atmosphere

Review

Radiation in the Atmosphere—A Hazard to Aviation Safety?

Matthias M. Meier [1,*], Kyle Copeland [2], Klara E. J. Klöble [3,4], Daniel Matthiä [1], Mona C. Plettenberg [1], Kai Schennetten [1], Michael Wirtz [1] and Christine E. Hellweg [1]

1 German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, 51147 Cologne, Germany; daniel.matthiae@dlr.de (D.M.); mona.plettenberg@dlr.de (M.C.P.); kai.schennetten@dlr.de (K.S.); michael.wirtz@dlr.de (M.W.); christine.hellweg@dlr.de (C.E.H.)
2 Numerical Sciences Research Team, Federal Aviation Administration (FAA), CAMI, AAM-631, Oklahoma City, OK 73169, USA; kyle.copeland@faa.gov
3 Lufthansa German Airlines, Lufthansa Basis, 60546 Frankfurt/Main, Germany; kkloeble@students.uni-mainz.de
4 Department of Oral and Maxillofacial Surgery, Section of Oral Radiology, University Medical Center of the Johannes Gutenberg-University Mainz, 55131 Mainz, Germany
* Correspondence: matthias.meier@dlr.de; Tel.: +49-2203-601-2789

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Abstract: Exposure of aircrew to cosmic radiation has been recognized as an occupational health risk for several decades. Based on the recommendations by the International Commission on Radiological Protection (ICRP), many countries and their aviation authorities, respectively have either stipulated legal radiation protection regulations, e.g., in the European Union or issued corresponding advisory circulars, e.g., in the United States of America. Additional sources of ionizing and non-ionizing radiation, e.g., due to weather phenomena have been identified and discussed in the scientific literature in recent years. This article gives an overview of the different generally recognized sources due to weather as well as space weather phenomena that contribute to radiation exposure in the atmosphere and the associated radiation effects that might pose a risk to aviation safety at large, including effects on human health and avionics. Furthermore, potential mitigation measures for several radiation sources and the prerequisites for their use are discussed.

Keywords: cosmic radiation; space weather; atmospheric radiation; aircrew; radiation exposure; radiation protection; health effects; avionics; disturbance of high-frequency radio communications; mitigation

1. Introduction

The atmosphere of our planet is not only a prerequisite for aviation but also a protective layer to shield life on Earth against radiation of cosmic origin such as ultraviolet or ionizing radiation impinging from outer space. Electromagnetic and high energy charged particulate radiation from extraterrestrial sources are able to pass the Earth's magnetosphere, reach the top of the atmosphere, and interact with its matter. While the interaction of electromagnetic radiation strongly depends on its wavelength, a charged particle generates a cascade of secondary particles in the atmosphere, i.e., a secondary radiation field. For example, the omnipresent Galactic Cosmic Radiation (GCR) component creates a secondary radiation field, the ionization maximum of which depends on various parameters and was measured for the first time at an altitude of around 15 km under the prevailing conditions [1]. Furthermore, this secondary atmospheric radiation field changes in composition and energy distribution with increasing atmospheric depth. The intensity of the radiation field at the cruising altitudes of civil aviation is usually still about one to two orders of magnitude stronger than at sea level. The dominant shielding parameters are geomagnetic position, altitude, and solar activity. On rare occasions, solar storms classified as Solar Particle Events (SPEs) that manifest in so-called Ground Level Enhancements (GLEs) might significantly increase the intensity of ionizing radiation in the atmosphere, e.g., the radiation exposure at aviation altitudes. The term Ground Level Enhancement refers to a solar radiation event that is strong enough to be even observed as an increase in radiation against the omnipresent galactic background on the ground using instruments called Neutron Monitors (NMs) [2].

The International Commission on Radiological Protection (ICRP) already recommended treating the exposures of aircrew due to cosmic radiation as occupational radiation exposures in 1990 [3]. This recommendation was adopted by the European Union (EU) in 1996 and implemented in the EU directive 96/29/EURATOM that became effective as legal regulation within the member states of the EU in 2000 [4]. The legally stipulated radiation protection measures primarily consisted of an individual assessment of the radiation exposures of crew members, of taking into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed aircrew, of informing the workers concerned of the health risks their work involves, and of limiting the doses of pregnant crew members after reporting pregnancy to 1 mSv for the remainder of the pregnancy. European legislation was amended by the EU directive 2013/59/EURATOM in 2013 which further ameliorated the radiation protection standards of aircrew in the EU [5] based on the most recent recommendations of the ICRP from 2007 [6]. The assessment of the exposure due to cosmic radiation is covered in the series of standards ISO 20785, which include "Conceptual basis for measurements", "Characterization of instrument response", "Measurements at aviation altitudes" and "Validation of codes" [7–10].

Although the ICRP recommendations have not been implemented in binding U.S. legislation yet, U.S. aircrews are also considered occupationally exposed to ionizing radiation. The U.S. Federal Aviation Administration (FAA) has actively supported research into the unique ionizing radiation environment of aviation since the 1960's and the FAA has adopted a mostly advisory role for airmen and air-carriers, publishing Advisory Circulars, e.g., [11], educational documents [12,13], and technical reports, e.g., [14]. FAA recommends following a combination of ICRP and National Council of Radiation Protection and Measurements (NCRP) exposure recommendations [6,15]. These include: for crewmembers, a 5-year average effective dose of 20 mSv per year, with no more than 50 mSv in a single year; for a pregnant crewmember, an added equivalent dose limit for the conceptus of 0.5 mSv in any month and a total of 1 mSv during the remainder of the pregnancy, starting when the pregnancy is reported to the management. Because the mother's body provides little shielding from cosmic radiation, a reasonable estimate of the equivalent dose to the conceptus is the effective dose to the mother [16]. There are only a few ionizing radiation-related regulations for airmen and air carriers. Operations in polar regions (except those completely within Alaska) require a plan of action for mitigation of ionizing radiation exposure in the event of a significant solar storm (U.S. Code of Federal Regulations, Title 14, Part 121, Appendix P, Section III,b,7; also same language in Part 135, Subpart B, 135.98).

Radioactive cargo and contamination are also regulated, e.g., by the U.S. Code of Federal Regulations, Title 49, Parts 175.700–175.705, such that radioactive cargo must be packed to limit exposures in any occupied space to <20 μSv/h and avoid criticality dangers. Aircraft suspected of contamination must be inspected and, if needed, decontaminated. A contaminated aircraft cannot be returned to service until the dose rate at every accessible surface is <5 μSv/h and no more contamination can be removed.

In addition to extraterrestrial radiation sources, weather phenomena associated with lightning can also significantly contribute to the radiation field in the atmosphere. For example, Terrestrial Gamma-Ray flashes (TGF) which are short, high energetic and intense bursts of gamma radiation in the atmosphere remained undiscovered until 1994, when they were first detected from a satellite by chance [17]. Although the underlying physical processes have not been completely understood yet, this phenomenon is associated with high energy electrons accelerated in the electric fields of thunderclouds. High energy gamma radiation, strictly speaking X-rays, results from interactions of these electrons with atoms in the atmosphere and can subsequently even create radioactive isotopes in the atmosphere due to photo-nuclear interactions as well [18].

In contrast to the exposure due to ionizing radiation from cosmic sources, there are no regulations on the exposure to Ultra-Violet (UV) radiation in aircraft cockpits so far. However, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has provided an advisory for the maximal occupational UV exposure. According to the commission's recommendations, the exposure of the eyes to unweighted UV-A should not exceed 10 kJ/m^2 and the exposure of both the skin and the eyes to weighted UV radiation should not exceed 30 J/m^2, within a time period of 8 h respectively [19]. These values have been frequently used as a guideline when assessing UV exposure in the cockpit. It has been demonstrated that the recommendation for unweighted UV-A can be exceeded in some scenarios which involve types of windshields that have a significant transmittance for UV-A [20].

The effects of radiation, both ionizing and non-ionizing, are in principle based on its capability to change the energy content and the structure of matter and depend on the energy transferred. This can have an impact on living cells that might be damaged which could result in severe health effects such as cancer and cataracts. Furthermore, the interaction of radiation with matter may lead to malfunctions in electronic devices and the disruption of radio communications. The interested reader will find more detailed information on each of the aspects discussed hereinafter in the corresponding references.

2. Radiation Sources

Several radiation sources can contribute to the radiation field in the atmosphere. The most important source of occupational radiation exposure of aircrew is the omnipresent Galactic Cosmic Radiation (GCR) that was discovered by Viktor Hess in 1912 [21]. The Sun is not a significant source of cosmic radiation except during Solar Cosmic Radiation (SCR) events such as transient GLEs which are rare but might increase the radiation intensity in the atmosphere significantly. Weather phenomena associated with lightning such as TGFs have been discussed as potential significant atmospheric radiation sources for about two decades. Moreover, aspects concerning UV radiation and the transport of radioactive goods are addressed in this chapter. There has been no sufficient and consistent evidence for health effects due to the exposure to electric, magnetic, and electromagnetic fields in the Intermediate Frequency (IF) and Radio Frequency (RF) range so far [22,23]. However, as far as the susceptibility of avionics to RF is concerned, standard procedures to limit potential interferences in aircraft are defined in RTCA DO-160G [24].

The explanation of the most important dosimetric quantities is given in Appendix A. Furthermore, the instruments most commonly used to measure radiation exposure in the atmosphere are described in Appendix B.

