased relative risks of galactic cosmic rays and with secondary radiations generated in shielding material. In the case of a lengthy Mars mission a minimum shield thickness of 20 g/cm2-25 g/cm2 of aluminium may be needed in transit to meet annual exposure limits.

1.5. Exposure levels encountered on ground

It is worth noting that natural radiation occurs also at ground level. Residents of the United Kingdom are exposed to a total overall background ionizing radiation level of approximately 2.6 mSv per annum. For example, in parts of Cornwall (UK) the natural radiation level is at about 6 mSv per year and in most of Finland is around 8 mSv per year. Similar levels are reached in Denver and other parts of Colorado (USA).

Natural radiation is emitted by radioactive elements in both rocks and living tissues. Potassium-40, a radioactive isotope of stable potassium (present in a 1/10 000 proportion) has a live of 1.3 billion years. It is hence still present just as Uranium-235, which was also produced since earth's origin. This matter was present in death star's dust, which gave birth to our solar system. Given the affinity of Potassium with most of our human tissues, it is always present in living organisms just as other minerals have long live isotopes. A human being of 70 kilograms contains radioactive substances which are the siege of some 10 000 des-integrations per second, a small part of which can be detected, the remainder being absorbed by tissues. Natural radiation formed by mesons stemming from cosmic radiation and by beta and gamma rays emitted by rocks hence constitutes the background noise against which live developed. Even if it is possible for them to have caused genetic damage, living tissues did elaborate genetic repair mechanisms. What finally matters here is the sensitivity of the human body constituted as it is by 10^{28} atoms ,split over some 10^{14} cells and a rapid electron perturbs at most 10^{5} atoms in a cells that contains up to 10^{14} .We simply have to into account that all along live, cells amass thousands of spontaneous damages that are constantly being repaired through complex and marvellous processes endowed by living tissues. Differences exist between radiation types' capacities in destroying living cells depending on the weight and speed of particles. Biologists characterise these through the relative biological effectiveness (RBE) of radiations assigning a "quality" factor, Q.

1.6. Exposure levels keeping other radiation sources in mind

Since there is background radiation at ground level from the Earth itself, any suspected issues must be expressed relative to the background level to make any sense. In order to take this into account, two physicists, i.e. Nobel laureate George Charpak and US National Academy of Sciences advisor Richard L. Garwin proposed to introduce a new unit of measurement, the DARI[1], understandable by all who are prepared to relativize. Since the human body is naturally subject to radiation effects through its radioactive components such as K^{40} and C^{14}, it is being suggested to take as reference the effect of these natural radiations that have an intensity of 10 000 becquerels (10 000 nuclei decaying per second). To the extent of 90%, this radiation is due to this potassium 40,of mean life 1.3 billion years, that was present in the cosmic dust from which earth was formed about 4.5 billion years ago. The dari amounts to less than 10% of the natural radiation to which the body is subject, arising from external irradiation from rocks and from cosmic rays. Hence the dari is the annual irradiation undergone by a human being through the natural radioactivity emitted by its own body substances and in total independence of professional activities. It corresponds to an effective dosis of 0,17 mSv.

0.1 dari	Dosis received in France as a result of public use of nuclear energy for electricity generation
5 daris	Ile-de-France soil
10 daris	Bretagne soil
5 daris	Cosmic radiation at sea level with a standard increase of 1 dari per 50m height variation
5 daris	Average in France for medical radiology
40 daris	Average for complete body scan (variable)
6 daris	Tolerated limit for public effects of nuclear energy and all industrial sources with ionizing radiations
600 daris	Maximal annual dosis for a nuclear industry worker for five consecutive years
30 000 daris	Mortal Individual dosis
300 000 to 500 000 daris	Dosis delivered during local irradiation for cancer treatment

Table 4: Relative Importance of some well spread radiation sources (from “Le DARI: Unité de mesure adaptée à l’évaluation de l’effet des faibles doses d’irradiation” by Georges Charpak, Richard Garwin, Bull. Acad. Natle Méd, 2001,185,n°6,1087-1096,June 19th2001)

The 600 daris (120 per annum) imposed upon nuclear industry workers corresponds to a reduction of life expectancy as a result of smoking 10 cigarettes per month. It requires to be compared to specific risks associated with a variety of professional occupations. For example, driving a car induces a potentially greater risk because of automobile exhaust fumes. A specific norm is being imposed: the dose of external radiation should not exceed that associated with natural radioactivity by more than 2%, bearing in mind that natural variations often exceed this amount by far. From the above table it appears that subsonic and supersonic pilots would respectively be subject to the following doses: Concorde pilots would be subject to 23 daris, subsonic pilots from 24 to 38 daris (95% confidence interval). This needs to be compared to the average of medical radiology, which ranges from 1 to 40 daris and remains well below the maximal annual dosis for a nuclear industry worker, which stands at 120 daris in France.

A clearer understanding by a wider public of the health effects of materials of radioactive origins is essential if the public interest is to be served. As Charpak and Garwin are saying, clear and continuous information provided to the public about radiation doses from industry is inadequate to an intuitive and correct understanding of relative risk in part because radiation exposure is expressed in units that non-specialists find difficult to grasp. Hence the need to propose a unit of irradiation dose that is equal to that provided to a human being by the naturally occurring radioactivity of human tissue, the dari, after the annual dose stemming from internal radioactivity. It is about time to stop total irrationality surrounding nuclear matters as internal radioactivity is fundamentally linked with any living or inert tissue and as ecological fussiness has finally termed these matters out of proportion with reality. That is why as from now on we will continue benchmarking with respect to the dari so as to put phenomena in the correct perspective. The use of this unit for expressing the individual’s radiation dose from an incident or an accident involving radioactive materials will facilitate a proper judgment of its impact and would avoid unwarranted concerns. The adoption of the dari helps eliminate sterile debates with shear dis-information or political maneuvering not taking into account scientific reality.

