DOT/FAA/AM-21/8
Office of Aerospace Medicine
Washington, DC 20591

Ionizing Radiation and Radiation Safety in Aerospace Environments

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March 2021

Final Report

NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. DOT/FAA/AM-21/8	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IONIZING RADIATION AND RADIATION SAFETY IN AEROSPACE ENVIRONMENTS		5. Report Date March 2021 6. Performing Organization Code
7. Author(s) Copeland, K., and Friedberg, W. (ret., deceased)		8. Performing Organization Report No.
9. Performing Organization Name and Address Civil Aerospace Medical Institute FAA		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency name and Address Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplemental Notes		

16. Abstract

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17. Key Words Ionizing Radiation, Cosmic Radiation, Radioactive Contamination, Space Weather, Geomagnetism, Radiation Exposure Limits, Flight Doses, Radiation Health Risks.		18. Distribution Statement Document is available to the public through the Internet: http://www.faa.gov/go/oamtechreports/	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 57	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

For help in preparing and reviewing this revised and updated report, we thank Roni G. Anderson (CAMI Librarian), Kathy Wade (CAMI Librarian, Ret.), Michael Wayda (CAMI Editor, Ret.), Stacey Zinke-McKee (Protection and Survival Research Laboratory Manager), and Anthony Tvaryanas (Aerospace Medical Research Division Manager). This work was performed in fulfillment of Project 2016-AAM-631-NUM-10058, sponsored by the FAA's Office of Aerospace Medicine.

CONTENTS

LIST OF ABBREVIATIONS

ALI	Allowable level of intake
ARS	Acute Radiation Syndrome
CAMI	Civil Aerospace Medical Institute
CFR	Code of Federal Regulations
CME	Coronal mass ejection
CVD	Cardiovascular disease
DDREF	Dose and dose-rate effectiveness factor
EU	European Union
FAA	Federal Aviation Administration
GCR	Galactic cosmic radiation
GLE	Ground-level event
GOES	Geosynchronous Operational Environmental Satellite
Gy-Eq	Gray equivalent
ICRP	International Commission on Radiological Protection
ISS	International Space Station
KI	Potassium iodide
LET	Linear energy transfer
LEO	Low-Earth orbit
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OSHA	Occupational Safety and Health Administration
PCA	Polar Cap Absorption
RBE	Relative biological effectiveness
SCR	Solar cosmic radiation
SPE	Solar proton event
TGF	Terrestrial gamma-ray flash
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UV	Ultraviolet

EXECUTIVE SUMMARY

This report can be used as a sourcebook for the instruction of crewmembers on ionizing radiation exposure of air and space travelers and updates information and guidance materials in DOT/FAA/AM-11/9. The report discusses the nature and hazards of ionizing radiation, subatomic particles of matter and packets of electromagnetic energy (photons) with sufficient energy to eject orbital electrons from atoms. Sources of ionizing radiation most likely to be encountered during air travel include galactic and solar cosmic radiations, radioactive cargo, radioactive substances released into the atmosphere, lightning, and terrestrial gamma-ray flashes. In space travel, radiation trapped in the Earth's magnetic field is also possible. There are two classes of health effects that may result from ionizing radiation exposure. A health effect following exposure to ionizing radiation for which the severity is related to the radiation dose is called a deterministic effect. Deterministic effects may occur soon after radiation exposure. If instead, the probability (risk) but not the severity of a health effect after exposure to ionizing radiation is related to dose, it is called a stochastic effect. Stochastic effects seldom occur until years after the radiation exposure. Scientific committees recommend dose limits based on current knowledge of health effects resulting from exposure. Recommendations are considered by regulatory authorities and may be enacted into laws and regulations. This report describes sources of ionizing radiation and the resultant radiation doses to aircrew, passengers, and astronauts along with the possible resulting health effects and risks. This report also discusses the regulations and recommendations intended to minimize radiation risks.

Ionizing Radiation and Radiation Safety in Aerospace Environments

1. INTRODUCTION

A 1987 Presidential Document (Thomas, 1987) recommended that individuals occupationally exposed to ionizing radiation be instructed on their health risks. The U.S. Federal Aviation Administration (FAA) also mandates information on risks of space travel be provided to space flight participants before their participation on space flights under its jurisdiction (Aeronautics and Space, 2019).

The FAA's Civil Aerospace Medical Institute (CAMI) is charged with identifying health hazards in air travel and commercial human space travel. This report addresses one of these hazards—*ionizing radiation*. The FAA has funded the study of exposures to ionizing radiation and its associated risks for decades and recommends that air carrier crews be informed of their radiation exposure and the associated health risks. This report updates and revises information in DOT/FAA/AM-11/9 (Friedberg and Copeland, 2011) and can be used as a sourcebook for instruction on ionizing radiation exposure of air and space travelers. It provides information on (a) basic characteristics of ionizing radiation, (b) the types likely to be encountered during air and space travel, (c) the most likely natural and man-made sources, and (d) exposure levels and known associated health risks.

Radiation is a general term for energy in transit (i.e., moving energy). Ionizing radiation can be either fast-moving matter, such as a subatomic particle or atomic nucleus, or a massless particle such as an X-ray or gamma-ray photon. Ionizing radiation differs from other radiations because it is sufficiently energetic to directly or indirectly eject an orbital electron from an atom (a process called *ionization*).

Visible light, ultraviolet (UV) light, radio waves, and microwaves are nonionizing radiations. Nonionizing radiations are not necessarily harmless—they can carry enough energy to dissociate chemical bonds and disrupt chemical structures—but they do not have sufficient energy to eject an orbital electron. Nonionizing radiations can cause electron excitation (i.e., the forcing of an orbital electron to a higher energy level). An electron so affected is in an unstable energy level and soon falls back to a more stable level, releasing energy in the form of one or more nonionizing photons. The photons released include thermal photons and light photons of different wavelengths. The aurora borealis (northern polar lights) and the aurora australis (southern polar lights) result from the excitation of atmospheric atoms by charged particles from the Sun (i.e., solar wind). Auroras are commonly centered over the Earth's magnetic poles, between 60° and 70° north and south geographic latitudes. Occasionally, during high solar activity, the auroras are visible at lower latitudes. Also, during high solar activity, some particles from the inner Van Allen radiation belt (described in Section 5. *Earth's Atmosphere and Magnetic Field*) may enter the atmosphere and contribute to the aurora display.

In 1895, Wilhelm Conrad Roentgen discovered ionizing radiation while experimenting with a Crookes tube (a primitive vacuum tube). Working in a dark room with the tube in a carton, Roentgen found that a paper plate coated with barium platinocyanide (a chemical that fluoresces when exposed to UV light), which was outside the carton and 9 feet away from the tube, emitted fluorescent light when the tube was supplied with an electric current. Roentgen concluded that invisible radiation from the tube, which he called X-rays, penetrated the wall of the carton and traveled to the barium platinocyanide. He could not deflect the radiation with a magnetic field, and he found that objects in the path of the radiation showed variable transparency. With a photographic plate, Roentgen used the device to take a photograph of the bones of his wife's hand (Nobel Foundation, 1967).

The discovery of ionizing radiation from natural sources is accredited to Antoine-Henri Becquerel in 1896. He discovered a natural source of ionizing radiation while investigating phosphorescence (Becquerel, 1896). He observed that a photographic plate covered with an opaque paper was fogged when placed near uranyl potassium sulfate (a uranium salt) and demonstrated that, unlike X-rays, the radiation from uranium could be deflected by a magnetic field and, therefore, consisted of charged particles.

Theodore Wulf measured ionizing radiation levels with an electroscope at the top and bottom of the Eiffel Tower (height, 300 m). He found that radiation levels at the top of the tower were higher than at ground level (Perricone, 2001). In 1912, Victor F. Hess measured ionization rates with an electroscope during balloon flights to altitudes of several kilometers (Nobel Foundation, 1965). He found that, at an altitude of 5 km, the ionization rate was several times the rate at ground level. Hess concluded that a highly penetrating radiation enters the atmosphere from above. This radiation is now called *cosmic radiation*.

Air and space travelers are constantly exposed to cosmic radiation. *Galactic cosmic radiation* (GCR), which is mostly ionizing radiation from exploding stars (supernovae), is continuously present in low levels at aviation altitudes. Ionizing radiation from the Sun is sometimes present in significant amounts and is called *solar cosmic radiation* (SCR). Other potentially significant sources of ionizing radiation during air or space travel include radioactive cargo (including passengers), radioactive substances released into the atmosphere from a detonated nuclear weapon or a nuclear reactor as the result of an accident or terrorist attack, terrestrial gamma-ray flashes (TGFs), and trapped radiation (space travel only).

2. IONIZING RADIATION DOSE TERMINOLOGY

2.1. Introduction

This section introduces several key concepts and terms used throughout this report that are commonly used in the measurement of ionizing radiation and managing risk from ionizing radiation exposure. These include the biology and physics of radiation damage and common terms used to describe radiation dose and its biological effectiveness.

2.2. Background Biology and Physics

Living material consists of molecules composed of atoms held together by electron bonds. Ejection of orbital electrons can break the bonds that combine atoms as molecules. Particularly harmful to a biological system is the breakup of DNA molecules. DNA carries information required for the function and reproduction of an organism. Most often, the cell either repairs the damaged DNA or commits suicide (apoptosis), but survival after improper repair can happen. Improper repair of damaged DNA may lead to cancer (National Research Council, 2006). Ionizing radiation can damage DNA directly or by production of *free radicals*. Free radicals can also result from chemical processes in cells and may have a role in the etiology of atherosclerosis, rheumatoid arthritis, and other diseases. A free radical is an electrically neutral atom or molecule containing one or more unpaired electrons in the valence shell, and this makes it very chemically reactive. Ionizing radiation particles produce free radicals when they react with the water in cells and with some cellular components.

The ionizing radiation encountered in air and space travel includes both subatomic particles of matter (e.g., electrons, neutrons, protons, alpha particles, pions, muons), and energetic photons[1]. Photons and electrically charged particles cause ionization (i.e., *ionize*) directly by means of electromagnetism[2]. A neutron can only cause ionization indirectly. It can decay into a proton and an electron[3]. If it does not decay before encountering an atomic nucleus (e.g., atmospheric nitrogen or oxygen), a neutron can induce emission of a gamma-radiation photon (which can ionize directly) by nuclear excitation, or it can break apart a nucleus, releasing protons (which can ionize directly), neutrons, and pions (which can ionize or undergo decay processes shown in Table 1 [p.4]).

