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Aircrews and Ionizing Radiation

Note: This paper provides additional information to 18POS02 - Protection from Ionizing Radiation

BACKGROUND

Flying exposes aircrew to ionizing and non-ionizing radiation. Non-ionizing radiation (e.g. UV-radiation exposure) is not addressed in this Briefing Leaflet. Ionizing radiation has enough energy to produce ions by pulling electrons from atoms and molecules. Ionizing radiation can be electromagnetic, such as x-rays and gamma-rays, or corpuscular, such as alpha particles, electrons, neutrons, protons, or heavy-ions.

Crew members are exposed to various sources of ionizing radiation, such as cosmic radiation (1), radiation released by lightning propagating inside thunderclouds, terrestrial gamma-ray flashes (2), radioactivity released into the atmosphere in nuclear accidents, airport security equipment such as the x-ray backscatter body scanner, on-board radioactive cargo, medical examination using x-ray and other natural sources.

Ionizing radiation can cause somatic and genetic changes, which may result in cancer, cardiovascular diseases, cataracts or genetic defects in offspring.

COSMIC RADIATION

Cosmic Radiation (CR) is originated from deep space (Galactic Cosmic Radiation - GCR) and from the sun (Solar Cosmic Radiation – SCR). The magnitude of galactic cosmic radiation (GCR) is nearly constant, whereas that of solar cosmic radiation (SCR) varies with the solar cycle.

Radiation striking the outer Earth's atmosphere collides with gas molecules and produces particle showers with a high number of secondary particles, of which only a small number reach the Earth's surface.

The galactic cosmic radiation at typical commercial flight altitudes is mainly composed by neutrons, protons, electrons, positrons, muons, pions and photons (gamma and X-rays).

The solar cycle

The solar cycle indicates the periodicity in the frequency of sunspots, which has an average period of 11 years. The peak of sunspot activity is known as solar maximum and the lull is known as solar minimum.

Often no spots are seen for months during solar minimum, whereas during solar maximum the number of spots may range to hundreds.

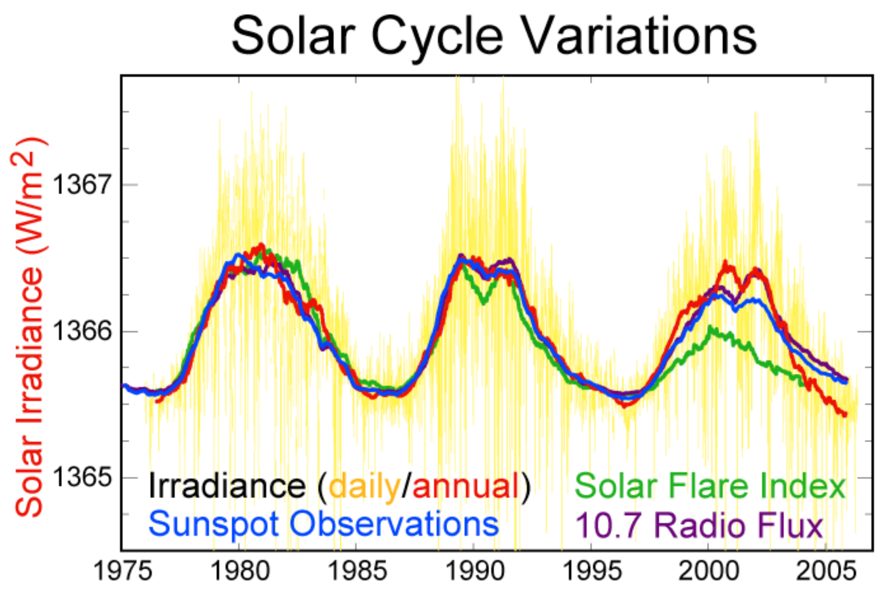

Fig. 1 Solar Cycle Variations

Background GCR also varies with the solar cycle. When solar cycle is at its maximum, the background GCR is at its minimum. This is due to a stronger solar wind (see below) interacting with the Earth's magnetic field (magnetosphere), thereby providing more protection. Conversely, the magnetosphere offers less protection during the solar minimum.

SOLAR ACTIVITY

Solar Wind

The solar wind streams plasma and particles from the sun out into space. Though the wind is constant, its properties are not; fast particles are slowed down to the speed of the solar wind, slow ones are accelerated.