[1] DARI: Dose Annuelle due aux Radiations Internes

1.7. Exposure levels encountered during flight

Airlines and independent research organizations have performed in-flight measurements of cosmic radiation. Actual measurements in flight were performed both on the Concorde and on the Boeing 747-400 by British Airways Health Services and by the British National Radiological Protection Board. On the first aircraft type, Concorde, aircraft dosimeters measured an effective dose in the range of 12-15 µSv per hour, varying with the solar cycle. On the second aircraft type, the Boeing 747-400, an effective dose rate of 6 µSv per hour was measured on the Heathrow-Tokyo route, flown at relatively high altitude, albeit lower than on the first type. The effective dose on short haul, low altitude European flight was in the range of 1-3 µSv per hour. Based on the above it is grossly estimated that the maximal dose received by long haul flight crewmembers would be less than 10 mSv per year, less than 59 daris.

Surveys were also performed by Air France and the Institut de Protection et de Sureté Nucléaire using a “Compteur Proportionel Equivalent Tissu” developed with the CNES (Centre National d’Etudes Aérospatiales). Lowest mean doses measured on long-haul flights were observed for routes close to the equator during periods of maximal solar activity that correspond to minimal cosmic radiation on ground. By way of example the mean value per flight on the Buenos–Aires sector was about 3 µSv per hour. Values at highest latitude and in periods of minimal solar activity are higher: for a Paris-Tokyo flight via Siberia, the mean measured dose reached 8,4 µSv per hour in 1996 as compared to 6,6 µSv per hour in 1991/92. In 1997 and for the same flight a mean dose was measured slightly below at 7,5 µSv per hour, partly because of the smaller latitude flown (max 61°N versus 65°N in 1996). A cargo flight on the same city pair but via Fairbanks displayed 5,7 µSv per hour. For a polar route the value is comparable as radiation is considered constant above the geomagnetic latitude of 65°N. The mean altitude is however lower on the polar and hence less exposed. With regard to supersonic flights altitudes flown being markedly higher (up to 18000 m). For the entire Paris – New York flight and during a period of minimal solar activity, the mean dose was 11,3 µSv per hour. Major events linked with solar eruptions can lead to much higher exposures. The maximal dose received by passengers during a solar eruption in 1956 whilst on a flight at 10000 m and at high latitude, was estimated at 10mSv. Such events are very rare and very short-lived as they occur within a few hours. It is hence very improbable that a same person- even as a crewmember- would experience such an exposure twice in his or her life.

Concorde data recently received from Air France indicate an annual absorbed dose of 210 mRem measured on 41 crewmembers for the one-year period from end October 2001 to early November 2002 with a standard deviation of 87mRem. Taking a 95% confidence interval this would amount to 384 mRem/year or 3,840 mSv, which is 23 daris. This corresponds in France to the average of medical radiology, which ranges from 1 to 40 daris and remains well below the maximal annual dosis for a nuclear industry worker, which stands at 120 daris. Long-range data received from Air France on subsonic aircraft indicate an hourly dose between 5 and 8 µSv per hour covering Polar, North and South Atlantic routes. For a maximum of 800 flying hours per annum this would lead to an exposure of between 4 and 6,4 mSv per year or 24 to 38 daris, again equivalent to medical radiology exposure.

In conclusion, Air France and British Airways results are consistently showing average annual exposure rates of about 4 to 6 mSv per year for long haul crew. It is noted that these results include measurements taken on Concorde, whose hourly received dose rate is higher than that with subsonic aircraft because of its higher cruising altitude. But whose total annual flying hours are markedly less because of its much higher cruising speed. Other sources include the American Medical Association quoting 7mSv per annum on the New York Tokyo run for a total of 950 annual block hours and 9,1 mSv per annum on the Athens New York route for the same amount of flying. The Association of European Airlines cites 8mSv per annum as a theoretical maximum for a total of 900 annual hours. German, Russian and Swedish sources quote between 3 and 10 mSv per year, Chinese 3 to 10 µSv per hour on all their measurements. IATA estimates 5,6 µSv per hour.

Radiation may be measured either directly using sophisticated equipment as in Concorde, or estimated using a computer software program. This program looks at the route, time at each altitude and the phase of the solar cycle and calculates the radiation dose received by crew or passengers for a particular flight. British Airways, Air France and other airlines have compared actual measurements taken on board an aircraft with computer estimations and both are very close. The program British Airways set up was validated with the NPRB to record and compute individual radiation exposure based on individual flying rosters. When calculating individual dose rates, it is important to remember that crewmembers are at high altitude for only a portion of the recorded flying hours. Computer models take into account climb and descent profiles, as well as latitude, altitude, time of year and point in the solar cycle.

Passengers can encounter the level of 1 mSv if they exceed 5 return antipodean flights per year. Nevertheless, if these passengers are business travelers, the applicable limit is the 100 mSv or 588 daris in consecutive 5 years (limit applicable to workers). This is equivalent to the maximal annual dosis for nuclear industry workers fixed at 600 daris.

To conclude conservatively, in-flight exposure will depend on the route, altitude and aircraft type.
However, on average, dose rates received is in the order of:

- Concorde, 12-15 µSv (microsieverts) per hour;
- Long haul aircraft, 5 – 8 µSv (microsieverts) per hour;
- Short haul aircraft, 1-3 µSv (microsieverts) per hour dependent on the altitude reached.

2. RECOMMENDATIONS

Since it is not possible to predict a maximum safe threshold of exposure as individuals do vary in their biological response, a minimum safe threshold of exposure is proposed. But as will be seen in the following recommended thresholds were properly and realistically recommended for no harm.