Table 1. *Decay of Pions and Their Muon Decay Products*

Particle	Decay Products	Mean-life (s)
Positive pion	1 positive muon + 1 muon-neutrino	2.6×10^{-8}
Negative pion	1 negative muon + 1 muon-antineutrino	2.6×10^{-8}
Neutral pion	2 gamma-radiation photons	8.4×10^{-17}
Positive muon	1 positron (positive electron) + 1 electron-neutrino + 1 muon-antineutrino	2.2×10^{-6}
Negative muon	1 electron + 1 electron-antineutrino + 1 muon-neutrino	2.2×10^{-6}

Note. Adapted from *The Particle Hunters (2nd Ed*) by Y. Ne'eman and Y. Kirsh, 1996, Cambridge University Press.

Neutral pions decay so rapidly that they are unlikely to impact an atom before decaying into gamma rays. Neutrinos and antineutrinos do not decay; they pass through matter with almost no effect. Neutral pions, neutrinos, and antineutrinos are important participants in the physical processes, but their resulting ionization in people is negligible, and, usually, they are not considered in dose calculations. Muons (resulting from pion decay) are the main contributor to radiation dose at very low altitudes, while protons and atomic nuclei are the primary contributors to radiation dose at the highest altitudes. Neutrons are the most important contributors at commercial aviation altitudes.

Radiation dose is the amount of energy absorbed by a medium. The medium could be a semiconductor device, a whole human body, or a particular tissue or organ in the body. Various terms are used to quantify the absorbed dose and its biological impact.

2.3. Linear Energy Transfer

Linear energy transfer (LET; Table 2) is the average amount of energy per unit track length (energy transferred per unit of distance traveled) transferred to a medium by ionizing radiation of a specified energy when penetrating a short distance. The energy imparted to the medium includes energy from any secondary radiation, such as nuclear particles released from a nucleus impacted by a high-energy neutron. The LET is usually expressed in units of $keV \times \mu m^{-1}$ (thousand electron volts per micrometer). A radiation with an LET less than 10 $keV \times \mu m^{-1}$ is generally considered a low LET radiation.

[1] Photons are packets of electromagnetic energy, which includes visible light, UV light, radio waves, microwaves, gamma radiation, X-radiation. Categorically, radio wave photons have the least amount of energy, while gamma ray photons have the most energy.

[2] Electromagnetism is one of four fundamental forces that physicists use to describe interactions: strong nuclear, weak nuclear, electromagnetism, and gravity.

[3] This process is a source of protons for the inner Van Allen radiation belt.

Table 2. *Typical LET Values of Various Radiations*

Type of radiation	LET (keV×μm^{-1})
cobalt-60 gamma-radiation	0.3
250 kVp X-radiation	2.0
10 MeV protons	4.7
150 MeV protons	0.5
recoil protons from fission neutrons	45.
14 MeV neutrons	12.
2.5 MeV alpha particles	166.
2 GeV Fe nuclei	1000.

Note. LET = linear energy transfer. Adapted from *Radiobiology for the Radiologist (6th Ed.)* by E. J. Hall, and A. J. Giaccia, 2006, Lippincott Williams & Wilkins.

2.4. Relative Biological Effectiveness

Relative biological effectiveness (RBE) is the relative amount of absorbed dose of a reference radiation (usually 250 kVp X-rays or cobalt-60 gamma rays) required to produce the same magnitude of the same effect as the absorbed dose of the radiation in question in a particular experimental organism or tissue (an RBE >1 indicates the radiation is more effective than the reference radiation).

The RBE is influenced by both the biological effect (cell killing, cell survival with mutations) and the LET of the radiation. It is also influenced by the choice of reference radiation. With killing human cells as the effect, the RBE increases with an increase in LET to approximately 100 keV×μm^{-1} and then decreases with further increase in LET. At LET 100 keV×μm^{-1}, the average separation between ionizing events is close to the diameter of the DNA double helix. Therefore, a radiation with LET 100 keV×μm^{-1} can most efficiently produce a double-strand break in a DNA molecule by means of a single track (Hall and Gaccia, 2006). Double-strand breaks in DNA molecules are considered to be the main cause of biological effects; a single strand break is almost always repaired before it causes problems in the cell.

2.5. Gray

Gray (Gy) is the International System unit (SI unit) of an absorbed dose of ionizing radiation. One Gy is 1 joule (J) of radiation energy absorbed per kilogram (kg) of matter (enough to raise a human body temperature by 0.00025 K[4]). The rad (radiation absorbed dose) is an older unit of absorbed dose of ionizing radiation (1 Gy = 100 rads). The roentgen (R) is another older unit of ionizing radiation. One R is the amount of X-radiation or gamma radiation that creates 1 electrostatic unit (esu) of ions in 1 ml of air at 0°C and 760 torr (760 mm mercury, 1 atm). The effect of 1 R and 1 rad on dry air is about the same.

2.6. Gray Equivalent

Gray equivalent (Gy-Eq) is a measure of the capacity of ionizing radiation to cause deterministic biological effects (described in Section 3. *Health Effects of Ionizing Radiation*). A dose in Gy-Eq is the absorbed dose in Gy multiplied by a recommended RBE (Table 3). The RBE takes into account that ionizing radiation of different types and energies affects living organisms differently.

[4] This is about ½ of one thousandth of a degree F.

Table 3. *Gy × RBE = Gy-Eq*

Type and energy of the radiation	RBE
Low-LET radiations (e.g., photons, electrons)	1.0
Protons >2 MeV	1.5
Heavy ions (e.g., helium, carbon, neon, argon)	2.5
Neutrons <5 MeV	6.0
5 MeV	5.0
>5 MeV	3.5

Note. RBE = relative biological effectiveness; LET = linear energy transfer. Adapted from "Radiation Protection Guidance for Activities in Low-Earth Orbit (NCRP Report No. 132)." by National Council on Radiation Protection and Measurements (NCRP), 2000.

Example

An astronaut is exposed to 10 mGy of low-LET radiations, 4 mGy of >2 MeV energetic protons, 1 mGy of heavy ions and 2 mGy of >5 MeV fast neutrons, a total of 17 mGy. What was the resulting exposure in units of Gy-Eq?

(10 x 1) + (4 x 1.5) + (1 x 2.5) + (2 x 3.5) = 10 + 6 + 2.5 + 7 = 25.5; because the absorbed doses are in mGy the result in in mGy-Eq, i.e., **25.5 mGy-Eq**

2.7. Organ Equivalent Dose (Equivalent Dose)

Organ equivalent dose is the total absorbed dose to a specific tissue or a conceptus[5] after the absorbed dose from each radiation incident on the tissue or conceptus is multiplied by a *radiation weighting factor* (w_R; Table 4). For multiple radiations, the organ equivalent dose is the sum of the individual organ equivalent doses. The radiation weighting factor takes into account the effectiveness of the primary radiation (or radiations) and all secondary radiations and is an RBE for stochastic effects (described in Section 3. *Health Effects of Ionizing Radiation*).

Table 4. *Radiation Weighting Factor (w_R)*

Type and energy of the radiation	w_R
Low-LET radiation: photons, electrons, muons	1
Protons,[a] charged pions	2
Alpha particles,[b] fission fragments, heavy ions	20
Neutrons (energy, E_n): E_n <1 MeV	$2.5 + 18.2 \times \exp[-(\ln(E_n))^2/6]$
$1 < E_n \leq 50$ MeV	$5.0 + 17.0 \times \exp[-(\ln(2E_n))^2/6]$
E_n >50 MeV	$2.5 + 3.25 \times \exp[-(\ln(0.04E_n))^2/6]$

Note. LET = linear energy transfer. Adapted from "The 2007 recommendations of the International Commission on Radiological Protection (ICRP Publication 103, Annals of the ICRP, 37(2-4))" by the International Commission on Radiological Protection, 2007.

[a] Hydrogen-2 (deuterons) and hydrogen-3 (tritons) ions have the same LET and track structure as protons. Therefore, the same radiation weighting factor (w_R = 2) seems appropriate.

[b] Helium-3 (helions) ions have nearly the same LET and track structure as alpha particles. Therefore, the same radiation weighting factor (w_R = 20) seems appropriate.

[5] An unborn child at any stage of development from fertilized egg until birth.

2.8. Dose Equivalent

Dose equivalent is the total absorbed dose to a specific tissue or a conceptus after the absorbed dose from each radiation incident on the tissue or conceptus is multiplied by a radiation quality factor (*Q*, Table 5 [p. 7]). For multiple radiations, the total dose equivalent is the sum of the individual dose equivalents. *Q* relates the LET of the radiation to its RBE. Since the introduction of equivalent dose, dose equivalent is no longer used by the International Commission on Radiological Protection (ICRP) for human dosimetry, but it is still used in other applications.

Table 5. *Quality Factor (Q); Considers the LET of the Radiation*

LET (keV×μm^{-1})	*Q*[a]
<10	1
10–100	0.32 × LET - 2.2
>100	300 × LET$^{-1/2}$

Note. LET = linear energy transfer. Adapted from "1990 recommendations of the International Commission on Radiological Protection (ICRP Publication 60, Annals of the ICRP, 21(1-3))" by the International Commission on Radiological Protection, 1991.

[a] *Q* should be rounded to the nearest whole number.

2.9. Effective Dose

Most dose limits are in effective dose. Effective dose is the total sex-averaged, whole-body absorbed dose after the absorbed dose to each tissue from each radiation incident on the body and/or from each internal radiation emitter is multiplied by a radiation weighting factor (w_R, Table 4 [p. 6]) and by a tissue weighting factor (w_T, Table 6). The w_T considers the risk of stochastic effects from irradiation of a specific tissue.

Table 6 *Tissue Weighting Factor (w_T); Considers where Radiation Energy Is Deposited*

Where radiation energy is deposited	w_T	Σ *w*T
Remainder tissues,[a] red bone-marrow, breast, colon, lung, stomach	0.12	0.72
Gonads	0.08	0.08
Bladder, esophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
	Total	1.00

Note. Adapted from "The 2007 recommendations of the International Commission on Radiological Protection (ICRP Publication 103, Annals of the ICRP, 37(2-4))" by the International Commission on Radiological Protection, 2007.