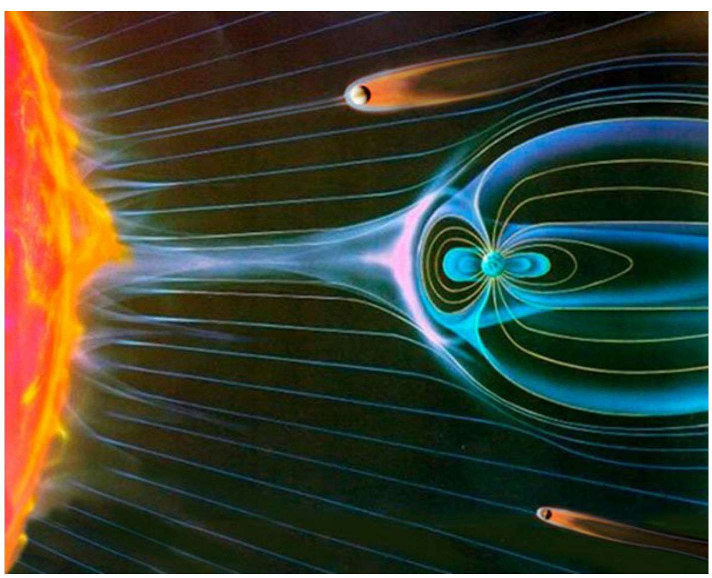

Fig. 2 Artist's impression of Venus, Earth, and Mars interacting with the solar wind.

Solar Flare

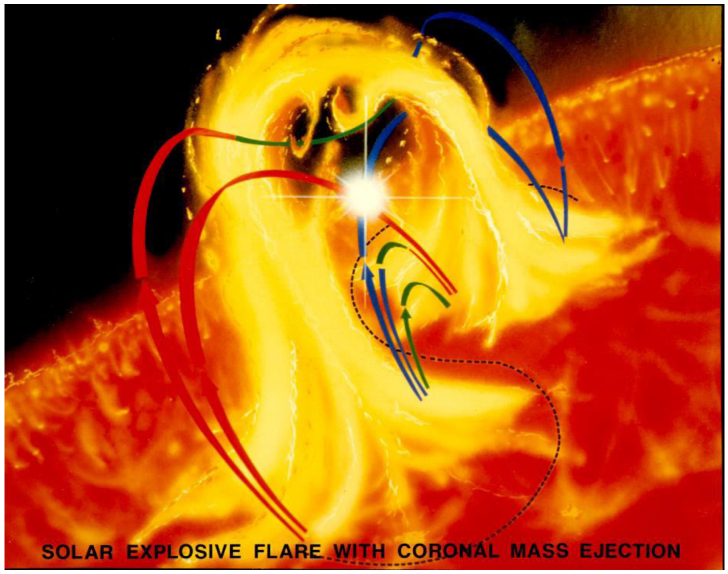

Fig. 3 Birth of a Coronal Mass Ejection

Sunspots are local disturbances in the solar magnetic field. Between two adjacent sunspots, solar magnetic field lines of opposite polarity may connect and cause solar flares. Flares are bursts emitting high-energy radiation, mainly composed by gamma and X-rays. These electromagnetic components propagate at the speed of light, reaching the Earth in about 8 minutes.

Coronal Mass Ejection

Coronal Mass Ejection (CME) is a large expulsion of plasma and magnetic field from the Sun's corona containing both charged (e.g., protons, ionized atoms) and neutral particles (neutrons). It can eject billions of tons of coronal material and carry an embedded magnetic field. CME may or may not be directed towards Earth.

Interaction between CME and Solar wind forms a broad shock front, which is responsible for the acceleration of particles. This process of acceleration is called solar particle event (SPE). The speed of a CME is significantly lower than the speed of a flare. CME particles may reach the atmosphere in few hours or days.

A solar flare increases radiation doses at flight altitudes for a short period of time (usually 1-2 minutes). The increase of radiation dose at flight altitudes because of SPE depends on the energy of CME, and quite often the upper atmosphere absorbs this energy, and thus radiation is not increased at flight altitudes after CME. The atmospheric absorption of the energy is often seen as Aurora Borealis.

Atmospheric Shielding

The Earth's magnetic field protects human beings from much of the particles' radiation by deflecting charged particles away from their collision course with the Earth's atmosphere. However, high-energy charged particles, neutral particles and photons can still penetrate the Earth's atmosphere. At typical cruising altitudes, effective shielding from the entire spectrum of radiation up to the highest energies is unfeasible.

The Effect of Latitude

Particles are deflected to the poles where the magnetic field points to the Earth's surface. At low latitudes (closer to the equator), the field lines are nearly parallel to the Earth's surface, providing the most effective shielding.