2.1. Evolving Recommendations

2.1.1. International Commission on Radiological Protection (ICRP)

In 1991 the ICRP recommended an occupational exposure limit of ***20 mSv per year for exposure of crew to cosmic radiation in jet aircraft (118 daris).***
For passengers, the International Commission on Radiological Protection (ICRP) recommends a limit of 1 mSv or 5,88 daris per year. This is marginally higher than the annual exposure at sea level and equates to about 80 hours flying per year on Concorde or about 200 hours flying per year on subsonic trans-equatorial routes. Although the dose rate received on board Concorde is greater than that received on subsonic aircraft because of its higher cruising altitude, the total dose for a transatlantic journey is approximately the same because of the reduced time of exposure.

2.1.2. EURATOM Council Directive 96/29[2]

The Council Directive Euratom (Reference 2) has entered into force for the EC Members States on May 13, 2000. This Directive provides that:

- ***Flight crews and others exposed workers shall not been exposed to more than 100 mSv (588 daris) in a consecutive five years period*** (max effective dose not exceeding 50 mSv in any single year or 294 daris).

- If crew exposure is more than 1 mSv in a year or 5,88 daris, the individual radiation exposure has to be assessed, the crew have to be informed about the risks, and the working schedules have to be organized in order to minimize the individual exposure.

- Pregnant women should avoid being exposed at all to more than 1 mSv during this period.

Doses for passengers shall not exceed 1 mSv in a year or 5,88 daris (the limit can be exceeded, provided the average doses do not exceed 1 mSv a year during 5 consecutive years).

Particular attention must be paid to Article 42, which specifically refers to the protection of air crew and stipulates:

- Each Member State shall make arrangements for undertakings operating aircraft to take account of exposure to cosmic radiation of air crew who are liable to be subject to exposure to more than 1 mSv per annum or 5,88 daris per year.

[2] EURATOM Council Directive 96/29 requires member states of the European Union (EU) to comply with the directive before 13 May 2000 (Article 55)

2.1.3. Institut de la Protection et de la Sûreté Nucléaire

The French DGAC and the IPSN state that no study as of today showed any measurable effect of radiation levels on crew health sustained in flight. ***Levels where radiation effects would start to be measurable are estimated to be around 120-150 mSv per year (706–882 daris)***. An extensive survey on European flight crew health in connection with radiation was launched by the EC and will be available next year.

2.1.4. National Council on Radiation Protection and Measurement

The NCRP of Britain has issued recommendations for a better protection of flight crew and of the flying population. They stress the necessity to increase at first our knowledge in solar radiation prediction at high altitude, and in prediction of carcinogenesis under the solar cosmic radiation (neutrons and protons). The report does not make many references to the necessity of a protection through aircraft shielding.

2.2. FAA Requirements

In the advisory circular N° 120-52 the US Federal Aviation Administration (FAA) published estimates of cosmic ray exposures for crewmembers on various subsonic flights. Doses in the range of 0.2 mSv to 9.1 mSv per year were estimated with most of the higher doses on long haul routes at altitudes up to 41000 ft. In the USA, the FAA has no plans to adopt regulations on cosmic-radiation exposure.
A rule is not being planned since cosmic radiation is not being perceived as an immediate risk but just as an educational matter. The FAA therefore wants to ensure that passengers and crewmembers alike are given all the necessary information on cosmic radiation and its consequences.
The FAA recommends that crewmembers and passengers be exposed ***to no more than 20 mSv per year (118 daris) over a five-year period, with a maximum of 50 mSv (59 daris) in one given year.*** The FAA recommendations hinge on guidelines established by the International Commission on Radiological Protection (ICRP).

FAA's recommended limit for a pregnant crewmember is 1 mSv or 5,88 daris. After that level has been reached, FAA recommends that the crewmember not fly until after the child is born. ICRP recommends that pregnant crewmembers be reassigned to flight that are relatively short in duration and are conducted at relatively low altitudes, or be reassigned to ground duties for the remainder of the pregnancy. For a pregnant crewmember, the effective dose is a reliable estimate of the equivalent dose received by the conceptus. An interactive Web version of CARI-6 can be run, at no charge, at the Radiobiology Research Team Web site. This software is distributed without restriction.

http://www.cami.jccbi.gov/aam-600/610/600radio.html

Also, there are two versions of the CARI program that can be downloaded from the same site, CARI-6 and CARI-6M. The downloadable version of CARI-6 is more sophisticated than the interactive Web version. Both assume a great-circle route between origin and destination airports, but the downloadable version allows the user to enter, store, and process multiple flight-profiles, and to calculate dose rates at user-specified locations in the atmosphere. CARI-6M allows the user to specify the flightpath by entering the altitudes and geographic coordinates of waypoints.

Computer program CARI-6 developed at the FAA's Civil Aerospace Medical Institute (CAMI) can be used to calculate the effective dose of galactic cosmic radiation received by a crewmember flying an approximate great-circle route (the shortest distance). Based upon the flux of primary particles linked with cosmic radiation, the software computes the transfer of secondary particles to flight altitudes taking into account the interaction with atmospheric nuclei. And readily derives the effective doses (in µSv) received by the aircraft, in conformity with the recommendations of the IRCP[3] 60. It is hence possible to calculate the effective dose for each altitude, longitude and latitude as a function of solar activity. For a given flight plan it is possible, point by point, to calculate the dose received in order to deduce the flight's dosimetric profile as well as to obtain total exposure. Taking the example in Figure 6 of a Paris- San Francisco flight the effective dose received (in µSv) is based on monthly values of cosmic radiation.