[a] Remainder tissues (13 males, 13 females): adrenals, extrathoracic region, gall bladder, heart, kidneys, lymph nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix. For each remainder tissue, w_T = 0.12/13 = 0.00923. Females do not have a prostate, and males do not have a uterus/cervix.

Estimating effective dose to a Reference Person (adult) from external isotropic exposure is a multistep process:

(1) Estimate absorbed dose in each tissue of an adult female and of an adult male, using a Monte Carlo transport code such as MCNPX (from Radiation Safety Information Computing Center at Oak Ridge National Laboratory, Oak Ridge, TN), and mathematical models of the bodies, such as the ICRP Reference Phantoms (ICRP 2009).

(2) For each tissue, multiply absorbed dose by the appropriate w_R (Table 4, [p. 6]). Tissues that received only trivial amounts of radiation may be excluded from dose calculations.
(3) For each tissue, average w_R-adjusted absorbed doses to the female and the male.
(4) For each tissue, multiply sex-averaged w_R-adjusted absorbed dose by the appropriate w_T (Table 6 [p. 8]).
(5) Effective dose to the Reference Person is the sum of sex-averaged w_R-adjusted and w_T-adjusted absorbed doses to tissues.

2.10. Effective Dose Equivalent

Effective dose equivalent is the total sex-averaged, whole-body absorbed dose after the absorbed dose to each tissue or organ from each radiation incident on the body and/or from each internal radiation emitter is multiplied by a radiation quality factor (Q, Table 5 [p. 7]) and by a w_T (Table 6 [p. 7]). The National Council on Radiation Protection and Measurements (NCRP) considers effective dose equivalent as an acceptable approximation of effective dose and promotes using it as a surrogate for effective dose in space radiation applications (NCRP, 2000).

2.11. Sievert

Sievert (Sv) is the SI unit of organ equivalent dose, dose equivalent, effective dose, and effective dose equivalent. It is a measure of harm to the body from the stochastic effects of ionizing radiation (described in Section 3. *Health Effects of Ionizing Radiation*). The roentgen equivalent man (rem) is an older measure of harm (1 Sv = 100 rem). An estimate by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) of the global average effective doses of ionizing radiation received by humans on Earth from natural sources is presented in Table 7 (UNSCEAR, 1993).

Table 7. *Typical Worldwide Annual Effective Doses of Ionizing Radiation to an Adult Human at Ground Level, From Natural Sources*

Source	Effective dose (mSv)
Galactic cosmic radiation	0.39
Terrestrial gamma radiation[a]	0.46
Radionuclides in the body (except radon)[b]	0.23
Radon and its decay products[c]	1.30
Total	2.38

Note. Adapted from "United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 1993 report to the General Assembly, with scientific annexes" by the United Nations Scientific Committee on the Effects of Atomic Radiation, 1993.
[a] Sources include uranium-238, radium-226, thorium-232, potassium-40, and cesium-137.
[b] Potassium-40 and carbon-14.
[c] Radon-222 is a decay product of radium-226, which is a decay product of uranium-238. Some areas have high concentrations of uranium-238 in the soil. Radon-222, a gas, leaks into homes from the ground below. Inhaled radon travels through the bronchial tubes to the lungs and decays into polonium-210, a solid.

2.12. Summary

Key points:

- Ionizing radiation can damage cells, leading to cancer and other diseases.

- Not all ionizing radiation is the same. Biological damage depends on particle kind, particle energy, and tissue exposed.
- The physically measurable quantity absorbed dose is the most basic measure of radiation exposure.
- While there are several ways to express dose, effective dose is the standard measure used in radiation protection dosimetry.
- There are several natural sources of ionizing radiation.

3. HEALTH EFFECTS OF IONIZING RADIATION

3.1. Introduction

This section discusses the health effects of ionizing radiation exposure. Health effects are categorized by mechanism: diseases caused by cell death and diseases caused by cell miss-repair. This section also discusses prenatal exposure.

3.2. Deterministic Effects (Nonstochastic Effects, Tissue Reactions)

Most tissues of the body can lose a substantial number of cells without an observable decrease in tissue or organ function. However, if the number of cells lost is sufficiently large, harm will be observed. Harm from ionizing radiation is called *deterministic* if the harm increases with radiation dose above a threshold dose (ICRP, 1991). The threshold dose is the dose below which either no harm is observed, or the harm is not clinically significant. For most deterministic effects from low-LET radiation, the threshold dose is higher if the exposure time required to reach the dose is more than a few hours (NCRP, 2001). Deterministic effects can occur soon (sometimes within minutes) after radiation exposure if the dose and dose rates are sufficiently high. Doses of sufficient magnitude to result in deterministic effects in aviators are expected to come from nuclear materials releases due to accidents or warfare. In space, where Earth's magnetic field and atmosphere provide much less protection, and trapped radiation is another important source of particles, doses from naturally occurring radiation sources can be sufficient to cause these effects.

The effect of radiation on the hematopoietic system is largely dependent on damage to the bone marrow. The bone marrow contains three cell renewal systems: erythropoietic, myelopoietic, and thrombopoietic. Normally, a steady-state condition exists between the production of new cells by the bone marrow and the number of mature, functional cells in the circulating blood. The erythropoietic system produces mature erythrocytes (red blood cells) with a lifespan of approximately 120 days. Red blood cells carry oxygen from the lungs to the rest of the body and carry away some of the carbon dioxide. The myelopoietic system produces mature leukocytes (white blood cells) with a lifespan of approximately 8 days. White blood cells are important in combating infection. The thrombopoietic system produces platelets with a lifespan of 8 to 9 days. If the endothelial lining of a blood vessel is traumatized, platelets are stimulated to go to the site of injury and form a plug, which helps reduce blood loss. Platelet deficiency causes one to bruise easily and even hemorrhage.

The intestines are highly vulnerable to radiation damage. The mucosal layer that lines the intestines is completely renovated every 72 hours. Injury of the microvasculature of the mucosa and submucosa, together with epithelial-cell denudation, results in hemorrhage and marked loss of fluids and electrolytes. These events typically occur within 1 to 2 weeks after irradiation.

Table 8 lists deterministic effects in young adults from an acute whole-body dose of ionizing radiation. Survivors of deterministic effects are at risk of stochastic effects (Gusev et al., 2001). Early deterministic effects of ionizing radiation are called *Acute Radiation Syndrome* (ARS) or sometimes *radiation sickness*. Symptoms during the first stage of this illness, such as nausea, fatigue, vomiting, and diarrhea, occur within minutes to days after exposure; they may come and go for several days unless the dose is acutely incapacitating or lethal. The irradiated individual usually looks and feels healthy for short periods. During the next stage, there may be a loss of appetite, nausea, fatigue, vomiting, diarrhea, fever, seizures, and coma. This seriously ill stage may last from a few hours to several months and ends with death from infection and/or internal bleeding. The symptoms, their time to onset, severity, and duration generally depend on the absorbed dose, and symptomatology can vary significantly from one person to another. The cause of death is usually from infections and internal bleeding because of bone marrow damage. Some late deterministic effects are cataracts and a decrease in germ cells.

Table 8. *Deterministic Effects in Young Adults from Ionizing Radiation Received in <1 Day*

Dose (Gy-Eq)	Effects
0.15	Threshold dose for temporary sterility in males (NCRP, 2001).
0.35	Within a few hours, some suffer nausea, weakness, and loss of appetite. Symptoms disappear a few hours after appearing (NCRP, 2001).
1–2	After 2 to 3 hours, nausea and vomiting in 33% to 50% (Gusev et al., 2001).
1.5	Threshold dose for mortality (NCRP, 1989).
2	Permanent sterility in premenopausal females (Hall and Giaccia, 2006). Minimum cataract dose (NCRP, 2000).
2–4	Mild headache in about 50% of those exposed. Almost constant nausea and vomiting in 70% to 90% (Ricks et al., 2002). There may be initial granulocytosis, with pancytopenia 20 to 30 days after irradiation. Possible later effects are infections, hemorrhage, and impaired healing (Ricks et al., 2002). The latent period for cataracts is normally about 8 years, after 2.5 to 6.5 Gy (Hall and Giaccia, 2006).
3.5–6	Threshold dose for permanent sterility in males (ICRP, 2007).
4	About 50% die within 60 days from hematopoietic failure (ICRP, 2007). For adult males, shielding 10% of the active (red) bone marrow will result in almost 100% survival (Gusev et al., 2001).
5–7	Up to 100% vomit within 2 days (NCRP, 1989). Mortality is approximately 90% within 60 days (ICRP, 2007).
>8	Within minutes, there may be severe nausea, vomiting, and watery diarrhea. After 1 to 2 hours, there is almost constant severe headache: there may be renal failure and cardiovascular collapse. Mortality is 100%, usually within 8 to 14 days (Ricks et al., 2002).
>20	Often, burning sensation within minutes. Nausea and vomiting within 1 hour, followed by prostration, ataxia, and confusion; Mortality is 100%, usually within 24 to 48 hours (Ricks et al., 2002).

To date, cataract formation is the only deterministic effect associated with exposure to ionizing radiation in space (NCRP, 2006). Excess cataracts have been seen in former astronauts who received 8 mGy to 2 Gy of high-LET radiation (p=.002) (Cucinotta, 2001).

3.3. Stochastic Effects

Harm from ionizing radiation is called a *stochastic effect* (expressed in Sv) if the probability (i.e., risk), but not the severity of the effect, is a function of the effective dose. These effects may result from the miss-repair of individual cells, and there is no expectation of a threshold dose for stochastic effects (Hall and Giaccia, 2006). Disease occurs sooner after exposures in the young, whose cells are dividing more rapidly than those of adults. Thus, the latent period (i.e., the period between exposure and disease) of stochastic effects appears to depend on the rate of cell division. Stochastic effects include cancers, cardiovascular disease, genetic disorders in succeeding generations, and loss of life from such effects. The risk is cumulative and persists throughout the life of the exposed person. Thus, individuals exposed to ionizing radiation have an increased lifetime risk of cancer, and their progeny have an increased risk of inheriting genetic disorders.

Radiation-induced cancers cannot be distinguished from cancers of the same type in the un-irradiated population, and, as of this writing, it cannot be predicted which individuals in an irradiated group will develop cancer (National Research Council, 1990). Regardless of the age when irradiated, radiation-induced tumors tend to appear when tumors of the same type occur in the un-irradiated population (Hall and Giaccia, 2006). Commonly occurring cancers, induced as stochastic effects of ionizing radiation, are shown in Table 9.