Generally speaking, Earth's magnetic field is weaker at the magnetic poles, and therefore the cosmic radiation levels are higher in the Polar Regions and decline towards the Equator. The radiation dose at the poles, with normal solar activity is about 3 to 5 times greater than in in equatorial latitudes.

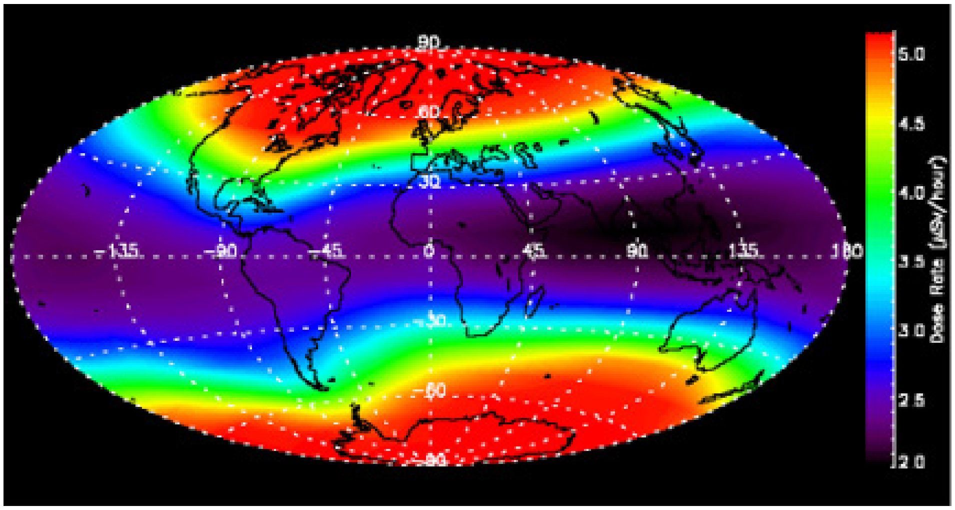

Fig. 4 Typical Background Radiation Dose

The Effect of Altitude

With increasing altitude, the shielding effect of the atmosphere is reduced. Half the mass of the atmosphere lies below the altitude of five kilometers; consequently, higher altitudes represent higher radiation doses and vice-versa.

LIGHTNING AND TERRESTRIAL GAMMA-RAY FLASHES

Terrestrial Gamma-Ray Flashes (TGF) may occur in the vicinity of tropical thunderstorms and, in one event, can release a dose equivalent to that acquired in a normal lifetime. This relatively new discovery and its significance to aviation are currently being researched. TGFs and Lightning from "ordinary" thunderstorms may also result in gamma-ray exposure of about 30 to 100 mSv (2).

RADIOACTIVITY IN THE ATMOSPHERE

Nuclear reactor accidents may contaminate the atmosphere by clouds containing radioactive particles and gases. Normally the affected airspace would be closed as part of the action plan in response to the event.

These radioactive contaminants can travel long distances carried by the wind and end up being inhaled. Whenever possible, flying in radioactive contaminated airspace should be avoided.

DOSES OF IONIZING RADIATION

Ionizing radiation can be objectively measured by absorbed dose: the energy deposited per unit mass. The absorbed doses of different types of radiation cause different biological effects, and sensitivity of different body tissues to these different types of radiation varies. Therefore, tissue-absorbed doses are multiplied by radiation weighting factors to give equivalent doses, and by tissue weighting factors to give the effective dose. The unit of the equivalent dose and the effective dose is called Sievert (Sv) and it allows a comparison between the health effects of different types of radiation.

Some examples of radiation doses and dose rates

Table 1 shows a few examples of doses that might help to clarify the magnitude of exposure. The additional annual cosmic radiation dose that aircrew generally receive is 2-5 mSv.

RADIATION DOSE	SOURCE
0.01 millisievert (mSv)	Tooth X-ray
0.09 mSv (90 µSv)	Flight FRA-SFO
0.1 mSv (100 µSv)	Chest X-ray
1 mSv	Annual dose limit for members of the public, excluding background and medical radiation
2-5 mSv	Average annual cosmic radiation dose for aircrew
2.1 mSv	Average annual German radiation dose (background radiation, indoor radon, medical radiation, etc.)
20-70 mSv	CT scan
100 mSv	Limit on effective dose for exposed workers in a consecutive five-year period, subject to a maximum effective dose of 50 mSv in any single year
> 500 mSv	Dose required for acute radiation illness
4000 mSv	Lethal dose, when received at once