2.1. Cosmic Radiation

2.1.1. Galactic Cosmic Radiation

Galactic Cosmic Radiation originates outside our solar system. High energy charged particles from stellar sources are deflected by intergalactic magnetic fields so that they reach our solar system nearly isotropically, i.e., equally from all directions. The source of the permanently elevated radiation exposure at flight level is the hadronic component of the GCR, i.e., fully ionized atomic nuclei with extremely high energies. The relevant energy range of primary GCR particles extends approximately from 100 MeV/nucleon up to one TeV/nucleon depending on the atmospheric and magnetic shielding. Of the primary GCR nuclei, only protons (hydrogen nuclei) contribute both directly to the exposure at aviation altitudes and indirectly through the formation of a secondary particle field. Heavier nuclei, helium above all others, contribute about 30% to the dose and only through the secondary particle field that is created in repeated interactions of the primary and secondary radiation with the constituents of the atmosphere. However, the direct contribution of primary ions becomes more important at higher altitudes [25,26]. For the relevant dose quantities in radiation protection, e.g., effective dose, neutrons and protons dominate the radiation field at aviation altitudes with a combined contribution between 60% and 80%. The remaining dose is caused by electrons, positrons, gammas and muons (Figure 1).

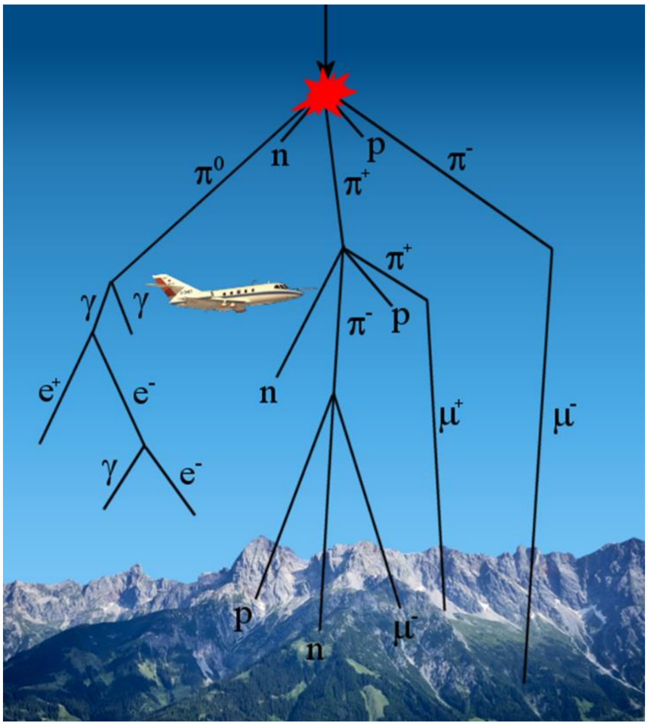

Figure 1. The radiation field at aviation altitudes is created in repeated interactions of the primary and secondary radiation with the constituents of the atmosphere.

The effective dose rate at commercial aviation altitudes can reach approximately 8 μSv/h at 41,000 ft. during solar activity minimum. In many situations, however, the dose rate is reduced by three natural protective mechanisms: increased mass shielding by the atmosphere at lower altitudes, increased magnetic shielding by the Earth's magnetic field at low latitudes, and reduced GCR intensity during periods of increased solar activity. Increased solar activity leads to a stronger interplanetary magnetic field which decelerates the charged GCR particles traversing the interplanetary space between the boundary of the solar system and Earth. As a consequence, the intensity of GCR particles is reduced during solar active times leading to an anti-correlation between solar activity and radiation exposure from GCR. The interested reader is referred to a comprehensive review article by Potgieter for more information [27]. Figure 2a illustrates the effect of solar modulation: the variations of the effective dose rate at 41,000 ft. and 29,000 ft. during the past decades are caused by the variation of the GCR intensity during the solar cycle. The maximum values are reached during periods of solar minimum and especially the recent two solar minima (in 2009 and 2020) showed peak values in the effective dose rates. The minimum values reached during solar activity maximum can be up to a factor of two lower than the peak values. A similar pattern can also be observed on the International Space Station (ISS) and other exposure scenarios in the heliosphere [28].

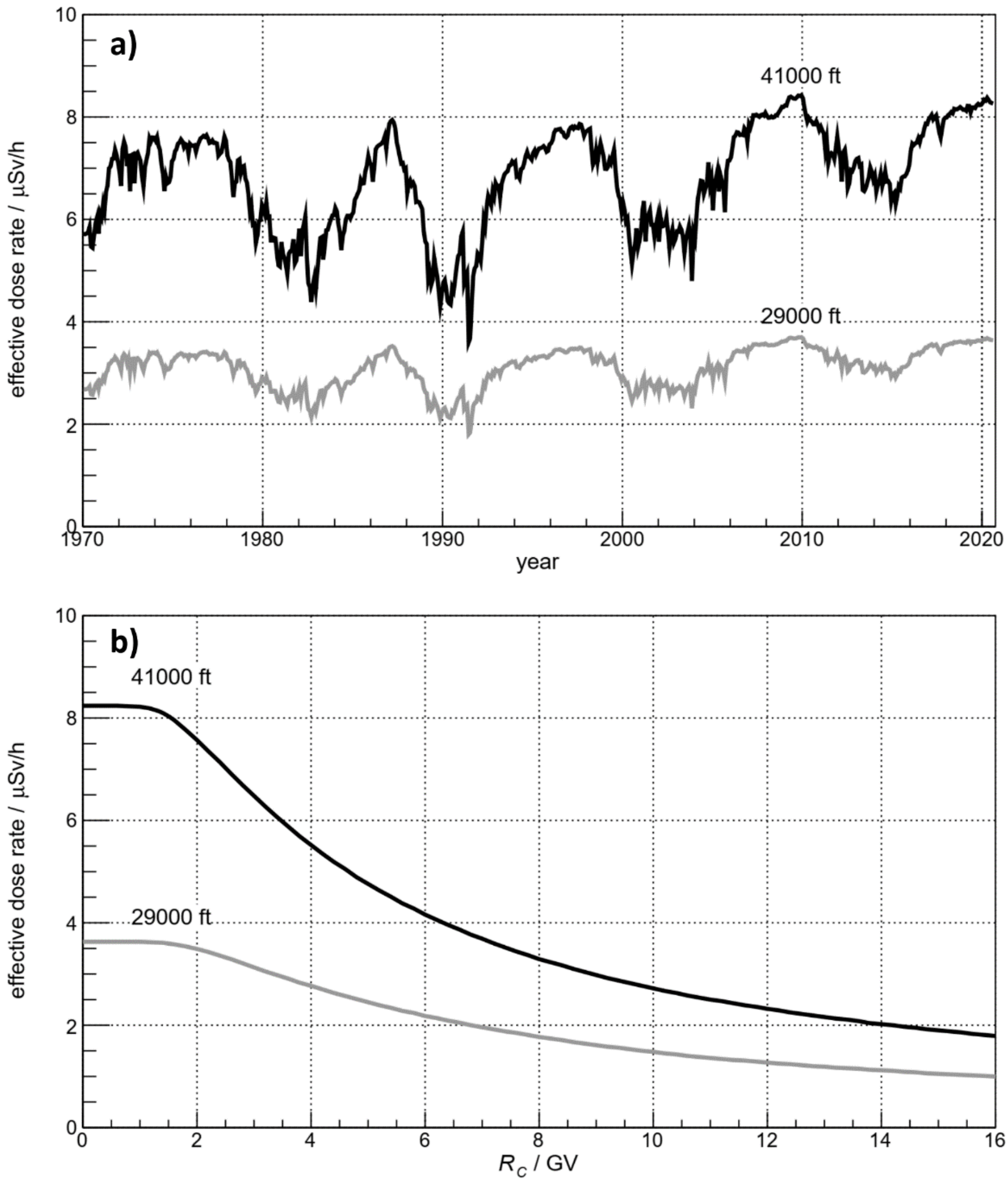

Figure 2. Variations of the effective dose rate over time (**a**) and the dependency on the magnetic shielding expressed by the cut-off rigidity R_C (**b**) at 29,000 ft. and 41,000 ft. during solar minimum (dose rates are calculated with the PANDOCA model [29]).

The atmosphere provides shielding against the primary GCR particles and reduces the dose rates at lower altitudes. Figure 2a,b show the resulting effect on effective dose rates, which are reduced by approximately a factor of two between 41,000 ft. and 29,000 ft. These altitudes correspond to an atmospheric mass shielding of approximately 180 g/cm^2 and 320 g/cm^2, respectively. The Earth's magnetic field provides powerful protection at low latitudes but has no effect on GCR intensity and dose rates at high latitudes. This is a consequence of the dipole-shaped magnetic field of Earth with field lines that are horizontally orientated at the equator and vertically oriented in the polar region, which leads to a strong deflection of vertically impinging charged particles at low latitudes and essentially no deflection of vertically impinging charged particles at high latitudes. The shielding effect by the magnetosphere on charged GCR particles is most often expressed by the effective vertical cut-off rigidity R_C. The rigidity of a particle is defined by its momentum divided by its charge. High cut-off rigidities correspond to a high shielding effect and low cut-off rigidities correspond to a low shielding effect. The effective cut-off rigidity can be interpreted as the lower threshold for particles to reach the atmosphere. The cut-off rigidity is quantified as voltage. In the magnetosphere, the corresponding values reach from 0 GV to about 16 GV in some equatorial regions. The effective dose rate at 41,000 ft. is reduced by a factor of four between locations with the highest exposure at high latitudes (R_C = 0 GV) and equatorial regions where the highest magnetic shielding effect is reached ($R_C \approx 16$ GV, cf. Figure 2b). At lower altitudes, the reduction factor is slightly lower due to the fact that lower energy primary GCR particles which are more effectively shielded at lower latitudes (higher cut-off rigidities) have a decreased impact on dose rates.

Although the Earth's magnetosphere shields the planet from a substantial amount of GCR and from charged particles due to extreme radiation conditions of solar origin, it is not a rotationally symmetrical protective shield. The simplified concept of the magnetosphere assumes a magnetic dipole field that is tilted and shifted with respect to the rotational axis of the Earth. Thus, the so-called inner radiation belt, an accumulation of charged particles trapped within the magnetosphere, reaches closer to the Earth over the South Atlantic Ocean in terms of geometry. As a result, this South Atlantic Anomaly (SAA) induces a comparatively high-intensity radiation environment regionally closer to the Earth's surface [30]. While this phenomenon is potentially hazardous to objects and humans in the low Earth orbit, measurements in the geographical SAA region at aviation altitudes during quiet solar conditions have not shown any effects on dose rates so far [31]. However, the effects of the SAA on aviation and on the ground during extreme radiation events remain an important part of current research with regard to both radiation exposure and High Frequency (HF) radio communications.