Table 9. *Commonly Occurring Cancers with Ionizing Radiation as a Risk Factor (Stochastic Effects)*

Cancer	Radiation related knowledge
Leukemia	Shortest latent period of radiation-induced cancers (Hall and Giaccia, 2006). Minimum latent period: 2 to 3 years (NCRP, 2001). Peak incidence: 5 to 7 years after irradiation, with most cases in the first 15 years. Acute leukemia and chronic myeloid (myelocytic) leukemia are the main types in irradiated adults. Susceptibility to acute lymphatic leukemia (stem-cell leukemia, leukemia too premature to classify) is highest in childhood and decreases sharply during maturation. Chronic lymphocytic leukemia is not radiation-induced (Hall and Giaccia, 2006).
Lung cancer	Most common cancer worldwide and the major cause of death from cancer (UNSCEAR, 1993). With increases in age at exposure, the latent period decreases and the risk increases. Dose-fractionation decreases risk (based on low-LET radiation) (NCRP, 2000). Radon causes about 10% of lung cancer deaths in the U.S. (Hall and Giaccia, 2006).
Breast cancer	Most common cancer among women worldwide and one of the leading causes of death from cancer. Risk highest if irradiated before age 15 years, with little or no risk if irradiated at age 50 or older (Hall and Giaccia, 2006). Family history is a strong predictor of risk (UNSCEAR, 1993). Dose-fractionation data are conflicting. Risk is reduced by ovariectomy (oophorectomy) or pregnancy at an early age (NCRP, 2000).
Gastrointestinal (GI) tract cancer (esophagus, stomach, colon, and rectum)	15% to 20% of benign colorectal tumors become malignant (NCRP, 2000). In the general U.S. population, lifetime risk of developing GI-tract cancer is 2.5% to 5% but is 2 to 3 times higher in persons with a first-degree relative (father, mother, brother, sister, child) who had colon cancer or an adenomatous polyp (Rudy and Zdon, 2000).
Bone cancer	External X-radiation may cause bone cancer, but the numbers are low, and the risk estimates are poor (Hall and Giaccia, 2006).

Cancer	Radiation related knowledge
Liver cancer	Risk from high-LET radiation, but uncertain if risk from low-LET radiation (NCRP, 2000).
Kidney and bladder cancer	Risk from radiation (NCRP, 2000).
Skin cancer	Most common cancer in Caucasians in the U.S. Latent period about 25 years. Skin exposed to low-LET radiation and sunlight (presumably from ultraviolet radiation) is at greater risk than skin protected from sunlight by hair, clothing, or pigmentation. Ionizing radiation causes basal-cell and squamous-cell carcinomas, but no unequivocal association has been found for ionizing radiation exposure and melanoma (the most malignant skin cancer). In fair-skinned individuals, radiation from sunlight or sunlamps is a risk factor for melanoma and other skin cancers. Skin cancer can develop in areas not exposed to sunlight. Skin cancer can develop in dark-skinned individuals. Family history is a predictor of risk (NCRP, 1989).
Thyroid cancer	Risk to a child is significant if dose ≥0.05 Gy. Little or no risk at age 30 years or older. Most likely radiation source is radioactive iodine (I-131) released into the atmosphere from a nuclear reactor as the result of an accident or terrorist attack. Radioactive iodine is also a major constituent of detonated nuclear weapons. Radioactive iodine is incorporated by the thyroid gland, and the radiation increases the risk of thyroid cancer (NCRP, 2000).

Note. LET = linear energy transfer; GI = gastrointestinal.

Table 10, Table 11 (p. 12), and Table 12 (p. 12) present estimates of the increased lifetime risk of cancer and heritable effects from a whole-body dose of ionizing radiation for a member of the whole population and a member of the working age population (i.e., age 18 to 64 years). If the radiation is low LET (electrons, photons, positrons, or muons) and <200 mSv and/or <100 mSv/hour, there is enough time and the dose is low enough that the cellular repair mechanisms are more effective at repairing the damage and the risks from exposure are somewhat reduced. Data support using reduced risk coefficients rather than those found by linear extrapolation from the high-dose region (Trabalka et al., 2017). The dose and dose-rate effectiveness factor (DDREF) can reasonably be applied (ICRP, 2007). Recommended values for this factor range from 1.5 to 2 (ICRP recommends DDREF=2). The factor should not be applied when estimating risks from exposures to high-LET radiations such as neutrons.

Table 10. *Increased Lifetime Risk of Fatal Cancer from Ionizing Radiation*

	Whole population [a]	Age group 18–64 years
----	8.0 in 100,000 per mSv	6.3 in 100,000 per mSv
DDREF = 2	4.0 in 100,000 per mSv	3.1 in 100,000 per mSv

Note. DDREF = dose and dose rate effectiveness factor. Adapted from “The 2007 recommendations of the International Commission on Radiological Protection (ICRP Publication 103, Annals of the ICRP, 37(2-4))” by the International Commission on Radiological Protection, 2007.

[a] In the U.S in 2016, cancer caused 22% of deaths among persons of all ages (Siegel et al., 2019).

Table 11. *Increased Risk of Genetic Effects in First Two Successive Generations (Children and Grandchildren), from Ionizing Radiation Exposure before Conception* [a]

	Whole population [a]	Age group 18–64 years
----	0.4 in 100,000 per mSv	2.4 in 1,000,000 per mSv
DDREF = 2	0.2 in 100,000 per mSv	1.2 in 1,000,000 per mSv

Note. DDREF = dose and dose rate effectiveness factor. Adapted from "The 2007 recommendations of the International Commission on Radiological Protection (ICRP Publication 103, Annals of the ICRP, 37(2-4))" by the International Commission on Radiological Protection, 2007.

[a] In the general population, 2–3% of live-born children have harmful abnormalities at birth (National Research Council, 1990).

Table 12. *Increased Lifetime Risk of Cancer (Nonfatal or Fatal) from Ionizing Radiation*

	Whole population	Age group 18–64 years
----	34 in 100,000 per mSv	23 in 100,000 per mSv
DDREF = 2	17 in 100,000 per mSv	12 in 100,000 per mSv

Note. DDREF = dose and dose rate effectiveness factor. Adapted from "The 2007 recommendations of the International Commission on Radiological Protection (ICRP Publication 103, Annals of the ICRP, 37(2-4))" by the International Commission on Radiological Protection, 2007.

Research indicates ionizing radiation also increases the risk of several forms of cardiovascular disease (CVD). There is also an accumulating body of evidence showing an association between low and moderate doses of radiation (<0.5 Gy) and increased risk of CVD after an estimated latency of 10 years or more, but data are not sufficient to give well-defined risk estimates at low doses (ICRP, 2012). In a review article, Donnellan et al. (2016) indicate that ischemic heart disease is the most common cause of cardiac death in patients who have undergone radiation therapy. The clinical presentation of coronary artery disease in radiotherapy recipients does not differ significantly from that in the general population, but the distribution of atherosclerotic coronary arteries correlates well with the areas exposed to the highest doses of radiation. They indicate that the risk of radiation-induced coronary artery disease is proportional to both the dose and the duration of radiation therapy. In a retrospective study of more than 2,000 women undergoing radiotherapy for breast cancer, Darby et al. (2013) found the relative risk of coronary artery disease increased linearly by about 7.4% per Gy of radiation to the heart with no apparent ceiling.

3.4. Prenatal Irradiation

As noted above, prenatal exposure is more serious than it would be for older people who have much larger and slower dividing cell populations. However, a dose < 100 mGy to a conceptus is not considered a justification for terminating a pregnancy (Gusev et al., 2001). Because of the small numbers of cells, exposure to a high dose of ionizing radiation in the first 3 weeks after conception may kill a conceptus but is not likely to cause deterministic or stochastic effects after the child is born. Irradiation in the period from 3 weeks after conception until the end of pregnancy may cause deterministic and stochastic effects in a liveborn child, and specific risks vary as the conceptus develops. The risks are highest early in the pregnancy and decrease as the conceptus develops. Because a conceptus is not well shielded from cosmic radiation by the mother's body, the effective dose to the mother from SCR is a good estimate of the equivalent dose to the conceptus (Nicholas et al., 2000).

3.5. Summary

Key points:

- Deterministic effects, also called radiation sickness, occur when too many cells performing the same function are killed in a short period.
- Deterministic effects do not occur below a minimum dose, called the threshold dose, which is usually at least a few hundred millisieverts.
- Other radiation health effects result from nonlethal damage to cells. These effects do not have a minimum required exposure, and their probability of occurrence is related to the dose.
- Children, particularly early in development, are more at risk from ionizing radiation exposure than adults.

4. RECOMMENDED IONIZING RADIATION DOSE LIMITS

4.1. Introduction

While individual nations control radiation protection laws and regulations, there are also recommendations from national and international committees formed by scientists. In the U.S., each federal agency sets its regulations or adopts pre-existing standards, while in the European Union (EU), the legislated Directives are presented to the member states which pass national laws to enact them. This section discusses these recommendations, regulations, and laws.

4.2. International Commission on Radiological Protection

For a nonpregnant, occupationally exposed person, the ICRP 2007-recommended limit for exposure to ionizing radiation is a 5-year average of 20 mSv per year (100 mSv in 5 years), with no more than 50 mSv in a single year. Annual equivalent dose limits are recommended for the lens of the eye (150 mSv), for skin (500 mSv; averaged over a 1 cm^2 area), each hand (500 mSv), and each foot (500 mSv).

For a pregnant worker, starting when she reports her pregnancy to management, the working conditions should be such that the additional dose to the conceptus would not exceed approximately 1 mSv during the remainder of the pregnancy.

Radiation exposure as part of a medical procedure is not subject to recommended limits. However, before any pregnant woman is irradiated, the exposure of the conceptus should be considered.

4.3. National Council on Radiation Protection and Measurements

For a nonpregnant, occupationally exposed person, the NCRP recommended limit for exposure to ionizing radiation is 50 mSv per year, with no more than 10 times the person's age in mSv cumulative dose. Annual equivalent dose limits are recommended for the lens of the eye (150 mSv), for skin (500 mSv; averaged over a 1 cm^2 area), for each hand (500 mSv), and each foot (500 mSv) (NCRP, 1993).