EXAMPLES OF DOSES/HOUR	
0.00004 - 0.0003 mSv/h (0.04 - 0.30 µSv/h)	Natural background radiation in Finland
0.005 - 0.015 mSv/h (5-15 µSv/h)	FL 260-390 [UNSCEAR 2000, German Federal Office for Radiation Protection]
0.030 mSv/h (30 µSv/h)	The value (from distance of 1 meter), which after a patient can be discharged after received medical radiation treatment

Table 1 - Examples of Ionizing Radiation Doses and Doses/Hour

DOSE ESTIMATION: COMPUTER MODELS AND ONBOARD DOSIMETERS

There are numerous approved calculation models (e.g. EPCARD, SIEVERT, PCAIRE, FREE, CARI) that estimate radiation doses with an accuracy of approximately +/- 10%. However, doses of Solar Particle Events (SPE) and Solar Flares have not yet been taken into account.

Feasible, compact onboard monitors are reaching market. They can measure the whole range of radiation and provide a more accurate dose reading than mathematical models. TEPC (Tissue Equivalent Proportional Counter) dosimeters utilize simulated human tissue, being the only direct reading device that measures the absorbed dose to tissue as well as the radiation quality in terms of lineal energy. The principle of measurement over estimation is valid in radiation protection. When available, the use of onboard radiation monitors is encouraged.

For practical purposes, Table 2 presents estimates for the number of flying hours per year required to reach an effective dose of 1 mSv for a given flight level and latitude. The figures were calculated with CARI-3 computer program and have an uncertainty of about 20%. (3)

ALTITUDE (feet)	HOURS AT LATITUDE 60 N	HOURS AT EQUATOR
27,000	630	1330
30,000	440	980
33,000	320	750
36,000	250	600
39,000	200	490
42,000	160	420
45,000	140	380
48,000	120	350

Table 2 - Hours of exposure for effective dose of 1 mSv (Fig.5)

LOW DOSE RADIATION PROTECTION

There are three fundamental principles in radiation protection (5):

- Justification
- Optimization
- Application of dose limits

Aircrew radiation exposure is justified by the benefit of air travel to the world population.

Optimization signifies that the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and social factors. The result of this principle for aviation is, that flight planning and flight performing need to be optimized in respect to radiation exposure but also under socio-economic considerations.

Application of dose limits means that the total dose to any individual should not exceed the appropriate limits specified by the International Commission on Radiological Protection (ICRP).

There are two methods of dose radiation protection: either radiation shielding or applying dose constraints. Disregarding the shielding by the atmosphere, it is impractical to shield aircraft effectively from cosmic radiation. Therefore, the most viable option for flight crew is dose constraints/limits.

Dose limits, constraints and optimization

A long-haul pilot is occupationally exposed to an effective dose of approximately 4.5 mSv per year, whilst the short-haul annual average is about 2 mSv. By comparison, the mean radiation exposure of nuclear plant employees in 2009 was 0.6 mSv.

IFALPA recognizes 20 mSv as the annual limit for occupational exposure for airline flight crews as established by the ICRP 132 (2016) (4), but recommends that the State Regulations apply the concept of reference levels for the purpose of radiation exposure optimization/minimization in aircrew workers. Initial dose reference levels for all flight crew rosters in each fleet should be set at 6 mSv per year.

Flight crew radiation exposure doses should be individually monitored and optimized to As Low As Reasonably Achievable (ALARA), even if the reference level is not exceeded. The Flight personnel liable to exceed an effective dose of more than 1 mSv per year should be recognized as occupationally exposed employees and those that exceed 6 mSv per year should be classified as Category A workers[1].

ICAO AND AUTHORITY REQUIREMENTS

ICRP (4)

The International Commission on Radiological Protection (ICRP) is the primary body in protection against ionizing radiation. ICRP is an independent, non-governmental organization formed to advance the science of radiological protection for the public benefit. The ICRP provides recommendations and guidance on protection against the risks associated with ionizing radiation but has no binding power. However, most of the authority rules adhere to ICRP recommendations.

ICRP acknowledges aircrew to be occupationally exposed to ionizing radiation. The recommended effective dose limit is 20 mSv per year, averaged over defined 5-year periods (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year. In addition, the recommendation for pregnant crew members is 1mSv from declaration of pregnancy for the remainder of the pregnancy. For the general public (e.g. passengers) the annual limit is 1mSv.