The operational dose assessment of aircrew is performed using atmospheric radiation models, such as CARI and PANDOCA [14,29,32]. Model calculations have been confirmed by measurements, in particular with data acquired during solar minimum conditions [29,33] and the instruments used were validated by an intercomparison campaign [34]. Furthermore, several models have been compared with measuring data and it has been shown that the agreement of some model calculations with high-quality measuring data is on the order of about 5–10% [35].

2.1.2. Solar Cosmic Radiation

There are two kinds of events that occur at the Sun that may increase ionizing radiation levels in Earth's atmosphere, Coronal Mass Ejections (CME) and solar flares. Both are the result of solar magnetic field line reconnection, a reorganization of part of the Sun's magnetic field, but they occur in different parts of the solar atmosphere. When magnetic reconnection, usually originating in a magnetically active region around a visible sunspot group, results in an explosive ejection of ionized matter from the solar corona, the event is called a CME. A large CME can send billions of tons of material into interplanetary space at speeds > 1500 km/s [36]. If the CME is moving faster than the local solar wind (a few to several hundred km/s), it produces interplanetary shock fronts. These shock fronts can result in showers of high-energy ions impacting Earth's atmosphere [37]. A solar flare occurs much deeper in the solar atmosphere and from a relatively small volume of the Sun [37]. The amount of energy and matter released during a solar flare is relatively small compared to the amount released during a CME. The electromagnetic radiation (photons) from a solar flare arrives at Earth about 8 min after departing the Sun. Many CMEs and solar flares do not send many energetic solar ions to Earth. The interplanetary magnetic field and geomagnetic field influence the trajectories of solar ions in the same way they influence GCR ions, so those that approach Earth may eventually enter the atmosphere from any direction, not just on the Sun-facing side of the Earth. The most energetic charged particles from a CME or a solar flare follow the most direct paths and reach Earth in 15 to 20 min. The difference in arrival time between photons and charged particles is due to different speeds and the longer path the particles must follow to reach Earth.

A surge of subatomic particles from the Sun is defined as a Solar Particle Event (SPE) by the Space Weather Prediction Center (SWPC) of the U.S. National Oceanic and Atmospheric Administration (NOAA) if instruments on a Geosynchronous Operational Environmental Satellite (GOES) measure in three consecutive 5-min periods an average > 10 MeV solar proton flux ≥ 10 particles/(cm^2 × sr × s) [38]. A particle surge that meets these characteristics is most likely the result of a CME. However, it takes a huge number of particles of much higher energies than 10 MeV to generate an additional significant solar radiation component at cruising altitudes due to the geomagnetic and atmospheric shielding [39]. A significant contribution can be excluded if no concomitant GLE is observed. The impacts of several strong SPEs without concomitant GLEs on the radiation field at aviation altitudes have been studied using historic events [40]. In this study, it was shown that dose rates would not have exceeded values of 5 µSv/h at a conventional flight altitude of 12.2 km (40,000 ft.), not even during the largest SPE without GLE that was investigated. Nevertheless, the dose rates at aviation altitudes can be significantly increased during strong GLEs depending on the impinging solar particle flux and the corresponding energy spectrum described by a parameter named spectral index. GLEs have been enumerated since 1942. The strongest event that has been recorded so far occurred on 23 February 1956 and might have caused an additional radiation exposure on the order of 10 mSv at cruising altitudes [41].

2.2. Lightning

The most important known radiation source associated with lightning and discussed in the context of radiation exposure in the scientific literature is Terrestrial Gamma-ray Flashes (TGF). This phenomenon was discovered in 1994 by gamma measurements of the Burst and Transient Spectrometer Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) satellite [17]. TGFs are bursts of gamma radiation in the atmosphere on the order of a few milliseconds with energies of up to about 40 MeV [42]. Since gamma radiation is absorbed on its way through the atmosphere, only gamma rays produced in the upper atmosphere are able to escape to Low Earth Orbit (LEO) where they can be detected by satellites. The bursts of gamma radiation are created by electrons that are accelerated to nearly the speed of light in strong electrical fields generated by thunderstorms. These electrons create high-energy photons due to bremsstrahlung processes which are able to create electron-positron-pairs and neutrons by photo-nuclear reactions. Consequently, TGFs consist rather of X-rays than gamma radiation, a distinction that is usually not made in the area of astrophysics where the term TGF was coined. Although TGFs have been known for some time, the exact physical processes have not been completely understood yet. Most TGFs detected by satellites occur, similar to lightning, in the equatorial region. TGFs, as the abbreviation implies, are primarily associated with gamma rays, strictly speaking, X-rays from bremsstrahlung processes, which render this phenomenon observable from satellites. However, the prime component potentially contributing to the radiation field at aviation altitudes is the precursory electrons accelerated in strong electrical fields in the atmosphere. Dwyer et al. estimated the radiation exposure for the electron avalanche based on several assumptions, e.g., its spatial extent and a multiplication factor, to be up to 30 mSv in the region of the highest electron density within the avalanche without any additional unknown acceleration mechanism [43]. It is not clear if this assessment could be relevant for commercial aircraft since pilots try to avoid thunderstorms. It has been concluded from measurements with gamma-ray detectors on-board a research aircraft near thunderstorms that TGFs with intensities similar to those of events measured in LEO must be very rare at aviation altitudes (<1% per lightning) [44,45]. Furthermore, neutrons from photo-nuclear reactions can be captured which creates radioactive isotopes in the atmosphere [18]. However, the number of these nuclides is quite small and their contribution to the radiation field in the atmosphere is negligible.

2.3. Radioactive Goods

The speed of air transport is very advantageous when shipping isotopes with short half-lives often used for medical diagnosis and treatment, making radiopharmaceuticals the most common radioactive cargo shipped by air. Other radioactive materials shipped by air include those used for research or commercial purposes. Packing and shipment of radioactive substances are strictly regulated to limit exposure of any persons on board the aircraft, minimize criticality issues, and reduce the possibility of spillage. U.S. and U.K. government-funded studies of these shipments consistently have found doses to passengers, cabin crew, and flight crew to be extremely low [46–49]. The mean annual doses are less than the GCR dose received on some intercontinental flights. The highest estimate for any group was from the 1977 NRC study. For crewmembers working only on flights out of airports serving major radiopharmaceutical producers, researchers estimated annual exposures up to 0.13 mSv for cabin crew and 0.025 mSv for flight deck crewmembers. As noted previously, dose rates in occupied spaces from shipments of radioactive materials are regulated. In the U.S., the limit is 0.020 mSv/h. The choice of 0.020 mSv/h is consistent with U.S. regulations protecting the public from controlled sources. In practice, packing regulations collectively result in lower dose rates.

2.4. Ultra-Violet Radiation

The extraterrestrial solar spectrum resembles that of a black body with a temperature of 5700 K and a maximum wavelength of around 500 nm. The attenuation of this radiation by Earth's atmosphere depends on the wavelength. In the UV region, the most energetic part UV-C (200–280 nm) is absorbed by the ozone layer at an altitude of about 30 km, which is too high to affect commercial aviation. UV-B radiation (280–315 nm) is partly absorbed on its way to the ground and UV-A (315–400 nm) only to a small extent. At cruising altitudes, above the weather, the aircraft is in direct sunlight during almost all daytime hours. In literature, including an ICNIRP statement [50] for the occupational UV exposure, it was assumed that cockpit windshields block UV radiation completely. This assumption was based on measurements from the early 1990's [51], which were not sufficiently sensitive to UV-A. Although newer measurements confirmed that UV-B is blocked by the windshields, it was ascertained that this is not necessarily the case for UV-A. It should be mentioned here that UV exposure for the cabin crew is most probably negligible due to the small windows and the small field of view in the cabin. The FAA performed measurements with different types of cockpit windshields on the ground with artificial light sources and identified windshields with good and poor UV-A attenuation [52]. Several groups from different countries performed in-flight measurements in different types of aircraft on a variety of flight routes and detected UV-A radiation behind some of the windshields [20,53–55]. A dependence on the age of the aircraft was observed [53]. Furthermore, the transmittance of UV-A is highly dependent on the windshield type and manufacturer [20]. Although one study reports no significant UV-A irradiance in the examined cockpits [56], others found levels of UV-A that could have exceeded the maximal recommended UV-A exposure for the eyes for some scenarios [20,53,54,57,58]. It was shown that the visor of the windshield is very effective for reducing the UV-A exposure by measuring the UV-A irradiance of direct sunlight and behind the windshield visor, at the position of the pilot's face, respectively.

Besides the direct assessment of UV in the cockpit by measurements, there are also numerical methods that were applied to estimate the UV exposure in cockpits [59]. These calculations have already been validated by the first measurements [60]. The exposure due to UV radiation, or more generally due to sunlight in the cockpit, does not only depend on the spectral transmittance of the windshield. It also strongly depends on other factors like flight route and time of day. The solar radiation is strong, especially in lower latitudes with large solar elevation angles at noon. However, under these conditions the face and the eyes of the pilots are in the shade because of the obstruction due to the structure of the cockpit. At low solar elevation the solar radiation may not be so strong, but the pilots are hit by direct sunlight in the face. Therefore, the exposure in the cockpit is higher at low solar elevation angles, although the sunlight is overall weaker. It is also possible that only one pilot sits in direct sunlight for a major part of a long-haul flight while the other one on the other side of the cockpit is in the shade. Long-haul flights are often overnight which reduces the overall UV-A exposure. Although the attenuation of UV-A in the atmosphere compared to UV-B is weak, a significant decrease in UV-A irradiance with decreasing altitude of the aircraft of about 6.5% per km was observed for low solar elevation angles where the path of the sunlight through the atmosphere is comparatively long [20].