For a pregnant worker, starting when she reports her pregnancy to management, the working conditions should be such that the equivalent dose to the conceptus does not exceed 0.5 mSv per month during the remainder of the pregnancy and that the total dose does not exceed 5 mSv (NCRP, 1993).

For space missions in low-Earth orbit (LEO), the NCRP recommends a career limit excess-lifetime-risk of fatal cancer of 3% and uses sex and age-dependent risk coefficients (NCRP, 2000). The National Aeronautics and Space Administration (NASA) follows NCRP recommendations.

The risk coefficients for chronic exposures to low-LET ionizing radiation (lifetime percent increased risk of fatal cancer per 100 mSv) are (NCRP, 2000):

- for males (% per 100 mSv) = 0.895 + (-0.0177 × age) + (0.0000750 × age^2)
- for females (% per 100 mSv) = 1.60 + (-0.0339 × age) + (0.000172 × age^2)

Thus, for a 25-year-old man, the risk coefficient would be:

0.895 + (-0.0177 × 25) + (0.0000750 × 25^2) = 0.499 % per 100 mSv = 0.00499 per 100 mSv.

If exposed to 32 mSv during that year, his increased lifetime risk of fatal cancer would be:

32 mSv × 0.00499 per 100 mSv = 1.60 in 1,000 = 160 in 100,000 = 1,600 in 1,000,000 = 1 in 625

For acute or high-LET radiation exposure, the risk is doubled.

Table 13 shows the recommended organ dose limits for space missions in LEO.

Table 13. *Organ Dose Limits in Sv [a] Recommended by the NCRP for Space Missions in Low-Earth Orbit*

Period	Bone Marrow	Eye	Skin
Career	Men: 1.5 - 4 × (200 + 7.5 × (age - 30)), Women: 1 - 3 × (200 + 7.5 × (age - 38))	4.0	6.0
1 year	0.50	2.0	3.0
30 days	0.25	1.0	1.5

Note. Adapted from *Space radiation—frequently asked questions* by the Space Radiation Analysis Group, 2019. https://srag.jsc.nasa.gov/SpaceRadiation/FAQ/FAQ.cfm

[a] NASA uses the same numerical limits for dose equivalent in Sv and gray equivalent in Gy-Eq (NCRP, 2000).

4.4. U.S. Federal Aviation Administration

The FAA recommends air-carrier crews be informed about their radiation exposure and the associated health risks (FAA, 2014). In regards to limiting ionizing radiation exposure in the workplace for FAA employees, FAA Order 3900.19C requires a level of protection for all local FAA offices at least equivalent to using Occupational Safety and Health Administration (OSHA) regulations (FAA, 2019).

Federal regulations applicable to in-flight radiation exposure of passengers and crewmembers ensure safe shipping of radioactive cargo and handling of possible contamination of aircraft by radioactive substances (Transportation, 2004; Transportation 2016). These regulations are to limit dose rates from the mentioned sources in occupied spaces of the aircraft to < 20 μSv per hour and 5 μSv per hour, respectively. The FAA also requires a plan of action to mitigate ionizing radiation exposure of crewmembers for polar operations not confined entirely to Alaska in the event of an extreme solar storm (Code of Federal Regulations, Title 14, Part 121, Appendix P, Section III,b,7; also same language in Part 135, Subpart B, 135.98).

The FAA does not require radiation safety plans and programs beyond the above regulations, but the FAA provides recommendations and information (such as in this and earlier reports and Advisory Circulars). For occupational exposure, the FAA continues to recommend limits that essentially combine the ICRP and NCRP recommendations (ICRP, 2007; NCRP 2013):

- A 5-year average effective dose of 20 mSv per year, with no more than 50 mSv in a single year.

- For a pregnant air carrier crewmember, starting when she reports her pregnancy to management, an 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.

Radiation exposure as part of a medical or dental procedure is not subject to recommended limits, but any radiation exposure of a pregnant woman should consider the conceptus.

4.5. European Union

In the EU, member states implement the EU Directives through national law. Directive 2013/59/Euratom laid down basic safety standards for protection against the dangers of exposure to ionizing radiation and repealed several related, earlier Directives (European Agency for Safety and Health at Work, 2019). Article 5 of the new Directive indicates systems of radiation protection shall be based on the principles of justification (i.e., when benefits outweigh risks), optimization (i.e., the minimization of individual doses, the likelihood of exposure and the number of individuals exposed), and dose limitation (i.e., keeping planned individual exposures within dose limits). The age limit for occupational exposure is 18 years. Dose limits for occupational exposure are as follows:

- An effective dose limit of 20 mSv in a year when averaged over 5 years, with up to 50 mSv allowed in a single year in special circumstances;
- A limit for the lens of the eye of 20 mSv in 1 year or 100 mSv in any 5 consecutive years (the average annual dose over any 5 consecutive years shall not exceed 50 mSv);
- A limit of 500 mSv per year for the skin and extremities;
- A limit of 1 mSv (preferably zero) for an unborn child;
- No radionuclide intake or bodily contamination for breastfeeding workers; and
- A limit of 6 mSv per year for apprentices and students aged 16 to 18 years

Dose limits are not applied to medical exposures. The undertaking and/or the employer is responsible for ensuring the radiation protection of all workers (including students and apprentices).

Exposed workers are to be informed of radiation health risks and protection procedures; the relevant procedures, precautions, and emergency response plans; and procedures and the importance of complying with requirements. Female workers shall be aware of the importance of making an early declaration of pregnancy.

Operational protection of exposed workers is expected to be achieved through prior evaluation, optimization of radiation protection, classification of exposed workers, control measures and monitoring, medical surveillance, and education and training. This includes consultation with a radiation protection expert. Arrangements shall be made at workplaces where workers' exposures may exceed the effective dose of 1 mSv or an equivalent dose of 15 mSv (for the lens of the eye) or 50 mSv (for the skin and extremities). For workplaces where the effective dose of 6 mSv (or corresponding radon exposure) is exceeded (i.e., a planned exposure situation), the appropriate requirements are determined by the Member State.

A distinction shall be made at workplaces between controlled areas (i.e., areas subject to special rules for the purpose of protection against ionizing radiation or preventing the spread of radioactive contamination and to which access is controlled) and supervised areas (i.e., areas subject to supervision for the purpose of protection against ionizing radiation) on the basis of an assessment of the expected annual doses and the probability and magnitude of potential exposures. These areas are subject to radiological surveillance that may comprise measurements.

4.6. Summary

Key points:

- FAA Order 3900.19C requires a level of protection for all local FAA offices that is at least equivalent to OSHA regulations.
- Federal regulations applicable to in-flight radiation exposure of passengers and crewmembers ensure safe shipping of radioactive cargo and handling of possible contamination of aircraft by radioactive substances. Doses from these sources are limited to 20 μSv per hour and 5 μSv per hour, respectively.
- FAA requires a plan of action to mitigate ionizing radiation exposure of crewmembers for polar operations not confined entirely to Alaska in the event of an extreme solar storm.
- FAA recommended limits are based on a combination of ICRP and NCRP recommendations and are similar to EU regulations.

5. EARTH'S ATMOSPHERE AND MAGNETIC FIELD

5.1. Introduction

This section presents information on Earth's atmosphere and magnetic field. Both are important factors in radiation exposure for aviation and space operations near Earth.

5.2. Earth's Atmosphere

Gravity retains the Earth's atmosphere. At most altitudes, there are only trace amounts of water vapor in the air. The content (percent by volume) of this dry air is approximately 78% nitrogen, 21% oxygen, 0.93% argon, 0.034% (average) carbon dioxide, and trace amounts of other gases. In the lowest layer, a highly variable amount of water vapor (0.001% to 7%) is present (Anonymous, 1989a).

Atmospheric layers, from lower to higher, are the *troposphere*, *stratosphere*, *mesosphere*, *thermosphere*, and *exosphere*. Some of the basic physical and chemical properties of the lowest four layers are illustrated in Figure 1 (p. 19).

The troposphere extends from the Earth's surface to 8 to 10 km near the poles and 16 to 18 km in tropical regions, with some variation due to weather conditions. It contains about 80% of the atmosphere's mass, and it is where most daily weather occurs that is observed from the ground (Anonymous, 1992). With increasing altitude, temperatures decrease in the troposphere. Traditional subsonic jetliners fly at altitudes of 6 to 12 km (20,000 to 40,000 ft). Business jets usually fly above the jetliners (up to 51,000 ft). The Concorde supersonic passenger airliner (retired in 2003) cruised at 14 to 18 km (45,000 to 60,000 ft).

The tropopause is the boundary between the troposphere and the stratosphere. The tropopause is where air ceases to cool with height, and it is almost completely dry.

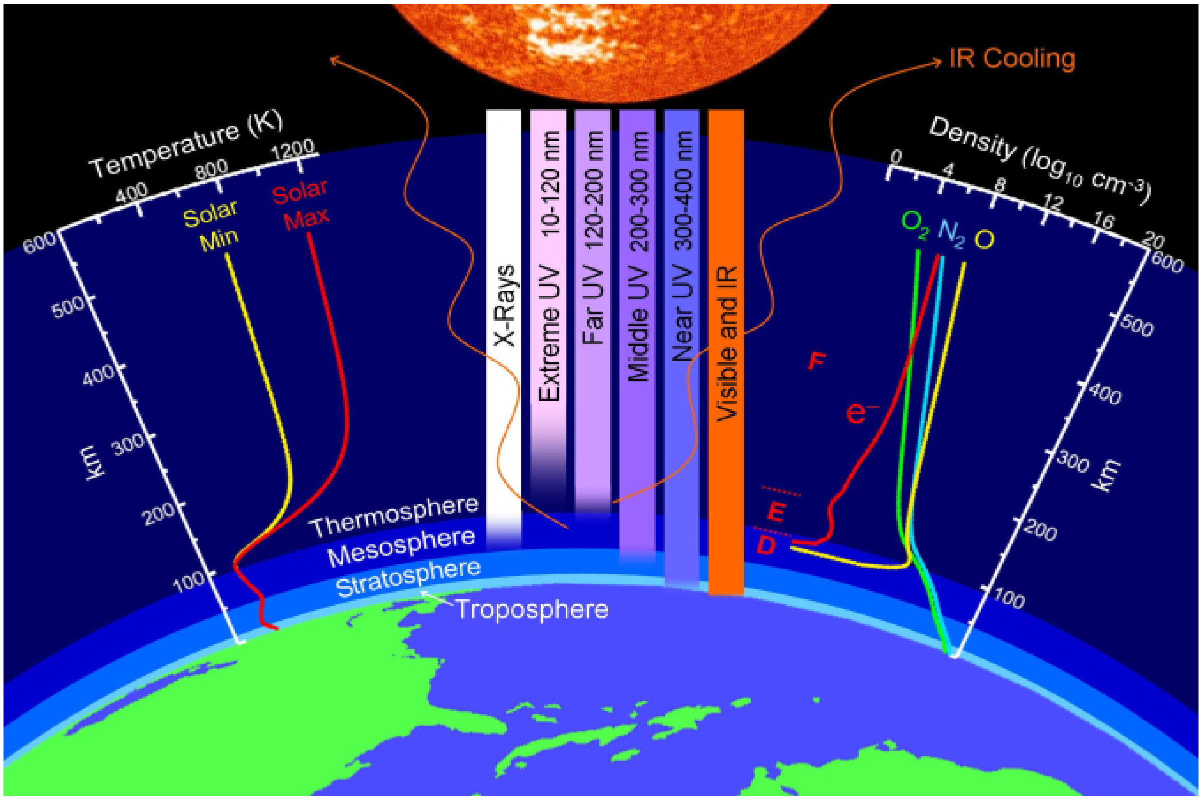
The stratosphere extends from the troposphere to about 50 km. The ozone and oxygen in the stratosphere absorb much of the UV radiation from the Sun. UV radiation can be very harmful to live tissues. Temperatures increase with altitude in the stratosphere.