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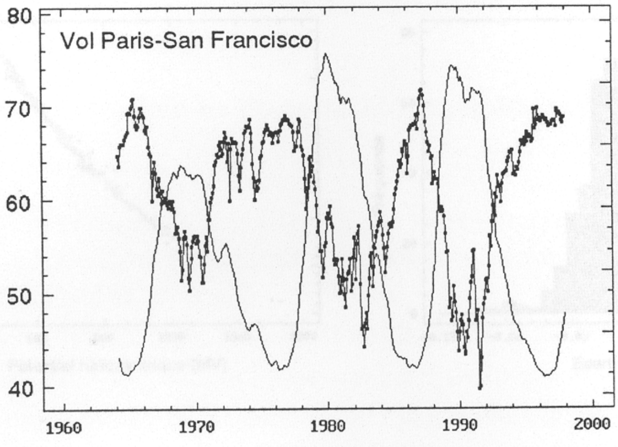
[3] ICRP : International Commission on Radiological Protection



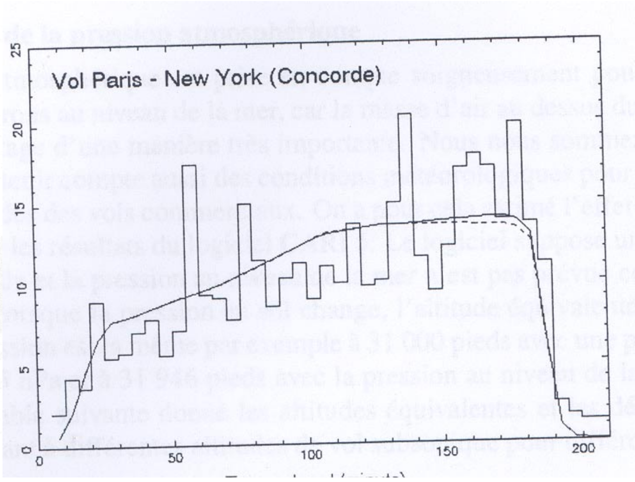


Figure 6 : Effective dose received during the last 3 solar cycles

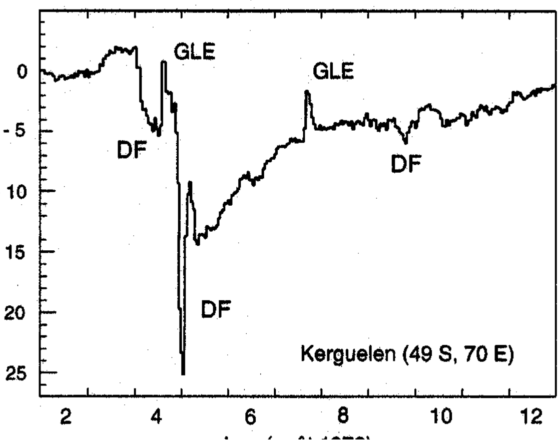
Figure 7 : Paris –New York Concorde flight of 21/08/1996

The solar spot index corresponds to the full line of Figure 6. Worth of note concerning the solar cycle is that a variation of 20% in cosmic radiation flux corresponds to a variation almost equivalent to doubling the effective dose received. Hence one has to take into account the solar cycle so as to estimate doses and still with an accuracy of 10-20%. This parameter is called the “heliocentric potential” since it quantifies the difficulty for cosmic rays to reach the terrestrial heliosphere. Figure 7 offers a comparative example between measurements performed by J-F Bottolier-Depois in his IPSN studies of Air France flights (Evaluation de l’Exposition au Rayonnement Cosmique à Bord d’Avion Long Courrier, Feb.1997) and the computations by means of the CARI Software. Worth of note is that these flights corresponded to the minimum in the 11 year solar cycle, i.e. when cosmic radiation is at its periodic strongest. The CARI program is based on monthly data for solar radiation.

2.3. Observatoire de Paris- Meudon Study

Hourly or daily data based on neutron monitors would hardly improve predictions, only just exceptionally. These exceptions would pertain to the following two cases:

- Solar eruptions evidenced with Ground Level Enhancements (GLEs) in Figure 8, and so called FDs
- “Forbush decrements” (FDs) during the passage of an interplanetary shock wave closeby earth,



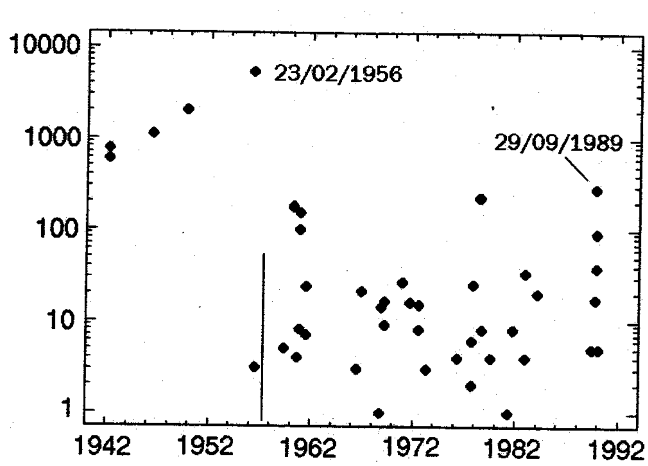


Figure 8: Cosmic Radiation plot for the very active period of August 4th 1972 with GLEs and decreasing FDs

Figure 9: Intensity of observed GLE s between 1942 and 1992 using different monitors

GLEs are rare events generally linked with solar eruptions. Before the International Geophysical year (1957) only exceptional events would be recorded. Figure 9 shows that -on February 23rd 1956 - a factor increase of 50 was recorded for particles detected by earth monitors, an augmentation of some 5000%. This includes important events on May 7th 1978 and on September 29th 1989, the former corresponding to an increase of 220%, the latter to 270%. Integrating the calculated dose on the whole event of February 26th 1956 alone, one would have obtained a maximal cumulated dose of 10 mSv for a subsonic flight.