3. Effects and Hazards

The primary concern of the effects of ionizing radiation in the atmosphere is the impact on human health. For this reason, radiation exposure of aircrew is regarded as occupational in many countries. Radiation protection measures include individual dose assessment of aircrew members, roster planning with a view to reducing the doses of the highly exposed crew, and advisory information.

When cosmic radiation interacts with electronics, different types of damage can be observed: total dose effects, displacement damage effects, and single event effects (SEE) [61]. Regarding atmospheric environments primarily the latter need to be considered. In electrical devices, single particles randomly interact with semiconducting components and immediately generate free charge carriers causing erroneous currents. Consequently, non-destructive soft errors such as Single Event Upsets (SEU) and hard errors such as Single Event Latch-Ups (SEL) or Single Event Burnouts (SEB) which lead to permanent damage of the device can be observed. Memory structures are particularly vulnerable to such events and can experience alterations [61].

Furthermore, communications can be affected as well during extreme radiation conditions. Usually, the ionosphere reflects radio waves for long-distance communication. However, X-ray bursts, solar particle events, and geomagnetic storms can cause enhanced ionization in the ionosphere. Hence, radio waves are rather absorbed or scattered than reflected, leading to disturbed or lost communication [62].

3.1. Health

The initial stage of any health effect due to radiation is the transfer of energy to living cells. For example, cellular radiation damage can result in a change in genetic information or cell death. If only a few cells in an organ are killed, the function of this organ will remain unaffected. However, if the number of cells killed by radiation exceeds the regeneration capacity and the functional reserve of the organ, i.e., above a corresponding threshold, its function will deteriorate as organ necrosis or degeneration progresses and clinical symptoms will appear. Furthermore, the severity of this effect, i.e., organ dysfunction or even failure, will increase with the radiation dose. Since this kind of radiation effect is known to occur above a threshold, it is regarded as deterministic. An important prerequisite of dose limits in radiation protection is to exclude deterministic radiation effects, i.e., the exposure to doses known to be detrimental with certainty. Another kind of radiation effect is of stochastic nature, e.g., the change of genetic information (or other damage) of a cell that might lead to cancerogenesis if cellular repair mechanisms and elimination by apoptosis [63] or the immune system fail. In radiation protection, the so-called Linear-Non-Threshold model (LNT-model) is applied to derive dose limits for stochastic effects [64]. For example, the risk of dying from a radiation-induced cancer is legally limited to 0.08% per calendar year for occupationally exposed persons in Germany with a related limit of the effective dose of 20 mSv. Several epidemiological studies have been performed to investigate the risk of aircrew due to their exposure to cosmic radiation in detail. In recent years, several cases of indirect medical radiation effects have been reported, namely the malfunctions of medical devices such as pacemakers associated with air travel.

3.1.1. Cancer

Radiation—both ionizing and ultraviolet—is a known human carcinogen based on epidemiologic and experimental evidence [63,65,66]. Following acute exposure in the dose range of 100 mSv to a few Sv, ionizing radiation can statistically significantly cause cancer in humans, and a linear increase with dose is assumed [67,68]. During the multistep process of carcinogenesis, cells acquire various hallmarks [69]. In the classical paradigm, radiation induces DNA damage which can result in genetic mutations, tumor suppressor genes or proto-oncogenes if DNA repairs fail [70,71]. In the radiation-exposed cell, several signaling cascades responding to these stress conditions are triggered [72]. Especially in the low dose range, effects beyond the classical DNA damage can modulate the cellular outcome, including gene expression changes in targeted and non-targeted cells, adaptive responses encompassing DNA repair and antioxidation reactions, apoptosis, cell cycle arrest, senescence and a complex network of metabolic and immunological regulation [71–77]. The latency periods between radiation exposure and the manifestation of the disease take years or even decades. For aircrew members, cancer induction is considered the primary lifetime health risk from ionizing radiation exposure. However, the doses and dose rates usually encountered in aviation are considered low (typically a few mSv per year of occupational exposure). Table 1 shows risk estimates for fatal and non-fatal cancers from the most recent ICRP recommendations [6]. The risk for low dose and low dose rate ionizing radiation is estimated to be about 4 in 100,000 per mSv for fatal cancers. Although the doses for aircrews are comparatively low, they are exposed to a mixed radiation field with a large fraction coming from high-LET radiations such as neutrons (typically 30–50 percent of the effective dose). Thus, the risk estimates from aircrews' doses should consider the particles as well as the doses, whereby the Dose and Dose Rate Effectiveness Factor (DDREF) = 1 case can be considered as an upper limit.

Table 1. Increased Lifetime Risk of Cancer (Nonfatal or Fatal) from Ionizing Radiation.

	Expected Cases Per mSv in 100,000 Persons	
DDREF *	**Whole Population ****	**Age Group 18–64 Years**
1	34 (8 fatal)	23 (6 fatal)
2	17 (4 fatal)	12 (3 fatal)

* DDREF = dose and dose rate effectiveness factor. ** In the U.S. in 2016, cancer caused 22% of deaths among persons of all ages [78]. Adapted from [6].

Epidemiological studies in aircrew have revealed that the mortality by all cancers is smaller compared to the general population (Table 2). With a few exceptions, the cancer incidence is comparable to the general population (Table 3). These exceptions can be explained by different risk factors associated with, e.g., Kaposi's Sarcoma, Non-Hodgkin-Lymphoma, etc., or by reproductive factors associated with breast cancer. An increased incidence of bone tumors was observed in one study among Finnish female flight attendants (Table 3). As this finding was based on two observed cases (one chondrosarcoma and one malignant chordoma which are usually not associated with radiation exposure) with only 0.1 expected cases, the authors of the study attribute it to the frequent effect of chance in a small cohort [79].

Furthermore, the influence of chronodisruption due to shift work might have been underestimated and remains an important research topic for the future [80]. Open questions concerning the pathogenetic role of occupational ionizing radiation exposure remain for brain tumors, skin melanoma and non-melanoma skin cancer such as basal cell carcinoma. The currently known main risk factors for melanoma include exposure to sunlight, naevus count, phototype, and family history of melanoma [81,82]. A meta-analysis of 19 studies with over 250,000 participants concluded that pilots and cabin crew have around twice the melanoma incidence (Table 3) compared with data based on different reference populations [83]. In this context, it is worth mentioning that an epidemiological study in the United Kingdom revealed no differences in skin melanoma rates between the flight crew and a reference group consisting of air traffic control officers, who also have an aviation-related profession with similar socioeconomic status, however without occupational exposure to cosmic radiation [84]. In this study, skin prone to sunburn and sunbathing for tanning were the strongest risk predictors of skin melanoma in flight crew and air traffic controllers [84]. Furthermore, the light-at-night theory was put forward to explain the higher melanoma incidence in aircrew. This theory suggests melatonin secretion that is suppressed by artificial light during the night to be involved in carcinogenesis [81].

Table 2. Cancer mortality studies in aircrew.

Aircrew Group	Control Group	Standardized Mortality Ratios *		Reference
		All Cancers	Specific Cancers	
German cohort				
Female cabin crew (16,014) Male cabin crew (4537)	General population (Germany)	0.79 (0.54–1.17) 0.71 (0.41–1.18)		[85]
Male cockpit crew (28,000)	General population (Germany)	0.68 (0.63–0.74)	Melanoma: 1.78 (1.15–2.67) Lung cancer: 0.53 (0.44–0.62)	[86]
Male cockpit crew (6017)	General population (Germany)	0.64 (0.51–0.81)	Lung cancer: 0.33 (0.17–0.57) Brain tumors: 2.1 (1.03–3.93)	[87]
Female cabin crew (17,022)		0.95 (0.72–1.26)		
Male cabin crew (3735)		0.89 (0.59–1.33)	Non-Hodgkin-Lymphoma: 4.24 (1.26–10.76)	
Female cockpit crew (90)	General population (Germany)—sex, age-group and calendar-period-specific controls	1 case (unspecified cause)		[88]
Male cockpit crew (6006)		0.57 (0.47–0.69)	Brain tumors: 2.01 (1.15–3.28)	
Female cabin crew (17,017) Male cabin crew (3733)		0.84 (0.69–1.02) 0.71 (0.52–0.96)		
Cohorts in other European countries				
Male cockpit crew (3022) Male cabin crew (3418) Female cabin crew (3428)	General population (Italy)	0.58 0.67 0.90		[89]
Male cockpit crew (843) Female cabin crew (1835-?) Male cabin crew (?)	General population (Greece)	0.6 (0.3–0.9) 0.8 (0.3–1.7) 0.4 (0.1–1.2)		[90]
European countries: pooled cohorts or meta-analysis of national cohorts				
Female cabin crew (16,014)	General population (8 European countries)	0.78 (0.66–0.95)		[91]
Male cabin crew (4537)		0.90 (0.74–1.12)	Non-Melanoma Skin Cancer: 1.98–30.45	
Male cockpit crew (843)	General population (8 European countries) —case-control study	0.72 (0.64–0.82)		[92]
Commercial airline crew (93,771) Male Cockpit Female Cabin Male cabin	General population (10 European countries)	 0.73 1.01 1.0	Melanoma: 1.57	[93]
North American cohorts				
Female cabin crew (9610)	General population (United States of America)	0.71 (0.62–0.81)	Respiratory tract tumors: 0.5 (0.36–0.68)	[94]
Male cabin crew (1701)		0.83 (0.67–1.02)	Respiratory tract tumors: 0.66 (0.43–0.98) Non-Hodgkin-Lymphoma: 2.3 (1.1–4.23)	
North American and European cohorts (meta-analysis)				
Pilots	Respective general population		Melanoma: 1.83 (1.27–2.63)	[83]
Cabin crew			Melanoma: 1.42 (0.89–2.26)	

* 95% confidence interval in brackets, if available. Standardized mortality ratios of specific cancers are listed if they are significantly different from 1.0.