The stratopause is the level of transition between the stratosphere and the mesosphere.

The mesosphere extends from 50 km to 80 to 85 km. Temperatures decrease with altitude in the mesosphere. Most meteors become visible 65 to 120 km above the Earth and disintegrate in the mesosphere.

The mesopause is the level of transition between the mesosphere and the thermosphere.

Figure 1. *Properties of Earth's Upper Atmosphere*



Note. From *Layers of Earth's Atmosphere*, by National Aeronautics and Space Administration, 2010. Credit: John Emmert/Naval Research Lab. https://www.nasa.gov/topics/solarsystem/sunearthsystem/atmospheric-layers.html. UV = ultraviolet; IR = infrared.

The thermosphere extends from 80 to 85 km to more than 500 km. Temperatures increase with altitude in the thermosphere. For aviation, the boundary between the atmosphere and outer space is 100 km (328,000 ft) above the Earth's surface. Above this altitude, the atmosphere becomes too thin to provide enough lift for conventional aircraft to maintain flight. The International Space Station (ISS) orbits Earth in the thermosphere at an altitude of 330 to 400 km (NASA, n.d.).

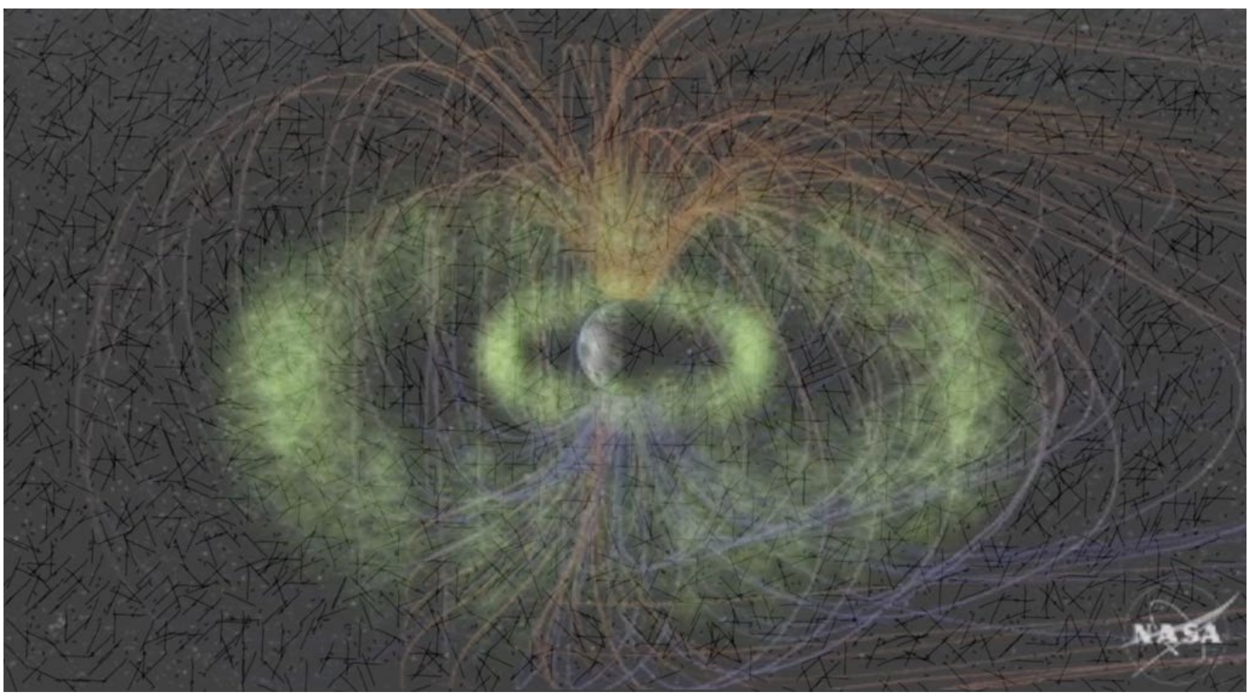
The exosphere is the highest atmospheric layer—the layer where Earth's atmosphere merges with interplanetary space. In this region, the probability of interatomic collisions is so low that some atoms traveling upward have enough velocity to escape Earth's gravity.

5.3. The Magnetosphere

The *magnetosphere* is the region around Earth influenced by Earth's magnetic field (*geomagnetic field*) and extends deep into interplanetary space (Walt, 1994). The region of the magnetosphere in the atmosphere, where Earth's magnetic field significantly influences charged particle motion, is called the *ionosphere*. The ionosphere contains both ions and neutral molecules, and it typically begins in the thermosphere and extends into the exosphere (Anonymous, 1989b). The ionosphere is used to reflect radio signals over long distances and is where auroral displays occur. On rare occasions, known as *Polar Cap Absorption* (PCA) events, the solar radiation increases ionization and enhances the absorption of radio signals passing through the ionosphere enough to absorb most (if not all) transpolar high-frequency radio transmissions (Smart and Shea, 1997). In extreme cases, PCA events can last several days, but they usually last less than one day

According to the dynamo theory, most of the geomagnetic field is generated by the rotation of liquid iron in Earth's outer core (Demorest, 2001). Other sources include the ring current (discussed later in this section) and magnetism in Earth's rocks. At Earth's surface, the geomagnetic field is predominantly an axial dipole (like a bar magnet), with magnetic field lines radiating between its north and south magnetic poles. Magnetic field lines are used to indicate the strength and direction of a magnetic field. On a map of geomagnetic field lines, the strength of the field is represented by the density of the field lines. The denser the field lines, the stronger the magnetic field. Thus, the field is strongest, where the field lines are closest together. The direction of the geomagnetic field is the same as the field lines. It is usually indicated by arrows drawn on the field lines, which run from the north magnetic pole (near the south geographic pole) to the south magnetic pole (near the north geographic pole; Figure 2 [p. 21]).

Figure 2. *Earth's Magnetic Field and Radiation belts*.



Note. From *Van Allen Radiation Belts*, by National Aeronautics and Space Administration, 2012. https://www.nasa.gov/mission_pages/sunearth/news/gallery/vab-graphic

The geomagnetic field is not uniformly produced, and the coordinates of the magnetic poles change frequently. The polarity has reversed at irregular intervals of about one million years, and the field is currently becoming weaker at such a rate that it will disappear in about 2,000 years. However, this may only be a temporary trend (Walt, 1994). If the magnetic field does disappear, the radiation belts (described below) will disappear, and worldwide GCR levels would increase to levels observed in polar regions.

The geomagnetic field provides some protection to aircrews and passengers by deflecting GCR away from the Earth's atmosphere. The direction of the magnetic force on a moving charged particle is at right angles (perpendicular) to both the particle's direction of motion (***v***) and direction of the magnetic field lines (***B***). The magnitude of the magnetic force (F) is proportional to the particle's electric charge (q), the particle's speed (v), the strength of the magnetic field (B), and the sine of the angle between the particle's direction of motion and the direction of the magnetic field ($\angle\ \boldsymbol{v}\ \boldsymbol{B}$):

$F = q\ \boldsymbol{v}\ \boldsymbol{B} \sin(\angle\ \boldsymbol{v}\ \boldsymbol{B})$

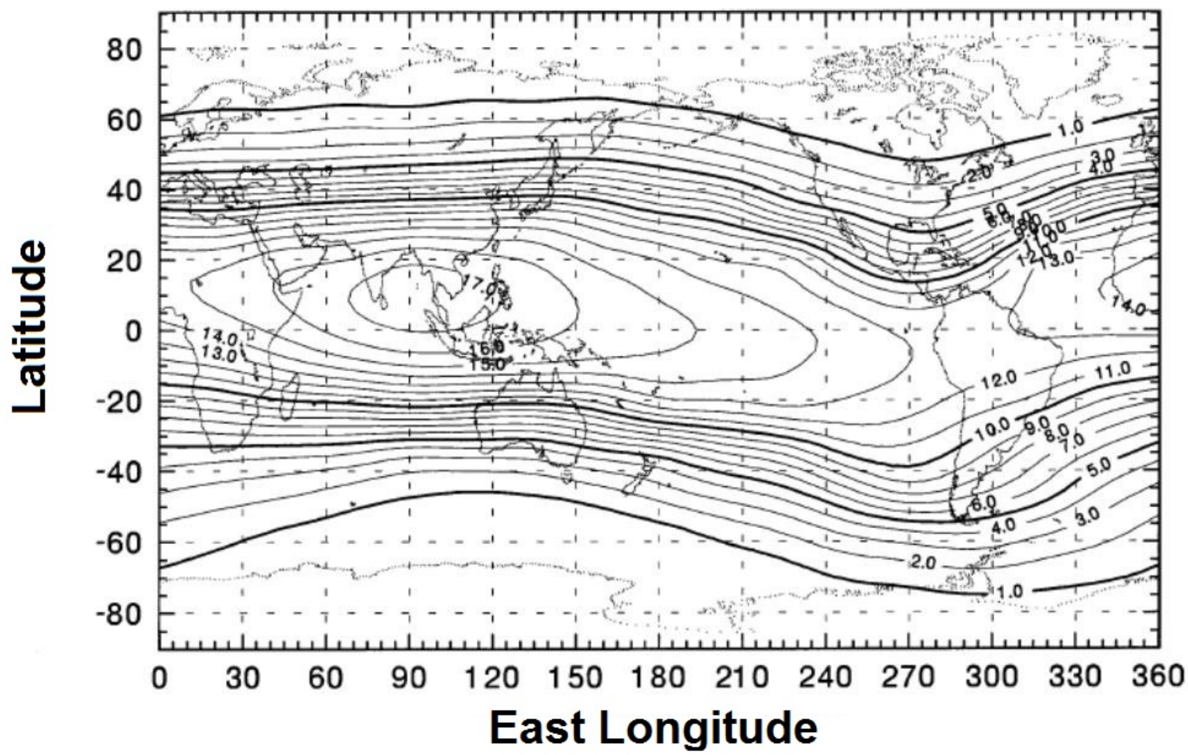
Thus, a charged particle moving parallel to the magnetic field (i.e., entering the geomagnetic field at a magnetic pole) experiences no deflection from its direction of motion ($\sin[\angle\ \boldsymbol{v}\ \boldsymbol{B} = 0°] = 0$). In contrast, a particle moving at a right angle to the magnetic field (i.e., entering the geomagnetic field at the magnetic equator) experiences a maximum in the magnitude of the force deflecting it from its direction of motion ($\sin[\angle\ \boldsymbol{v}\ \boldsymbol{B} = 90°] = 1$).