The GLE of September 29th 1989 is the only one corroborated with data measured on board the Concorde and is detailed on Figure 10. As calculated by O' Brien et al, at the peak of the GLE this corresponded to:

- 12 µSv per hour at an altitude of 40000 feet (12,2 km / subsonic flight), for a total of 12 mSv ,
- 32 µSv per hour at an altitude of 60000 feet (18,3 km / supersonic flight), for a total of 35mSv,

These aircraft were in flight at the moment of the eruptions as shown on the profile of Figure 10 observed by the monitor of Kerguelen. Concorde flights are shown at the bottom.
The Paris – New York flight of Air France left CDG at 10h19 GMT and arrived in JFK at 13h43. The New York-London flight of British Airways left JFK at 13h56 and arrived at LHR at 17h19.
The maximum GLE was recorded at 13h45.The Air France Concorde recorded an "amber alert" (flux between 10 and 50 µSv/h) and an equivalent dose of 0,12 mSv in full agreement with O' Brien's calculations. The British Airways Concorde appears to have recorded a "red alert" (beyond 50 µSv/h). The equivalent dose being 0,14 mSv. For supersonic flights these detectors are indeed essential provided these are reliable since red alerts call for a descent to an appropriate level where radiation is no longer critical.

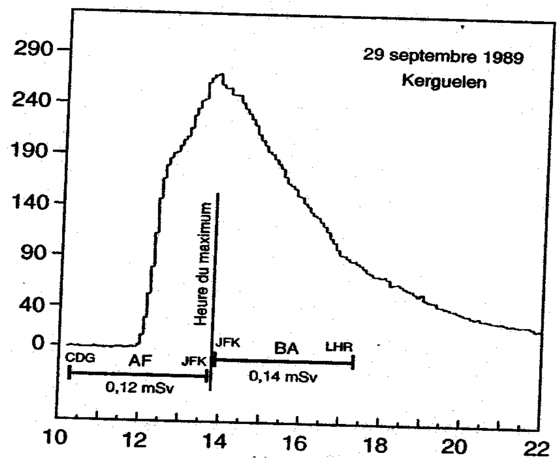


Figure 10: Plots of the September 1989 GLE with mention of the 2 measured Concorde flights having been exposed to it

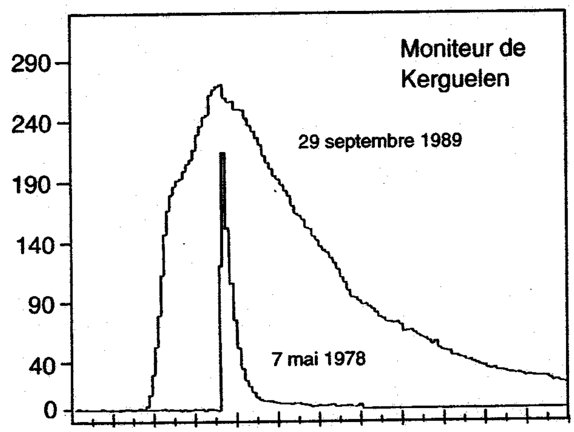


Figure 11: Comparison of the profile of 2 GLE's of similar maximal intensity

The occurrence of very strong eruptions cannot be predicted with reasonable operational accuracy, i.e. to the point of reasonably immobilizing aircraft on ground. However, once a GLE is declared, a neutron monitor can provide valuable alerts. The GLE of 1956 surpassed the level of cosmic radiation by a factor 10 for more than 2 hours. This warrants limiting flight's exposure depending on the GLE's duration. Figure 11 compares the profile of 2 GLEs measured at Kerguelen, both of similar amplitude but of different duration. Duration is quite variable and cannot be predicted at the moment.

The eruption of August 4th 1972 was one of the worst at lower energies (10 to 30 MeV), important for doses received by astronauts (several sieverts an hour) but did not provide in terms of high energy protons (energy > GeV), any noticeable GLE since it only reaches a mere 5%. The announcement of very important GLE's to commercial flights is hence subject to caution.

This study confirmed the choices made for the calculation of effective doses concerning cosmic radiation, i.e.:

- the CARI program (with the calculation of the heliocentric potential) or any equivalent/future European software that would help to adequately estimate doses,

- except for periods of very strong eruptions, neutron monitors are sufficient, with average monthly readings,

In the absence of adapted observation satellites, exceptional phenomena like the one of 1956 mandate using all available neutron monitors on earth, so as to first calculate characteristics of an event (energies involved) and only thereafter assess the impact of a GLE as a function of aircraft flight plans.
Passive dosimeters installed in some commercial aircraft, like on the Concorde, can also contribute but predictions are anyway bound not to be very reliable.

2.4. ICAO and JAR OPS

ICAO and JAR OPS rules require that aircraft intended to be operated above 49,000 [ft] have to be equipped with an instrument to measure and indicate (visible for the flight crew) continuously the dose equivalent radiation.

2.5. JAR Requirements

JAA in January 2001 amended Joint Aviation Requirements – Operations (JAR-OPS 1, the regulations governing the operation of commercial air transport airplanes, to require operators to ***"take account of the in-flight exposure to cosmic radiation of all crewmembers while on duty (including positioning) and (and to) take the following measures for those crew liable to be subject to exposure of more than 1mSv per year, that is 5,88 daris (1.1390)" :***

- Assess their exposure
- Take into account the assessed exposure when organizing working schedules with a view to reduce the doses of highly exposed crewmembers
- Inform the crew members concerned of the health risks their work involves
- Ensure that the working schedules for female crew members, once they have notified the operator that they are pregnant, keep the equivalent dose to the foetus as low as can reasonably be achieved and in any case ensure that the dose does not exceed 1mSv for the remainder of the pregnancy;
- Ensure that individual records are kept for those crewmembers that are liable to high exposure. These exposures are to be notified to the individual on an annual basis, and also upon leaving the operator.