ICAO Annex 6

ICAO Annex 6, provision 6.12 requires all airplanes intended to be operated above 15,000m (49,000ft) to carry equipment to measure and indicate continuously the dose rate of total cosmic radiation being received and the cumulative dose on each flight. ICAO Annex 6 provision 4.2.11.5 requires the operator to maintain records of flights above 15,000m (49,000ft) so that the total cosmic radiation dose received by each crew member over a period of 12 consecutive months can be determined.

European Council Directive 2013/59/EURATOM

This directive requires that the limit on effective dose for exposed workers shall be 100 mSv in a consecutive five-year period, subject to a maximum effective dose of 50 mSv in any single year. For pregnant women there is a maximum dose of 1 mSv during the remainder of the pregnancy. In addition, there are a few requirements for crew who are liable to be subject to cosmic radiation exposure of more than 1 mSv per year:

- to assess the exposure of the crew concerned,
- to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed aircrew,
- to inform the workers concerned of the health risks their work involves,
- to apply Article 10 (protection of pregnant and breastfeeding workers) to female aircrew.

In addition, each state in Europe may have, and quite few do have, more strict national legislation concerning radiation. Usually, this national legislation restricts the annual radiation dose from occupational exposure of cosmic radiation to 6 mSv.

1 Example of legislation for Category A workers from Finland: https://www.stuklex.fi/en/ohje/ST1-6

FAA regulations

There are no binding regulations concerning radiation within FAA rules. However, the FAA considers aircrews to be occupationally exposed to ionizing radiation and has the same recommended limits as ICRP recommendations. For pregnant crewmembers, starting when the pregnancy is reported to management, the recommendation is 1mSv limit for the remainder of the pregnancy.

IONIZING RADIATION AND CANCER RISK IN PILOTS

Does a commercial pilot's occupational exposure to ionizing radiation result in any long-term adverse health effects? The ICRP acknowledged the occupational radiation exposure for flight crew in 1990 and more recently in 2016 (4), which resulted in renewed research interest into this topic. Over the last 20 years, there have been more than 65 epidemiological studies published in scientific literature that investigate flight crew and cancer risk. This figure includes a number of reviews and meta-analyses. (5)

Overall cancer risk was not elevated in most studies and subpopulations analyzed, while malignant melanoma, other skin cancers and breast cancer in female aircrew have shown elevated incidence, with lesser risk elevations in terms of mortality. However, the only clearly established causal link between melanoma and radiation is with ultra-violet (i.e. non-ionizing) radiation as opposed to ionizing radiation. In breast cancer, radiation, circadian rhythm disturbances and shift work have been suggested to be contributing factors. Cardiovascular mortality risks were generally very low.

In the majority of studies, no clear-cut dose–response patterns pointing to a higher risk for those with higher cumulative doses were found. However, a recent Icelandic study suggests this kind of relationship, but it needs to be confirmed in other studies (6). Until now, the precise individual cumulative radiation doses have not been available, but now this kind of data is being built up.

However, it is certainly worth noting that radiation doses of airline flight crew do continue to increase, as advances in aerospace technology permit flights with longer duration, higher altitude, and higher latitude. Many of the epidemiological studies are ongoing and further information can be expected.

Pilots have quite strong “healthy worker effect” (Workers usually exhibit lower overall death rates than the general population because the severely ill and chronically disabled are ordinarily excluded from employment (7)) that may contribute to the lower cancer incidence and mortality compared to the general population.

HOW TO MINIMIZE RADIATION EXPOSURE:

- Comply with ALARA;
- avoid flying above optimum altitude;
- avoid short time step climbs;
- reduce exposure times by flying fewer hours;
- if possible, make use of options regarding selection of aircraft type(s) flown, the types of operation (short haul/ long haul), and retirement age;
- avoid flying close to thunderstorms, to reduce the risk of being reached by lightning strikes.

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FIGURES AND TABLES

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2. Fig. 2 Artist's impression of Venus, Earth and Mars interacting with the solar wind. (retrieved from https://www.esa.int/ESA_Multimedia/Images/2012/03/Artist_s_impression_of_Venus_Earth_and_Mars_interacting_with_the_solar_wind)
3. Fig. 3 Birth of a Coronal Mass Ejection, https://www.nasa.gov/mission_pages/hinode/solar_005.html
4. Fig. 4 Courtesy of Solar Metrics
5. Table 1 Vereinigung Cockpit e.V., SLL Finnish Air Line Pilots' Association
6. Table 2 ACJ OPS 1.390 (a)(1) – Assessment of Cosmic Radiation