The geomagnetic field traps charged particles in 2 toroidal (donut-shaped) overlapping radiation belts. The belts encircle the planet and are usually confined to an area from about 65° N to 65° S of the geographic equator. The radiation belts are called *Van Allen radiation belts* in honor of Dr. James A. Van Allen, who reported the inner belt in 1958 (Wilson, 1976). The inner radiation belt (nearest Earth) extends above the Earth's surface, from about 200 km to 11,000 km above the geomagnetic equator and is centered at about 3,000 km (Walt, 1994). It consists mostly of electrons and 10- to 100-MeV protons. Protons are the most important contributor to the radiation dose (NCRP, 2000). The flux of high-energy protons is relatively constant. Protons >50 MeV are believed to originate from the decay of free neutrons scattered into the inner belt after being dislodged from atmospheric atoms by GCR particles. The half-life of a free neutron is 10.2 minutes (mean life, 885.3 seconds [Nakamura et al., 2010]), and some decay into a proton and an electron while in the inner belt. At the geomagnetic equator, protons form a continuous distribution with peak fluences of 400 MeV protons at 2,000 km, 4 MeV protons at 6,000 km, and 0.3 MeV protons at 13,000 km (NCRP, 2000).

At the geomagnetic equator, where geomagnetic field lines are parallel to Earth's surface, particles have the least access to Earth's atmosphere (Wilson, 1976). Moving from the geomagnetic equator towards a magnetic pole, the field lines gradually become perpendicular to the Earth's surface and, therefore, more parallel to the trajectories of the incoming ions, and more ions can enter the atmosphere. At the magnetic poles, field lines are perpendicular to Earth's surface, there is no deflection, and ions of any energy can reach Earth's atmosphere. Access is characterized by a quantity called *rigidity*[6] since ions with the same rigidity follow the same path through a magnetic field. Figure 3 (p. 22) shows effective cutoff rigidities (practically, the lowest rigidities ions can have and still have access) calculated from the 2010 IGRF geomagnetic field.

[6] Rigidity = momentum / charge.

Figure 3. *World Map of Effective Cutoff Rigidities Calculated for an Altitude of 20 km*

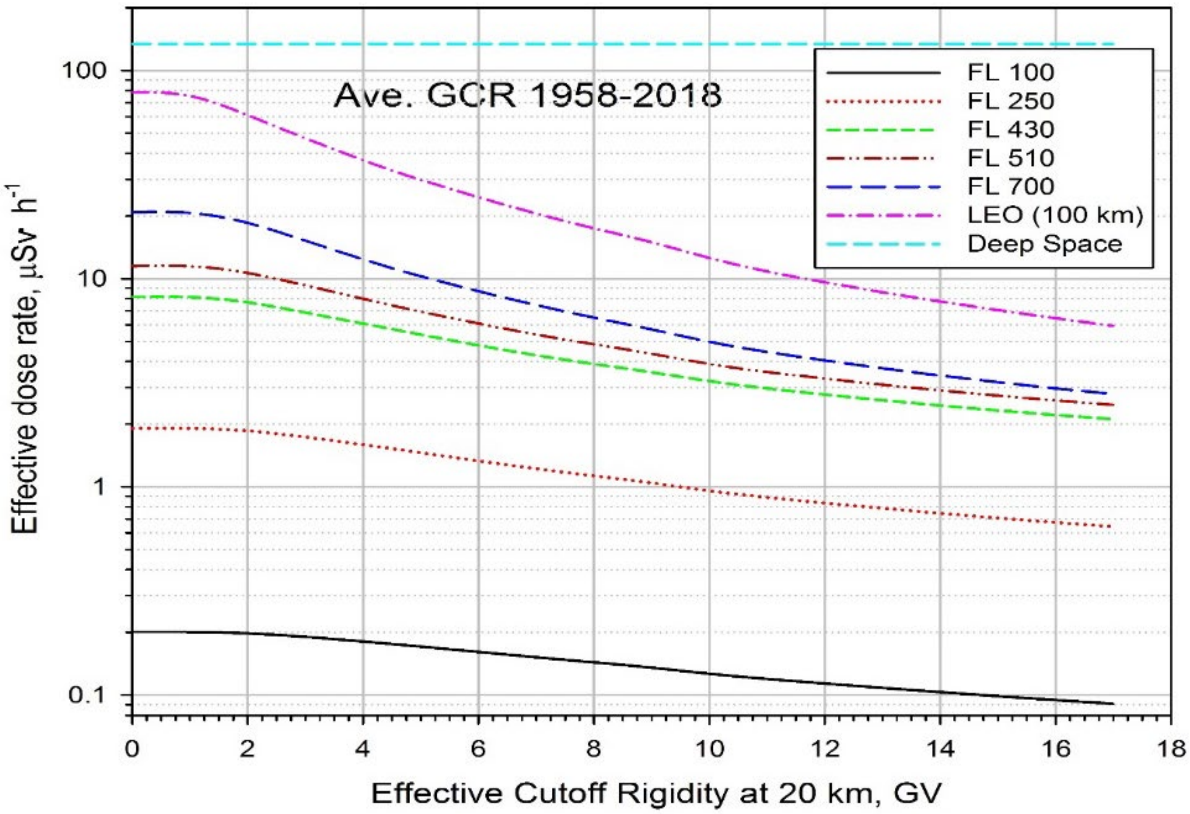


Note. Calculated from the 2010 IGRF geomagnetic field.

Figure 4 (p. 21) shows the effective dose rate at 20° E longitude, as related to geographic latitude. Dose rates in the figure were calculated for mean solar activity from January 1958 through December 2008. The calculations were made with CARI-7 software (CAMI, Oklahoma City, OK). If one were to fly an aircraft at a constant altitude from the geomagnetic equator towards the north or south magnetic pole, the dose rate would increase with distance from the equator. At high latitudes, shielding by the geomagnetic field is minimal. The primary radiation shielding of the aircraft would be the atmosphere, with some shielding by magnetic fields carried by the solar wind (the interplanetary magnetic field) even when solar activity is low. The North Atlantic Air Route, which is among the busiest in the world, is mostly at high latitudes.

The dipole axis of Earth's magnetic field is tilted about 11° from the rotation axis and offset 515 km from the rotation axis. As a consequence, the lower boundary of the inner radiation belt dips closest to Earth in a region off the coast of Brazil called the *South Atlantic Anomaly*, which extends from about 0° to 60° W longitude and 20° to 50° S latitude (geographic coordinates). The daily dose of ionizing radiation to occupants of the ISS is usually about 0.5 to 1.2 mSv, with approximately 25% of the dose coming from protons encountered when passing through the South Atlantic Anomaly and the rest from GCR (NCRP, 2006).

Figure 4. *Effective Dose Rate from GCR, as Related Effective Cutoff Rigidity at Selected Flight Altitudes*



Note. Dose rates were calculated using CARI-7A for the average solar modulation from January 1958 through December 2018. The heliocentric potential used to represent average solar modulation for the period was based on the Deep River neutron monitor equivalent count rate for the period. From "Cosmic radiation exposure of aircraft occupants on simulated high-latitude flights during solar proton events from 1 January 1986 through 1 January 2008," by K. Copeland, H. H. Sauer, F. E. Duke, and W. Friedberg 2008, *Advances in Space Research*, *42*, p. 1008-29. GCR = galactic cosmic radiation; FL = Flight Level, equal to feet in 100s; LEO = low Earth orbit.

The outer radiation belt, the belt farthest from Earth, consists mostly of electrons. It extends from about 11,000 km to 70,000 km in altitude (NCRP 1989). The center of the belt is at about 22,000 km at solar maximum and 26,000 km at solar minimum (NCRP, 2000). The most energetic electrons have energies >1.0 MeV and are centered at about 19,000 to 25,000 km (Walt, 1994). The electron flux in the outer belt varies considerably during a geomagnetic storm because of the fluctuating intensity of the solar wind. The main radiation hazard to space travelers in the outer belt is soft X-rays produced when electrons decelerate in the shell of the space vehicle (Newell and Naugle, 1960).

Individual particles in the radiation belts move towards a magnetic pole in spiral paths along geomagnetic field lines. As they approach a pole, the particles are reflected towards the opposite pole. As they spiral back and forth between the magnetic poles, many low-energy protons are lost from the inner belt by interacting with atmospheric constituents. The proton spectrum decreases sharply at energies >500 MeV because the magnetic field does not easily hold high-energy particles. The flux of trapped particles is highest over the geomagnetic equator, and there are relatively few trapped particles over the geomagnetic poles (Wilson, 1976).