Regulations prohibit operation of an aeroplane above 15 000m (49 000ft) unless the aircraft is equipped:

- with an instrument that measures and continually indicates the dosage of cosmic radiation being received by crewmembers,
- and that provides the cumulative dosage for each flight; or unless the operator uses an approved system for quarterly radiation sampling.

Regulations also require the pilot-in-command to begin a descent as soon as practicable when the cosmic-radiation-dose rate exceeds the limits specified in the company operations manual (JAR-OPS 1.680(a))

Advisory material issued by the JAA cites one acceptable method for determining whether crewmembers will be exposed to more than 1mSv of cosmic radiation per year. The determination is conducted with reference to data shown in Table 5 and produced by a computer program.

Altitude (feet)	Kilometre equivalent	Hours at latitude 60° N	Hours at equator
27 000	8·23	630	1330
30 000	9·14	440	980
33 000	10·06	320	750
36 000	10·97	250	600
39 000	11·89	200	490
42 000	12·80	160	420
45 000	13·72	140	380
48 000	14·63	120	350

Table 5 - Hours exposure for effective dose of 1 millisievert (mSv)

Note: This table, published for illustration purposes, is based on the CARI-3 computer program; and may be superseded by updated versions, as approved by the Authority. The uncertainty on these estimates is about ± 20%.A conservative conversion factor of 0.8 has been used to convert ambient dose equivalent to effective dose.

Doses from cosmic radiation vary greatly with altitude and also with latitude and with the phase of the solar cycle.
Table 5 gives an estimate of the number of flying hours at various altitudes in which a dose of 1 mSv would be accumulated for flights at 60° N and at the equator.
Cosmic radiation dose rates change reasonably slowly with time at altitudes used by conventional jet aircraft (i.e. up to about 15 km / 49 000 ft).
Table 5 can also be used to identify circumstances in which it is unlikely that an annual dosage level of 1 mSv would be exceeded. If flights are limited to heights of less than 8 km (27 000 ft), it is unlikely that annual doses will exceed 1 mSv. No further controls are necessary for crewmembers whose annual dose can be shown to be less than 1 mSv.

Where in-flight exposure of crewmembers to cosmic radiation is likely to exceed 1 mSv per year or 5,88 daris, the operator should arrange working schedules, where practicable, to keep exposure below 6 mSv per year or 35 daris. For the purpose of this regulation crew members who are likely to be exposed to more than 6 mSv per year or 35daris are considered being exposed and individual records of exposure to cosmic radiation should be kept for each crew member concerned.

Operators should explain the risks of occupational exposure to cosmic radiation to their crewmembers. Female crewmembers should know of the need to control doses during pregnancy, and the operator consequently notified so that the necessary dose control measures can be introduced.

2.6. IFALPA Position

The revisions to IFALPA policy on cosmic radiation reflect some recommendations of the Council of European Union so as to regulate exposures down to levels comparable to the natural background. Within this context there is however no general agreement within the scientific community to support this approach. According to IFALPA extensive research is still necessary before any conclusions and recommendations can be made as to the validity of the European approach.

The present recommendations include:

1) Radiation dosage assessment, either measured or mathematically modeled, for all aircraft operated above 8000m (26,00ft),
2) Revision of the current ICRP recommended annual cumulative dose rate of 20 mSv/year to 6mSv/year, that is from 118 to 35 daris,-
3) Cumulative radiation dose assessment for all crewmembers (involved in operations over 8000m) should be recorded and monitored on a permanent basis,
4) Medical surveillance of all flight crewmembers (annual dose rate 1-6 mSv/year), (5,88 to 35daris)
5) Warning of impending solar flares should be given to flight crews,
6) Adjustment of current radiation exposure limits to pregnant flight crew members from 2mSv to 1mSv/year, (11,76 to 5,88 daris),
7) Recommendation to legislate radiation exposure limits.

Some technical objections however preclude the above:

1)+3)
There is no scientific support/agreement for evaluating ambient dose by means of the Tissue equivalent proportional counter as a reference instrument with large uncertainty in results calculated from passive dosimetry using existing measurement techniques.

2) A flight crewmember working 700 block hours a year would receive an annual cumulative occupational exposure of 3-5 mSv/year, which is 17 to 29 daris. When normalized to occupational plus non-occupational natural radiation sources this crewmember has an annual effective dose of 5 to 7 mSv or 29 to 35 daris, somewhere about 2 times higher than the annual dose (3 to 3.5 mSv which is 17 to 21 daris) received by a member of the US or French population. Proposals advocating changing the tolerable cumulative dose rate from 20 mSv/year to 6 mSv/year (from 118 to 35 daris) appear unfounded and exaggerated, the 6 mSv figure lacking a funded basis.
4) Medical surveillance of all crewmembers is not feasible: even if damage were to be found in chromosomes, one could not assert that the problem would solely be related to ionizing cosmic radiation or that there even would be a biological problem. Also, the cost alone for medical surveillance of all flight crewmembers would be absolutely prohibitive.
5) Warning of impending solar flares may not even be possible even if NASA research attempts to correlate sun patterns with early warnings of approaching solar storms.
6) Adjustment of current radiation exposure limits to pregnant flight crew members from 2mSv to 1mSv/year appears justified as the equivalent dose at depth of the conceptus is approximately the same as the dose at the surface of the mother's body.
7) The cumulative cosmic radiation research is far from conclusive that would justify a legislative approach at this point in time.