Table 3. Cancer incidence studies in aircrew.

Aircrew Group	Control Group	Standardized Incidence Ratios *		Reference
		All Cancers	Specific Cancers	
Scandinavian and Icelandic cohorts				
Female cabin crew (1577)	General population (Finland)	1.23 (0.86–1.71)	Breast cancer: 1.87 (1.15–2.23) Bone tumors: 15.1 (1.82–54.4)	[79]
Male cabin crew (187)		2 cases (Non-Hodgkin-Lymphoma, Kaposi-Sarcoma)		
Female cabin crew (915)	General population (Denmark)		Breast cancer: 1.61 (0.9–2.7)	[95]
Male cockpit crew (3790)	General population (Denmark)	1.1 (0.94–1.28)	Melanoma: 2.4 (1.3–4.0) Other skin cancer: 2.3 (1.7–3.0)	[96]
Female cabin crew (3144)	General population (Norway)	1.1 (0.9–1.3)	Melanoma: 1.7 (1.0–2.7) Non-Melanoma Skin Cancer: 2.9 (1.0–6.9)	[97]
Male cabin crew (599)		1.7 (1.3–2.2)	Melanoma: 2.9 (1.1–6.4) Non-Melanoma Skin Cancer: 9.9 (4.5–18.8) Upper respiratory tract tumors: 6.0 (2.7–11.4) Liver tumors: 10.8 (1.3–39.2)	
Female cabin crew (1532)	General population (Iceland)	1.2 (1.0–1.6)	Breast cancer: 1.5 (1.0–2.1) Melanoma: 3.0 (1.2–6.2)	[98]
Female cabin crew (2324) Male cabin crew (632)	General population (Sweden)—case-control study	1.01 (0.18–1.24) 1.16 (0.76–1.55)	Melanoma: 2.18 (1.09–3.9) Melanoma: 3.66 (1.34–7.97)	[99]
Male cockpit crew (551)	General population (Iceland)	0.90 (0.71–1.11)	Melanoma: 3.31 (1.33–6.81) Basal cell carcinoma: 2.49 (1.69–3.54)	[100]
United Kingdom cohort				
Flight crew (16,329)	General population (United Kingdom)	0.71 (0.66–0.76)	Smoking-related cancer: 0.33 (0.27–0.38) Melanoma: 1.87 (1.45–2.38)	[84]
Air traffic control officers (3165)		0.80 (0.68–0.94)	Smoking-related cancer: 0.42 (0.28–0.60) Melanoma: 2.66 (1.55–4.25)	
North American cohorts				
Female cabin crew (6895)	California statewide sex-, age-, and site-specific incidence rates	1.05 (0.86–1.27)	Breast cancer: 1.42 (1.09–1.83) Melanoma: 2.50 (1.28–4.38)	[101]
Male cabin crew (1216)		2.43 (1.57–3.58)	Kaposi's Sarcoma: 9.29 (5.18–15.36) Melanoma: 3.93 (0.74–11.62)	
North American and European cohorts (meta-analysis)				
Pilots Cabin crew	Respective general population		Melanoma: 2.22 (1.67–2.93) Melanoma: 2.09 (1.67–2.62)	[83]

* 95% confidence interval in brackets, if available. Standardized incidence ratios of specific cancers are listed if they are significantly different from 1.0.

3.1.2. Teratogenicity

Teratogenicity is defined as potency to induce abnormalities in the physiological development of biological organisms. Radiation, e.g., at cruising altitudes, is generally regarded as exogenous teratogen [102]. As a consequence, the radiation exposure of an organism might, among other things, lead to the development of carcinogenic dysplasias or malformations. Developing organisms are more sensitive to radiation-induced damage, compared to adult individuals. This is due to a large amount of rapidly dividing cells and small numbers of cells forming the organ anlage (primordium). Therefore, unborn children are at higher risk for malformations than adults [103,104].

Teratogenic damage is categorized as stochastic radiation effect which is the result of random processes assessed with the LNT-model [64]. For ethical reasons no experiments regarding radiation effects on pregnant women and their unborn children exist. Therefore, the effects of radiation exposure have to be primarily assessed from studies of A-bomb survivors, animal experiments and occupationally exposed workers. Animal experiments using mouse embryos revealed significant increases in malformations after the exposure to 0.25 Gy X-rays and 0.12 Gy of fast neutrons with average energies of 6 MeV. Lethal effects for the embryo were already observed at low-LET radiation doses of 0.2 Gy. Especially, in the pre-implantation phase (until day 9 after fertilization) evidence for the “all-or-none-law” is found. Thus, according to this rule, exposed embryos rather die than develop malformations [105]. The conceptus is at the highest risk of death from ionizing radiation in the pronuclear zygote stage shortly after fertilization, when a single hit can result in death. Later, blastocysts surviving ionizing radiation exposure mostly develop normally as the remaining embryonic stem cells are pluripotent. Nevertheless, in case of a too high cell death rate considering the low total cell number of the blastocyst, the whole blastocyst dies and does not implant, resulting in regular occurrence of the next menses.

After implantation of the blastocyst, during organogenesis (day 10 to week 8), neuropathologic alterations, other anomalies, and growth retardation can result from ionizing radiation exposure of the pregnant mother. Evidence for teratogenic effects in humans is found for protracted exposures to ionizing radiation of 50 to 100 mGy and for acute exposures to doses from 10 to 50 mGy [106]. During organogenesis, the brain and the eye are organs at risk, and microphthalmy and microcephaly can be consequences of prenatal radiation exposure with threshold doses of 50 mGy during organogenesis and 300 mGy during the fetal phase starting at week 8, respectively (Table 4). However, these threshold doses are so high that only the most extreme solar proton events might be able to induce them at commercial aviation altitudes without corresponding mitigation measures. The risk of childhood leukemia is considered to be increased in the case of prenatal exposure to more than 10 mSv [107–111].

Table 4. Radiation effects on the unborn child.

Phase of Pregnancy in which the Radiation Exposure Occurs	Effect	Suspected Threshold Dose
From the first day of the last menstrual period, especially 2nd half of the cycle	Death/non-implantation of the fertilized egg cell (“all-or-none law”)	50 to 100 mGy
4 weeks after the last menstrual period	Damage to the embryonic primordium (organ anlagen, e.g., heart, eye, nervous system ...) ⇒ Risk of malformations	50 to 100 mGy
From the ~11th week of pregnancy	Malformation of the brain	300 mGy
Whole pregnancy	Increased risk of leukemia and solid tumors in childhood	~10 mSv

3.1.3. Cataracts

A cataract, the opacification of the eye lens, can cause blindness, and its prevalence increases with age [112]. Despite effective treatment by cataract surgery, it remains a major public health issue in the view of increasing life expectancy [112]. Besides alcohol consumption and smoking, diabetes, cardiovascular diseases, gout, eye trauma, myopia, sex, body mass index and systemic use of corticosteroid, exposure to sunlight or to ionizing radiation are additional risk factors of cataractogenesis [113–115]. The cataractogenic parts of the sunlight comprise UV-A and UV-B radiation and possibly short-wavelength blue light (400–440 nm) [116–119]. A connection between UV-A radiation and nuclear cataract was suggested [117]. The eye lens is an organ exhibiting radiation sensitivity [120] as it contains a germinative zone in the lens epithelium with actively proliferating cells that finally differentiate into transparent lens fibers and an elimination mechanism for damaged cells is lacking. An initial step in radiation-induced lens opacification is the induction of DNA damage in lens epithelial cells. The radiation response encompasses DNA repair and alterations in cell cycle control, apoptosis and differentiation. DNA repair might fail especially in the cells of the germinative zone and post-irradiation proliferative activity of these cells might result in cellular disorganization and disturbance of pathways controlling the differentiation into lens fiber cells. Damaged cells then migrate to the posterior pole of the eye lens [117]. Therefore, exposure to ionizing radiation can be associated with a higher risk for the development of sub-capsular cortical eye lens opacities. According to recent epidemiological indication, radiation-induced cataracts occur with a threshold absorbed dose of below 1 Gy of sparsely ionizing radiation [115]. Excess lens opacity formation was found in a study of former astronauts who received more than 8 mGy of high-LET radiation during space missions with high inclination orbits [121]. The ICRP now estimates the threshold dose as 0.5 Sv (0–1 Gy), and a few percent of exposed individuals might be genetically predisposed for radiation-induced cataractogenesis [6,114]. Furthermore, low dose rates or protracted radiation exposure do not result in lower cataract induction compared to high dose rate exposure [122]. Several studies on the prevalence of lens opacities were conducted in cohorts of airline or military pilots and astronauts, suggesting higher cataract prevalence in these occupational groups [121,123–126]. Some of these studies are either limited by small cohort size, missing dose records or assessment of other risk factors, subjective lens opacity assessment or inadequate controls [115], so that sufficient evidence of a higher prevalence of cataracts in airlines pilots requires further investigation [127].

3.1.4. Medical Devices

Active implanted medical devices (AIMDs) such as pacemakers, defibrillators, or insulin pumps are susceptible to the effects of cosmic radiation. In recent years, several incidents with malfunctioning devices during or after flights have been reported [128–131]. Effects on patients ranged from losing trust in the device, to increasing pace of stimulation of pacemakers or unnecessary shocks of defibrillators [128,129]. These were likely caused by Single Event Effects (SEE) in the microelectronics. Alterations in the memory are usually detected and corrected but can also force the device to make a reset. Still, in some cases, stimulation parameters can be changed as the device switches into safety mode during this process [132]. Therefore, patients can be subjected to incorrect therapy, possibly leading to life-threatening conditions, until the failure can be corrected. In the past 15 years, two manufacturers called back their devices due to the effects of background cosmic radiation [132,133]. A quantitative analysis found 22 events in 579 devices observed over 284,672 days in the daily life of patients which on average equals one event in 35 device years [134]. However, the failure rate for devices at aviation altitude or during solar particle events could be strongly increased.