2.7. ALPA Position

The Air Line Pilot Association (ALPA), CAMI and the Medical University of South Carolina's Department of Biometry and Epidemiology are conducting a two-phase study of harmful effects of cosmic radiation. The first phase of the study involves assessment of the incidence of cancer among pilots through a survey of more than 11 500 active and retired pilots. As part of this project, an extensive database on exposure rates using a flight-history survey is being used. Phase 2 of the study will involve determination of whether chronic low-dosage radiation can be detected from biological markers. A fourfold increase of melanoma (skin cancer) was found among pilots, compared to a standardized population. But among pilots with a higher incidence of melanoma were those who fly at lower altitudes and at latitudes where cosmic radiation is not a factor.

3. REVIEW AND AIRBUS PROTECTION PHILOSOPHY

3.1. Aircraft Protection

It is not physically possible to protect the aircraft from radiation. Such protection would require addition of a protective shell to the fuselage, e.g. a thick layer of steel or lead. This solution is technically not feasible due to weight repercussion. This is true for all aircraft and the new ultra long-range aircraft are no different in this respect from any other aircraft. According to the "New Scientist" a cosmic-radiation-proof lining for aircraft is one (unproven) possibility for a new polymer material, say its developers.

3.2. Measurement in Flight

In accordance with JAR-OPS regulations, aircraft intended to be operated above 15 000 m or 46 000 feet are required to be equipped with cosmic radiation detection and measurement equipment. Above this altitude increased cosmic radiation due to high levels of solar activity must be taken into account when determining crew doses.
Equipment capable of measuring cosmic radiation is installed in all Concorde supersonic transports, which entered commercial service in 1976. The monitoring equipment includes a rate meter that provides an instantaneous reading of total radiation dose equivalent. The readings are recorded at the beginning and end of each flight. The equipment also includes an alarm that activates if the dose equivalent reaches 0.10 mSv per hour, (or 0,588 daris) which could occur from a solar flare. It appears that this equipment has a low reliability level and that it is out of production.

3.3. Dosimetric Assessment and Reporting

3.3.1. Route dose calculation programs

Where as a result of the above stipulations, it is shown that aircrew are liable to receive in excess of 1mSv in any 12-month period, the operator must assess the doses received by the crew concerned. It is recommended that aircrew doses be determined by combining route doses with crew roster data. For aircraft operating below 15 000 m (46 000ft), where solar flares do not significantly influence the cosmic radiation dose to aircrew, route doses may be calculated using an approved computer code.

- SIEVERT is a program developed in 2002 by the DGAC in cooperation with others organisms (IRSN, IPEV, Observatoire de Paris-Meudon) to calculate the effective dose of cosmic radiation received by a person during a given flight. This program is for airlines use in order to apply the European Directive (EURATOM Council Directive 96/29, Art42) for the protection of air crew requesting to access the exposure and manage work organization when crews are supposed to be subject to exposure more than 1 mSievert per year or 5,88 daris .
  The program's access rights have to be requested directly by the airlines to the DGAC.

  www.irsn.fr/vf/04_act/04_act_2/04_act_21dossiers_irsn/pdf/dp_sievert.pdf

- FAA propose also a similar program called CARI-6M (and CARI-6) on their web site:

  http://www.cami.jccbi.gov/aam-600/610/600radio.html

  CARI is produced by the Radiobiology Research Team at the Civil Aeromedical Institute in the United States and can be downloaded free of charge. CARI calculates the effective dose of galactic radiation received by an individual on an aircraft flying a great circle route between any two airports. The program takes into account the altitude, geographic location and flight duration based on a user entered flight profile. CARI uses heliocentric potentials to adjust for changes in the galactic radiation intensity that occur with changes in solar activity. Before using the program, the user must enter heliocentric potential data for dates not already in the program database. These data are available on the Civil Aeromedical Institute Website and an estimate for each month is normally available by the 24th of the following month.

- The European Commission is currently developing a European route dose calculation code known as EPCARD. At the time of writing of this paper, this code was not yet available.

As a conclusion, the measurement of the cumulated radiation encountered by flight crews seems tedious to set up. As an alternative way, Airbus proposes to initiate airlines to the use of these programs.

3.3.2. Route Profile

Route doses may be calculated using typical flight profiles rather than actual flight data. Typical flight profiles must be defined individually for each route and should be based on historic flight data. Each profile will include:

- The origin and destination airports,
- The number of en route altitudes,
- The time to climb to the first en route altitude,
- The en-route altitudes (with CARI up to en route altitudes can be specified),
- The time spend at each en route altitude,
- The time to descend to the destination airport,

Route profile information must be reviewed periodically by the operator and updated as necessary to best reflect current practice.

3.3.3. Crew Dose Assessment

For the purpose of calculating crew doses a distinction is drawn between two categories of aircrew. These are:

- Firstly, either aircrew liable to receive in excess of 6 mSv in any 12-month period or female aircrew on declaration of pregnancy and,

- Secondly, any other aircrew liable to receive 1mSv and 6mSv in a year. For crew in the latter category, a simplified, calculation based on annual averaged route doses and group roster data may be used.

For crew in the first category, the dosimetric assessment must be based on monthly averaged route doses and individual roster data. Route doses must be calculated for each month using the heliocentric potential for that month. The monthly route doses are then combined with aircrew roster data to derive the doses to individual aircrew members. Each month, the operator must derive the cumulative exposure over the previous 12month period by summing the 12 monthly values. The assessment must be calculated individually for each crewmember taking into account the actual flying record for that individual.

For crew in the second category, the operator may opt to assess crew doses using a simplified calculation based on annual averaged routes and group roster data. For such assessments the annual average route dose should calculated for the calculated for the calendar year using the annual heliocentric potential, which is usually. For such assessments the annual average route dose should be calculated for the calendar year using the annual heliocentric potential, which is usually available towards the end of January of the following year. Crew exposures are then calculated for groups of aircrew likely to receive similar exposure, rather than for individual crewmembers. The groups must be defined on the basis of similar work rosters. The operator must maintain a record of such groupings, which must be available to the aircrew concerned.