3.2. Avionics

Cosmic radiation-induced errors in avionics have been reported in the scientific literature, in particular since the 1990s [135,136]. Furthermore, an important report describes the incident of Qantas Flight 72 (QF72) suddenly pitching down the nose and rapidly decent twice [137]. Although there is insufficient evidence available, an SEE in the air data inertial reference unit is considered to be the possible cause, as other causes were regarded as unlikely. Still, it helped refocus attention on SEEs as a possible threat for avionics. The Joint Electron Device Engineering Council (JEDEC) established standard requirements and procedures for measurement and reporting of terrestrial cosmic-ray induced soft errors in semiconductor devices in their report JESD89A released in 2006 [138]. Furthermore, the International Electrotechnical Commission (IEC) provides guidance on atmospheric radiation effects on avionics electronics used in aircraft operating at altitudes up to 60,000 ft by their report IEC 62396, which was issued in 2006 and has since been updated several times [139]. The most recent version of this standard now includes information on extreme space weather, whereas before it was mostly limited to background GCR conditions. According to this standard specification, it is crucial to assess all vulnerable and essential parts of the electronics and the overall system in terms of their sensitivity to cosmic radiation, especially to neutrons. In a simplified approach, it is suggested to use existing data on SEEs in specific parts of the integrated circuit from previous measurements. If such data are unavailable, further tests on components are supposed to be carried out to assure system compliance [139]. In standard procedures, neutron and proton facilities simulating atmospheric radiation environments or monoenergetic beam lines of several energies and consequent interpolations are used to estimate SEE cross-sections in the devices, e.g., 14 MeV, 50 MeV, 100 MeV, and 200 MeV [140]. Subsequently, they are multiplied by a reference differential flux at aviation altitudes to gain a Single Event Rate (SER) in a simplified approach [139]. However, with these methods, the SER might be underestimated due to the neglect of a potentially higher cosmic proton contribution [140]. A misinterpretation of the results can lead to placement of soft error-prone components at critical positions in avionics [141]. Furthermore, the contribution of neutrons below 10 MeV to the SER is assumed negligible in the scientific literature and in corresponding standards since SEEs of those particles in electronics are considered as rare [138]. However, smaller chip technologies might also be susceptible to the effects of neutrons with energies between 1–10 MeV [142]. Moreover, the sensitivity of modern components in avionics to thermal neutrons might have further effects and neglecting those during testing would also lead to an underestimation of the SER [141,143]. Due to the thermalization of neutrons in the structure of the aircraft, the risk from their effects on avionics might even be enhanced [144]. Boron-10 has a high cross-section for thermal neutron capture which results in a fission process and the emission of a Li-7 nucleus and an alpha particle. These are highly ionizing particles and can therefore induce further soft errors in electrical devices [61]. Boron is used as a p-dopant and as a constituent of Borophosphosilicate Glass (BPSG), a dielectric, in semiconductors [145]. Hence, components manufactured with BPSG are highly susceptible to SEEs induced by thermal neutrons [146]. Accordingly, the effect of thermal neutrons on electrical components in avionics is highly dependent on size, material, and fabrication. [147]. While previous testing has mainly focused on SEU and SEL in memory devices such as SRAMs [140,143,148], further measurements have shown that power MOSFETs might also be affected by SEB [148,149]. Figure 3 shows the large dependence of the calculated GCR neutron fluence rates at high latitude on altitude during solar activity minimum.

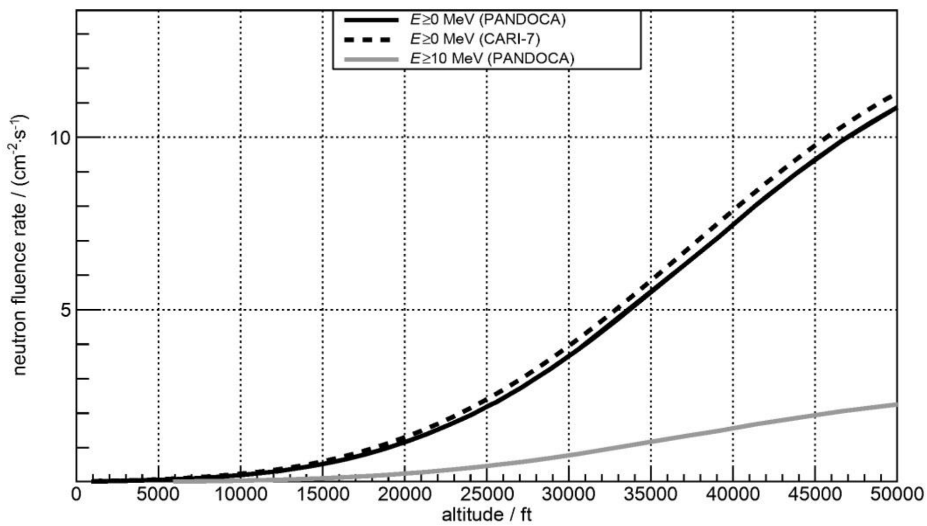

Figure 3. Model predicted GCR total neutron fluence rate dependence on the altitude from PANDOCA [22] (black solid line) and CARI-7 [25] (black dashed line) and for neutron energies greater than 10 MeV from PANDOCA (grey line) without geomagnetic shielding (R_C = 0 GV) during solar minimum.

Based on neutron measurements and simulations the number of SEEs for a chip with an average cross-section of 5×10^{-14} cm^2 per bit at a neutron flux greater than 10 MeV, an altitude of 12 km, and a cut-off rigidity of 1 GV could be estimated [150]. For the GCR during solar maximum conditions, there would be in the worst case 2.5 upsets per hour and gigabyte [150]. For extreme atmospheric radiation events such as the GLE of February 1956, the SER could increase to an estimated 2520 upsets per hour and gigabyte [151]. Therefore, avionics is likely to experience severe soft errors during these conditions [151]. First measurements in the area with the geographic coordinates of the SAA have not shown any effects on dose rates at aviation altitudes during quiet solar activity yet [31]. As far as TGFs are concerned, X-rays, electrons, as well as prompt photo-nuclear neutrons generated in the atmosphere and in aircraft structures might induce further system failures in avionics [152]. Several techniques have been established to mitigate radiation effects, including prevention, and recovery [153]. Purifying fabrication materials and radiation hardening of electronic devices can prevent errors induced by cosmic radiation [153]. Recovery mechanisms such as self-checking designs and error detection may help when a device has been influenced by cosmic radiation [153]. Redundancy of particularly susceptible components is a key issue as well [153,154].

3.3. HF-Communications

Space Weather events can also cause degradations or even total disruptions of High Frequency (HF) radio communications. X-rays from solar flares are not affected, i.e., deflected, by the magnetosphere and reach the Earth's atmosphere on the sunlit side of the Earth, where they can cause an increase in the ionization of the upper atmosphere, which can interfere with short-wave radio communications. The severity of the corresponding effects ranges from weak or minor degradation of HF radio communications to complete HF radio blackout on the entire sunlit side of the Earth lasting for a number of hours. Furthermore, impinging protons from solar particle events are deflected by the magnetosphere and focused on the polar regions of the Earth, where they can also increase the ionization rate in the upper atmosphere leading to ionospheric disturbances with comparable impacts on HF communications. For example, during the so-called Halloween Storms between mid-October and early November 2003, HF communications with aircraft experienced various disruptions. With increasing solar activity in the beginning of the events, the quality of communications was reduced. The following solar flares caused further limitations as well as complete breakdowns of the HF services lasting for several hours. Due to the magnetospheric shielding of the Earth, areas of low latitudes were less affected than regions of high latitudes. As a consequence, flights were rerouted in order to avoid high altitudes in the polar region, which ended up in higher costs in both passenger and cargo flights. Since the quality of communications dropped significantly, Air Traffic Centers (ATC) needed to increase the number of controllers [155]. According to U.S. Code of Federal Regulations, Title 14, Part 121, Subpart E § 121.99 it is mandatory for U.S. aircraft operators to "show that a two-way communication system, or other means of communication approved by the responsible Flight Standards office, is available over the entire route. The communications may be direct links or via an approved communication link that will provide reliable and rapid communications under normal operating conditions between each airplane and the appropriate dispatch office, and between each airplane and the appropriate air traffic control unit." Although the satellite communications system SATCOM might be less affected by a severe Space Weather event, this mode of communications is not available above 82° N latitude. Hence, permanent monitoring of the situation of the ionosphere is particularly important for operations in the polar region. The adverse effects on HF-communications due to solar X-rays and protons can be assessed using the dedicated Space Weather R-scale for radio blackouts and the S-scale for solar radiation storms, respectively. Both Space weather scales have numbered levels that are supposed to provide information about possible effects at each level and were introduced by the National Oceanic and Atmospheric Administration (NOAA) in 1999 [156,157].

4. Mitigation Measures

The total radiation exposure of an individual or an electronic device, respectively, depends on the intensity of the corresponding radiation field in terms of dose rate and the duration spent in this field. Thus, mitigation measures are quite limited in the context of the omnipresent GCR. However, the reduction of radiation exposure is in principle possible during severe transient solar radiation events, i.e., GLEs. For instance, in cases where the transport of passengers or freight is not time-critical, flights could be delayed until the additional radiation component due to a solar radiation event has decreased significantly in order to reduce the time spent in the radiation field in the atmosphere. A corresponding delay will usually take up to several hours depending on the temporal profiles of the GLEs, which can be quite different. For example, the solar contribution dropped below a radiation level of 20 µSv/h after some 1.5 h during GLE70 in 2006 while this level was exceeded for about 9 h during GLE42 in 1989 (Figure 4). Dose rates and accumulated doses in Figure 4 were calculated for an altitude of 41,000 ft. (FL410) and locations at 90° N 0° for GLE42 and 70° N 50° E for GLE70, respectively. At these locations, the shielding of the Earth's magnetic field is negligible but the exact dose rate profile and the accumulated dose during an event can differ at other high latitude locations depending on the angular distribution of the incoming energetic particles.

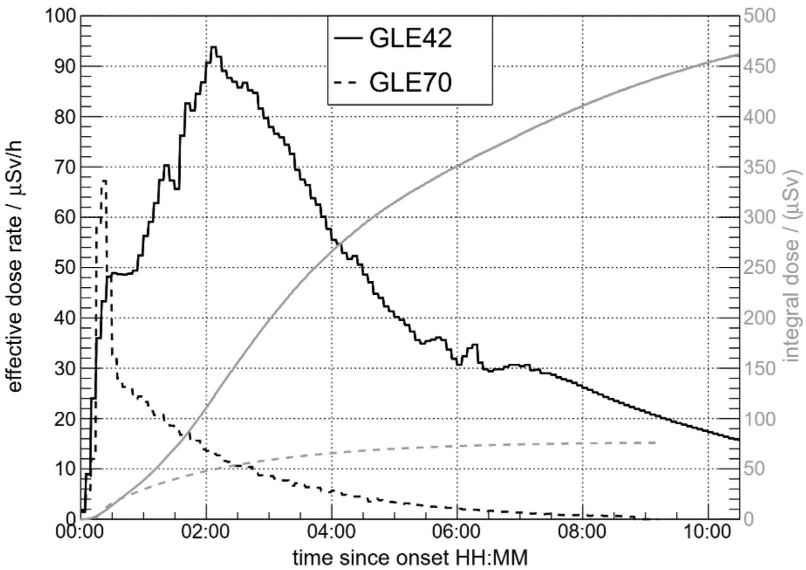

Figure 4. Dose rates and accumulated doses were calculated for the altitude of 41,000 ft. (FL410) and locations at 90° N 0° for GLE42 and 70° N 50° E for GLE70, respectively.

Since the intensity of the radiation field in the atmosphere during a GLE is given by solar activity, the only feasible mitigation measure consists in changing the position in the atmosphere, i.e., the flight trajectory, in order to increase the atmospheric or geomagnetic shielding, respectively. While the effect of geomagnetic shielding is quite limited to only a few flight routes, an increase in atmospheric shielding, i.e., a decrease in flight altitude, should be an option worldwide. However, a reduction in flight altitude usually results in higher fuel consumption, which is a safety-related parameter. A possibility to reduce the additional fuel consumption is to adapt the Mach number, i.e., the flight speed to the reduced altitude. Although a correspondingly reduced flight speed would likewise increase the time spent in the radiation field, the net effect of this measure would usually result in a considerable reduction in the additional radiation dose accrued to aircrew and passengers during such an event [158]. The reduction in flight altitude, however, would not mitigate the degradation of HF-communications. For this purpose, trajectories have to be restricted to areas with correspondingly stable ionospheric conditions.

The topical challenge for effective mitigation of significant space weather events is to forecast or detect such events in due time and to provide the relevant information in the right form to the right persons at the right time. As a first approach, the International Civil Aviation Organization (ICAO) established a system of space weather centers in 2019 [159]. The plan established three global and two regional space weather centers, which will share advisories they generate using existing distribution networks. The focus of these centers is on solar events which can potentially impact radiation levels on board civilian aircraft, satellite-based navigation and surveillance (GNSS), and air transport-related HF communications. A single advisory may contain information for all three types of events. Advisories are issued for specific geographic areas using a 3-tiered evaluation (Table 5).

Table 5. International Civil Aviation Organization (ICAO) thresholds for space weather advisories.

Impact	Units	Advisory Level	
		Moderate	Severe
Global Navigation Satellite System (GNSS)			
Amplitude Scintillation (S4)	dimensionless	0.5	0.8
Phase Scintillation (Sigma-Phi)	radians	0.4	0.7
Vertical Total Electron Content	TEC Units	125	175
Radiation			
Effective Dose *	mSv/h	0.030	0.080
HF			
Auroral Absorption (Kp)	Kp index	8	9
Polar Cap Absorption	dB (30MHz Riometer data)	2	5
Solar X-rays, 0.1–0.8 nm	W/m^{-2}	1×10^{-4}	1×10^{-3}
Post-Storm Depression (MUF) **	%	30	50

* Moderate advisories for ionizing radiation will only be issued when the threshold is reached at FL460 (46,000 feet, 14.0 km) and below. Severe advisories will be issued when the threshold is reached at any flight level up to FL600 (60,000 ft., 18.3 km). ** Compared to a 30-day running median of the critical frequency of the F2 layer (foF2).

While some of these quantities are regularly measured at sites around the world, others such as radiation dose rates must be calculated from models. For quantities requiring the use of models, model selection is left to individual centers.

ICAO recommends operators to develop operational procedures for managing flights in areas impacted by space weather events, including flight planning of tracks in advance based upon forecasts with provisions for plan revisions based on situational awareness. Additional information on ICAO space weather-related activities can be found in ICAO documents 8896 and 10100 and at the ICAO Meteorology Panel publics document website [160].

A more sophisticated approach for the description of the situational increase in radiation exposure at aviation altitudes during a GLE is the concept of the space weather D-index. Although the thresholds for ICAO space weather advisories are comparable to the corresponding levels of the D-index, this index is devised to provide more specific information. For this purpose, it is based on the additional rate of the effective dose $\dot{E}_{sol}$ that can be assessed by model calculations as well as measurements of the rate of the ambient dose equivalent [161]. A wide range of solar contributions can be covered with comparatively small natural numbers of the D-index using a multiple of 2 of the additional dose contributions which can be easily communicated to airlines in order to initiate proportionate mitigation measures [35,39]. The practical meaning of the different levels of the D-scale is comparable to the levels of the NOAA space weather scales. Figure 5 shows the D-scale, which has no upper limit, with indices from D 0 to D 5, their classification, dose rate intervals, and a respective comparison with other radiation environments.

Scale	Classification	Dose Rate Interval [μSv/h]	Additional Exposure
D 0	Quiet	$\dot{E}_{sol} < 5$	Variation of the natural background at cruising altitudes
D 1	Nominal	$5 \leq \dot{E}_{sol} < 10$	Natural background at high latitudes up to FL400
D 2	Minor	$10 \leq \dot{E}_{sol} < 20$	Natural background at high latitudes between about FL400 and FL600
D 3	Moderate	$20 \leq \dot{E}_{sol} < 40$	Average dose rate inside the ISS, threshold for FAA radiation alert
D 4	Strong	$40 \leq \dot{E}_{sol} < 80$	Average dose rate during an Extra-Vehicular Activity (EVA) on the ISS
D 5	Severe	$80 \leq \dot{E}_{sol} < 160$	FAA recommended monthly limit for pregnant women likely to be exceed on a long-haul flight

Figure 5. D-Scale for aviation with Space Weather D-Indices from 0 to 5.

According to the results by Kataoka et al., a space weather radiation event without a concomitant GLE would hardly bring about a situation different from the D 0 level [40]. A D-index of 3 characterizing a moderate space weather radiation event might be considered the first level for moderate mitigation measures, in particular for potentially long-lasting space weather radiation events and for long haul flights, even if exposure at D 3 level up to 10 h would hardly result in exceeding the monthly limit for pregnant women recommended by the FAA [11].

However, mitigation measures should be considered when this recommended dose limit for pregnant women is likely to be exceeded. This might be possible when exposed at D 5 level for more than three hours. The space weather surveillance system Maps of Ionizing Radiation in the Atmosphere (MIRA) was developed at the Civil Aerospace Medical Institute (CAMI) in 2017 and it is the first to implement the concept of the D-index into the framework of an already existing warning system. In case of a warning situation, messages are sent to the NOAA Weather Wire Service (NWWS). Text files are created from dose rate output files which can then be used to build custom map layers, including D indices [14,162]. Moreover, the D-index has been used to communicate space weather information to several European airlines since 2014, e.g., Europe's largest airline Lufthansa. In future applications, the D-index will be used to avoid false warnings, to inform about ongoing situations of increased radiation levels, and to facilitate specific mitigation measures for given positions in the atmosphere, since it depends on the geomagnetic and atmospheric shielding. Thus, it permits the development of a more differentiated picture of the radiation field for different geographic areas and altitudes similar to the essential local parameters in the field of terrestrial weather, e.g., temperature, air pressure, etc. and to communicate this information to aircrew correspondingly. The investigation of the impacts of severe space weather radiation events on flight routes for the entire air transport system remains a challenge for the future.

In contrast to the exposure to ionizing radiation, effective mitigation measures concerning the exposure to UV radiation can be comparatively easily implemented. Cockpit windshields of commercial aircraft are equipped with visors that efficiently block UV radiation. It is recommended to use these visors in case of direct sunlight in the cockpit. Wearing sunglasses that block UV-A (UV400) is recommended as well. Aircraft windshields have to be replaced from time to time which offers the opportunity to select windshield types that block UV-A effectively. Information given to the cockpit crew might help them adapt their behavior accordingly, i.e., using visors and sunglasses. Although there are scenarios in which the ICNIRP recommendation concerning the exposure to unweighted UV could be exceeded in the cockpit, it should be mentioned that this value is easily exceeded in a much shorter time period during every outdoor activity in direct sunlight.

5. Conclusions and Outlook

The initial question if radiation in the atmosphere is a hazard to aviation safety refers to a complex matter comprising a variety of different radiation sources and related adverse radiation effects. More than a century has elapsed since the discovery of cosmic radiation in 1912 and several other sources of radiation that affect both the Earth's atmosphere and aviation, e.g., radiation belts, SPEs, TGFs, have been discovered since then. Furthermore, the related radiation effects, in particular health effects, have been intensively studied all over the world for many years. Since the annual doses accrued by aircrew members are comparable to other radiation workers, flight personnel are recognized as occupationally exposed to radiation in many countries, e.g., EU, USA, etc. with corresponding advisories and legal regulations, respectively.