When the operator opts for group assessments, the calculation must be performed on the basis of the maximum dose to any individual member of the group and this figure must be recorded for each member of the group.

Where, on the basis of the annual calculation it is shown that any individual or group receives in excess of 5 mSv, the operator must reassess the doses for the individuals concerned according to the procedures set out above for the first category of aircrew. Traceability of dosimetric assessments must be properly secured to allow recalculation of any individual crew dose if necessary. Written procedures should be fully documented and operators must compile a summary of aircrew exposure on an annual basis.

3.4. Information to be provided to aircrew

When crewmembers are susceptible of receiving more than 1 mSv in any 12-month period, the operator is required to provide staff concerned with basic information about the risks associated with exposure to cosmic radiation as well as basic information to help them interpret their dose records. This is where some relativization is necessary through the notions of the daris. It is recommended that these notions should include the following questions:

- What is cosmic radiation?
- What is a millisievert, what is a dari and why does the dari put things into perspective?
- What are the main sources of ionizing radiation (medical, background industrial)?
- What is the annual dose received by a typical individual from background sources of ionizing radiation?
- What factors influence cosmic radiation intensity (latitude, altitude, solar cycle)?
- How is cosmic radiation measured (direct measurement and assessment)?
- What health risks are associated with ionizing radiation?
- What is the legal framework for the protection of aircrew from cosmic radiation?
- What radiation protection measures are relevant to cosmic radiation?
- What protective measures are necessary for pregnant aircrew?

3.5. Effects on Avionics

Aircraft avionics are possibly at risk of computer failures due to cosmic radiation. Better error correction or chips that are more radiation-proof are an answer.

4. CONCLUSION

- Measurements performed in long-range aircraft of many airlines concur and helped to estimate the spread of equivalent annual effective dose:
  - 2mSv (6 daris) for the less exposed flights (at low latitudes and maximal solar activity, e.g. Paris-Buenos Aires),
  - 6mSv (35 daris) for the more exposed routes (high latitudes and minimal solar activity, e.g. Paris - Tokyo via the Siberia or e.g. Paris- San Francisco),
  - The values observed on Concorde flights are in this overall range as the number of flying hours is markedly less.

- The generally agreed dose of 20mSv/per year or 118 daris is hence well funded as a realistic benchmark value to clear cosmic radiation threats and is in line with practical safety objectives. These values are off course above the limit fixed for the general public (1mSv per year) in the frame of European Directives and regulations. These stipulations also require evaluating crew exposure if their exposure exceeds 1mSv or 5,9 daris per year, measured or calculated.

- After investigations, the use of sensors on board the aircraft to measure the effective dose of cosmic radiation received by the crew appears not to be the right solution for the present.
  This can be performed using dedicated programs, knowing:
  - the inherent calibration difficulties of the sensors,
  - the low accuracy of sensors linked to the low level of cosmic radiation generally encountered,
  - that the route patterns flown per individual and corresponding dates need to be well bookkept,
  - that the actual measurement of cumulated radiation annually encountered by each crewmember seems very difficult to be set up.

- Airbus proposes therefore the operational utilization of one of these programs to the airlines:
  - FAA offers a dedicated program called CARI-6M on their web site, to calculate the effective dose of cosmic radiation received by a person during a given flight,

    http://www.cami.jccbi.gov/aam-600/610/600radio.html

  - SIEVERT hints towards a similar program developed in 2002 by the DGAC in cooperation with others organisms (IRSN, IPEV, Observatoire de Paris-Meudon). This program is for airlines use to apply the European directive (EURATOM Council Directive 96/29, Art42) for the protection of air crew requesting to access the exposure and manage the work organization when any crewmember is supposed to be subject to an exposure superior to 1 mSievert per year. Access right to the program has to be requested directly by the airlines to the DGAC.

    www.irsn.fr/vf/04_act/04_act_2/04_act_21dossiers_irsn/pdf/dp_sievert.pdf

  - The European Commission is currently developing a European route dose calculation code known as EPCARD. At the time of writing of this paper, this code was not yet available.

  These tools all use mathematical models validated by atmospheric measurements which are regularly updated. The calculation of the effective dose of cosmic radiation received by a person is based on the description of all the flights performed (date, departure airport, arrival airport, intermediate waypoints, etc…etc).

- A clearer understanding by a wider public of the health effects of materials of radioactive origins is essential if the public interest is to be served. As Charpak and Garwin are saying, clear and continuous information provided to the public about radiation doses from industry is inadequate to an intuitive and correct understanding of relative risk in part because radiation exposure is expressed in units that non-specialists find difficult to grasp. This is why they are proposing the establishment of the dari, after the annual dose stemming from internal radioactivity. The dari (Dose Annuelle due aux Radiations Internes) corresponds to an effective dose of 0,17 mSv.

- The adoption of the dari helps eliminate sterile debates with shear dis-information or political maneuvering not taking into account scientific reality. It appears that subsonic and supersonic pilots would respectively be subject to 23 daris annually, subsonic pilots from 24 to 38 daris (95%

confidence interval). This needs to be compared to the average of medical radiology, which ranges from 1 to 40 daris and remains well below the maximal annual dosis for a nuclear industry worker, which stands at 120 daris in France. The Ultra Long Range nature of A340-500 operation (including flights over the poles as well as extended flight duty times in excess of 20 hours) will not expose crews to radiation doses beyond the limits set by the various regulatory bodies. At most to 35 daris per year even not taking into account the more stringent duty time and rest regulations that may pertain to these flights. It is about time to stop total irrationality surrounding nuclear matters as internal radioactivity is fundamentally linked with any living or inert tissue and as uninformed ecological fussiness has confused these matters out of proportion with reality.