The omnipresent GCR component accounts on average for more than 99% of the occupational radiation exposure of aircrew, although it cannot be excluded that solar radiation events might contribute significantly in individual cases. GCR and solar UV are the best-known radiation sources in the atmosphere so far. A joint FAA-NASA program to study high-altitude cosmic radiation, including solar radiation storms, was started in 1965 to support supersonic transport development [163]. While no large solar events were measured, there were many balloon- and aircraft-based measurements of GCR, and significant model development. An example of this is the early program for assessment of route doses from GCR for U.S. based flights, ACRE. This software program was based on inflight measurements of ionization and neutron flux performed in the 1960s and was used to estimate passenger doses from commercial air travel and from proposed supersonic travel. Its predictions were close to measurements at commercial altitudes at mid-latitudes but compared less favorably with later measurements at higher latitudes and at lower and higher altitudes. The earliest widely adopted personal computer software designed for this use was the FAA's Carrier program. The first released version (1989) based upon developed using Schaefer's calculations from the SST period [164]. For CARI-2 (1991) through CARI-6 (1999) and their variants, the most recent version of LUIN then available was used to calculate the dose rate databases (e.g., [165]), while CARI-7 and its variants are based on MCNPX 2.7.0. results [14,32,166,167]. CARI was only the first of many software packages for personal computers developed to calculate in-flight radiation dose. Further examples include AVIDOS [168], EPCARD [169], NAIRAS [170], PANDOCA [29], PC-AIRE [171], and SIEVERT [172] among others [173]. In addition, measuring flights have been performed to acquire data for comparison and validation of models [34,174]. However, the amount of high-quality measuring data at aviation altitudes is still quite limited [35]. Hence, more measurements covering the whole range of altitudes, latitudes, and solar activity are required. This remains an important scientific task for at least the next decade. Although the potential exposure to UV behind cockpit windshields seems to have been underrated for many years, it plays only a minor role, since this radiation component can be shielded effectively. The assessment of the impact of solar radiation events associated with GLEs on the radiation field in the atmosphere is an ongoing challenge and considerable progress has been made, in particular within the last two decades since radiation protection for aircrew became regulated in many countries. Research on the impacts of weather phenomena such as lightning is still in its infancy. In particular TGFs might cause significant doses within a second. However, this phenomenon is still poorly understood.

Statistical radiation effects on both health and avionics cannot be excluded, although, e.g., epidemiological studies have not shown consistent evidence for significant dose–response patterns in aircrew for several investigated types of cancer yet. Since these effects depend on the accrued dose, radiation protection measures aim at limiting radiation exposure to a level that is as low as reasonably achievable. Proportionate mitigation measures taking into account social and economic factors are limited. A reasonable approach consists in a timely reaction to transient significant increases in radiation due to solar radiation events in order to avoid comparatively high radiation exposures and potential associated teratogenic effects. ICAO has already established a system of space weather centers for this purpose and advisories will be issued when certain levels of radiation are exceeded. More specific guidance for airlines can be provided by the space weather D-index, which has been used by several European airlines, e.g., Lufthansa to inform aircrew about space weather radiation events since 2014. As far as avionics is concerned, redundancy in system design is the primary key factor to mitigate radiation impacts. Furthermore, the use of radiation-hardened electronic components might be beneficial for crucial and vulnerable parts of avionics. In this context, it is worth mentioning that during a space weather radiation event the effects on complex avionics systems with unknown redundancies and vulnerabilities are still much more uncertain than the levels of dose, e.g., given by the D-index, which can be modelled quite well.

The science of atmospheric radiation weather with its different sources of ionizing and non-ionizing radiation and related effects comprises an interdisciplinary field of research that is alive and important to improve our knowledge for living with the Sun, our star.

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Appendix A. Dose Quantities

The term ionizing radiation describes its capability of transferring an amount of energy to penetrated matter that is sufficiently high to ionize its atoms. The ionization density of different types of particulate radiation is an important parameter for the assessment of biological effects and human health, which depends on the mass, the electric charge and the energy of the particle. Details on the definition of quantities and units can be found in [6,175,176].

Appendix A.1. Absorbed Dose

The principal physical quantity to describe the energy deposition of ionizing radiation in matter is the absorbed dose D with the corresponding unit gray (Gy) and defined as energy per mass (J/kg):

$$D = \frac{\Delta\varepsilon}{\Delta m} \tag{A1}$$

D: absorbed dose; $\Delta\varepsilon$: deposited energy in mass Δm.

The quantity absorbed dose does not consider that different types of radiation have different effects on human health. Neither does it account for the fact that the sensitivity to radiation differs between organs. The absorbed dose D is used for the assessment of acute health effects after exposure to high doses of radiation. An absorbed dose of 4–5 Gy in a short period of time is considered lethal without immediate medical treatment. The absorbed dose does not only depend on the type and the energy of the radiation, but also on the irradiated material. This is important when measuring absorbed doses, i.e., absorbed dose measured using a silicon detector is different from absorbed dose deposited in human cells which basically consist of water. However, absorbed dose measured with silicon detectors can be converted to the corresponding value in water by a factor that depends on the respective radiation field. This has to be considered when calibrating instruments.

Appendix A.2. Effective Dose

The effective dose E is a dose quantity that is used to assess the probability for radiation induced cancer and other genetic effects. This is accomplished using radiation weighting factors and tissue weighting factors that consider different types of radiation and irradiated organs [6]. The absorbed dose deposited in an organ by a particular type of radiation R is multiplied by a radiation weighting factor w_R defined for each type of radiation R. The resulting radiation weighted equivalent doses are summed up over all contributing radiation types for each organ. This results in an equivalent dose for each organ. As next step, these equivalent doses are multiplied by the tissue weighting factor w_T for the affected organs and summed up over all organs, which leads to the important quantity effective dose:

$$E = \sum_T w_T \sum_R w_R D_{T,R} \tag{A2}$$

E: effective dose; w_T: tissue weighting factor; w_R: radiation weighting factor; $D_{T,R}$: absorbed dose by tissue T due to radiation type R.

The unit of the effective dose is sievert (Sv) defined by energy per mass (J/kg). In this context, it is worth mentioning that the term effective dose refers only to the human body. Furthermore, this quantity cannot be directly measured and has to be estimated by calculations or measurable quantities, e.g., the ambient dose equivalent which is described below.

Appendix A.3. Ambient Dose Equivalent

The ambient dose equivalent *H*(10)* is an operational dose quantity that can be measured by specially calibrated instruments and is used as an estimate for the effective dose, e.g., using a conversion coefficient [161]. This dose quantity is commonly used to assess the radiation exposure at aviation altitudes. Its unit is energy per mass (J/kg) and it is called sievert (Sv). The ambient dose equivalent *H*(10)* is defined by the equivalent dose at a depth of 10 mm in a simple spherical phantom made of tissue-equivalent material called the ICRU sphere according to the International Commission on Radiation Units and Measurements (ICRU).

Appendix B. Measuring Equipment

Appendix B.1. Tissue Equivalent Proportional Counters

The tissue equivalent proportional counter (TEPC) is an instrument devised to measure the exposure in mixed radiation fields, e.g., at aviation altitudes. It consists of a metal sphere filled with a gas at low pressure and coated with tissue equivalent plastic (A-150). Ionizing particles that enter this sphere create a track of ionized gas. The generated ion pairs are accelerated by an electric field and multiplied near the anode, which allows measuring a signal that is proportional to the deposited energy. This sphere is equivalent to a few micrometers of tissue in terms of energy deposition by ionizing particles. This setup can measure the energy spectrum of single events in terms of lineal energy (energy imparted divided by the mean cord length of the detector). This information can be used to calculate the absorbed dose and the ambient dose equivalent by applying the quality factor for ionizing radiation [3]. The TEPC was originally developed for neutron radiation but there are different techniques to estimate the dose in the region of very low LET. The hardware usually consists of two different multi-channel analyzers working with different gains to achieve higher resolution in the low LET region. A configuration with an internal radiation source makes it possible to check the calibration of the instrument [177,178].

Appendix B.2. Semiconductor Detectors

Semiconductor detectors are commonly used for measurements of high-resolution energy deposition of ionizing radiation in matter. When a charged particle hits the sensitive area of this detector, electron-hole pairs are generated by the deposited energy. For this interaction, the required energy is only dependent on the material of the detector. Therefore, the generated charges are proportional to the absorbed energy. An applied electric field finally collects the free charges which induce an electrical pulse [179].

There are several types of semiconductor detectors. Liulin-type instruments are commonly used in aerospace dosimetry and can indicate the dose rate and particle flux of the measured radiation. The instrument consists of a silicon detector directly connected to a charge sensitive shaping amplifier (CSA) and additional pulse analysis components. The number of pulses detected at the output of the CSA is proportional to the particle flux through the sensitive area. Moreover, the amplitude of this pulse is proportional to the deposited energy in the detector. Hence, the corresponding dose and dose rate over the measurement interval are subsequently calculated and displayed [180].

Appendix B.3. Neutron Rem Counters

A neutron rem counter consists of a proportional counter filled with Helium-3 or boron trifluoride (BF_3), i.e., materials sensitive to thermal neutrons. Neutrons of higher energies are thermalized by a shell of hydrogenous plastic surrounding the sensitive volume of the counter. Measurements in radiation fields that contain a significant fraction of high-energy neutrons, e.g., at aviation altitudes, require a modified instrument with a lead layer as a converter. Spallation processes of the neutrons in the lead layer create several neutrons with lower energies in each reaction. These neutrons are subsequently thermalized and detected. Modified rem counters can be usually calibrated to measure the ambient dose equivalent in neutron fields.

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