As they spiral back and forth between the magnetic poles, positive particles drift westward, and electrons drift eastward. This creates a westward-flowing electric current called *ring current*, which overlaps the outer radiation-belt at altitudes of 13,000 to 25,000 km at the geomagnetic equator (Walt, 1994). The magnetic field produced by the ring current opposes the equatorial geomagnetic field at Earth's surface. During geomagnetic storms, charged particles injected into the Van Allen radiation belts from the outer magnetosphere cause a sharp increase in the ring current, with a corresponding decrease in Earth's equatorial magnetic field. The injected particles precipitate out of the magnetosphere into the upper atmosphere at high latitudes, causing auroral activity and interference with electromagnetic communications.

5.4. Summary

Key points:

- For aviation, the boundary between the atmosphere and outer space is 100 km (328,000 ft) above the Earth's surface.
- Most daily weather observed from the ground occurs below 18 km (60,000 ft.).
- Earth's magnetic field extends deep into space.
- Earth's magnetic field deflects charged particles away from Earth.
- The least protection occurs near the magnetic poles, while the most protection is at the geomagnetic equator.
- Earth's magnetic field traps some ionizing radiation in regions of space near Earth called Van Allen belts.
- Aurorae and PCAs occur in the ionosphere.

6. GALACTIC COSMIC RADIATION

6.1. Introduction

This section reviews GCR and its sources, composition, and interactions in Earth's atmosphere.

6.2. Composition and Sources

Earth is continuously irradiated from all directions by high-energy charged particles of GCR. GCR particles lose kinetic energy principally by ejecting orbital electrons from the atoms with which they interact. The particle intensity in free space varies from 1.5 particles$\cdot$cm$^{-2}\cdot$s^{-1} near sunspot maximum to about 4 particles$\cdot$cm$^{-2}\cdot$s^{-1} near sunspot minimum. All the natural elements in the periodic table are present in GCR. Outside the geomagnetic field, the composition of the GCR is 98% hydrogen nuclei (protons) plus heavier nuclei stripped of orbital electrons and 2% electrons and positrons (NCRP, 2000). The nuclei component of the radiation, in the energy range 100 MeV to 10 GeV per nucleon (where intensity is highest), consists of 87% protons, 12% helium nuclei (alpha particles), and 1% nuclei with an atomic number (Z) higher than helium. GCR nuclei with a Z higher than helium are called *HZE particles* (high Z and high energy) (NCRP 1989). Iron-56 is an important HZE particle because of its significant contribution to the GCR dose and high LET (Sections 2.1 and 6.3). HZE particles are a concern for a space traveler because the particles can injure the central nervous system (NCRP, 2006). HZE particles are not a concern at airline flight altitudes; they are broken apart at higher altitudes in the atmosphere.

The principal source of GCR in our galaxy is stellar material and surrounding interstellar gas, accelerated by exploding stars (supernovae). There are two ways a star can become a supernova. A star at least 8 times the mass of the Sun can evolve directly into a supernova once the hydrogen supply in the core becomes significantly depleted; hydrogen fusion no longer supplies enough energy to stop the gravitational collapse. As a result, the star contracts and the pressure in its core created by gravitational forces increases. When the pressure becomes great enough, fusion of helium to carbon occurs. The thermal energy released raises the temperature of the gases, temporarily halting the collapse of the star. When the helium runs out, the star begins to collapse again, and increasingly heavier elements are fused. Progressively less thermal energy is produced as heavier elements are formed until the fusion processes culminate with the production of nickel-56, which produces iron-56 by radioactive decay. Iron and elements of higher atomic weight do not emit heat on formation. When nuclear sources are almost exhausted, and outward pressure by the gases is not sufficient to balance gravitational forces, the core of the star suddenly collapses. This is followed by the collapse of the outer layers of the star, and the star explodes as a supernova.

A supernova can also evolve from a white dwarf, which is what remains of a low-mass star after fusion has stopped, and the star has begun to cool. If the white dwarf and another star orbit each other and the white dwarf accretes enough matter from the other star to start uncontrolled fusion of carbon and oxygen, it will explode as a supernova. A white dwarf may also accumulate enough mass and explode as a supernova by colliding with another star.

A supernova can shine for weeks to months. The star's luminosity increases by as much as 20 magnitudes. Li et al. (2011) estimated that there are about 2.8 supernovae in the Milky Way galaxy every hundred years. This estimate was based on a telescopic survey of more than 1,000 supernovae in nearby galaxies. Shock waves of a supernova surge out through space, occasionally initiating new star formations. These shock waves are thought to be the primary accelerators of most GCR particles. However, supernovae are not thought to be powerful enough to generate the highest-energy GCR particles. Such particles are believed to come from nearby galaxies with central black holes. Matter falling towards these black holes becomes superheated as it comes close to the black hole. As a result, the regions around the black holes eject jets of plasma (a gas with a portion of its components ionized) into intergalactic space (Pierre Auger Collaboration, 2007).

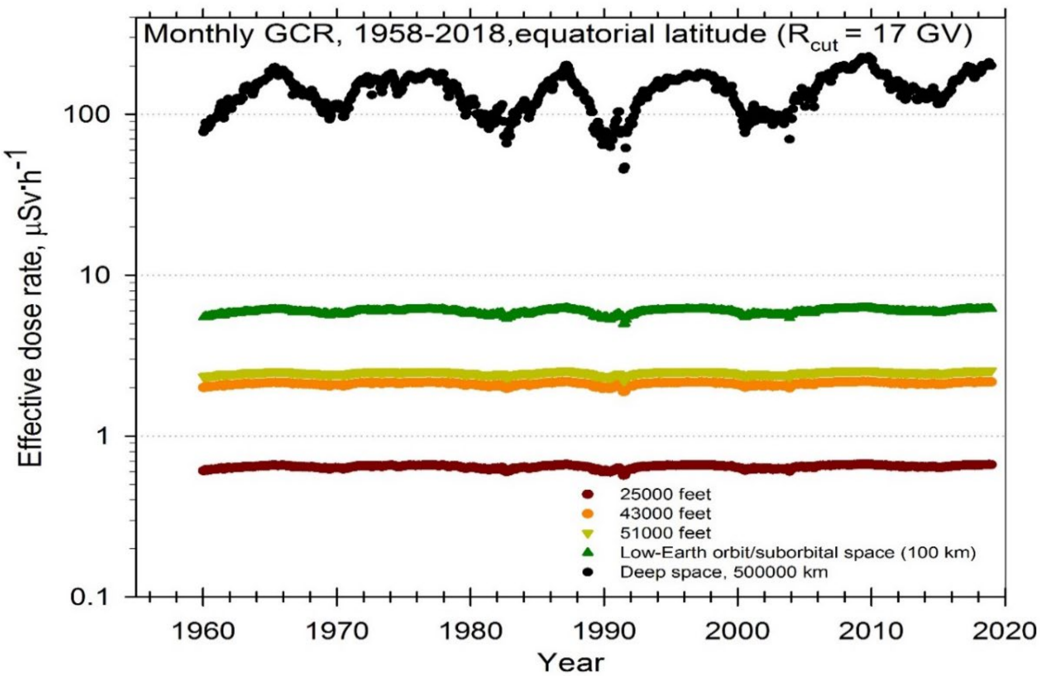
6.3. Galactic Cosmic Radiation in Earth's Atmosphere

GCR levels in Earth's atmosphere vary with latitude (because of Earth's magnetic properties), with altitude (because of Earth's atmosphere), and with solar activity. Figure 5 (p. 24) (calculated with CARI-7A [Copeland, 2017]) shows effective dose rates in the atmosphere during solar activity cycles from January 1958 through December 2008, at several altitudes at geographic coordinates 0° N, 20° E (where geographic and geomagnetic equators overlap), and at 80° N, 20° E.

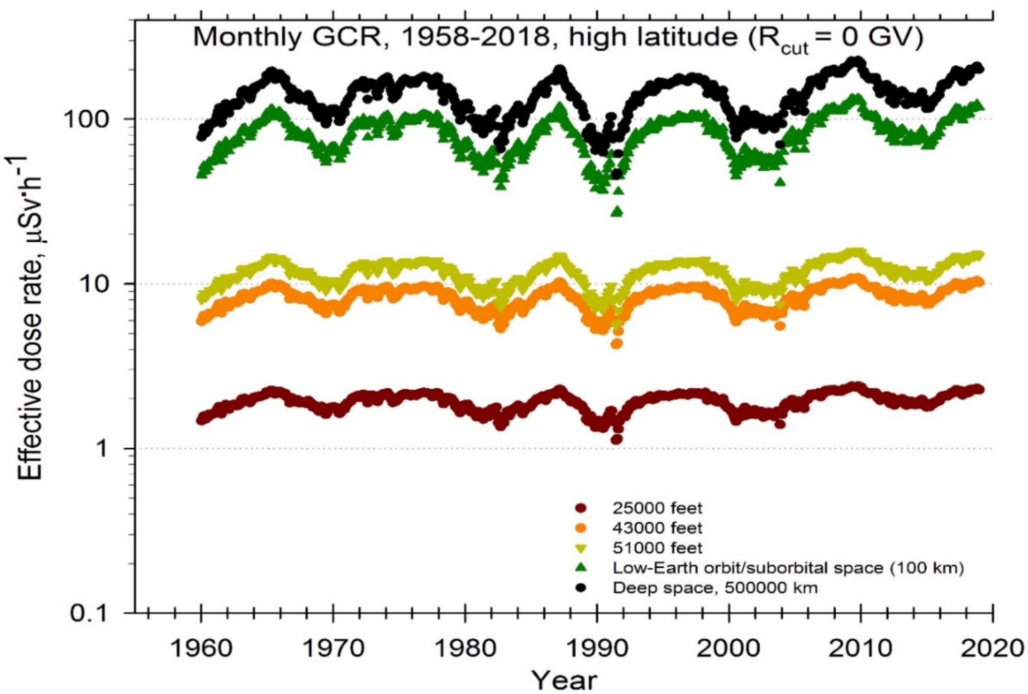
At the high-latitude location, cyclic variation in the radiation level is evident at 30,000 ft, which indicates that low-energy GCR particles reach Earth's atmosphere and penetrate down to this altitude. At the equator, the geomagnetic field repels most low-energy GCR particles that might otherwise enter the atmosphere during low solar activity. Consequently, there is little variation in the dose rate at equatorial latitudes.

Figure 5. *Variation of Dose rate with Altitude for the Last Few Solar Cycles at (a) Equatorial and (b) High Latitudes.*

(A)



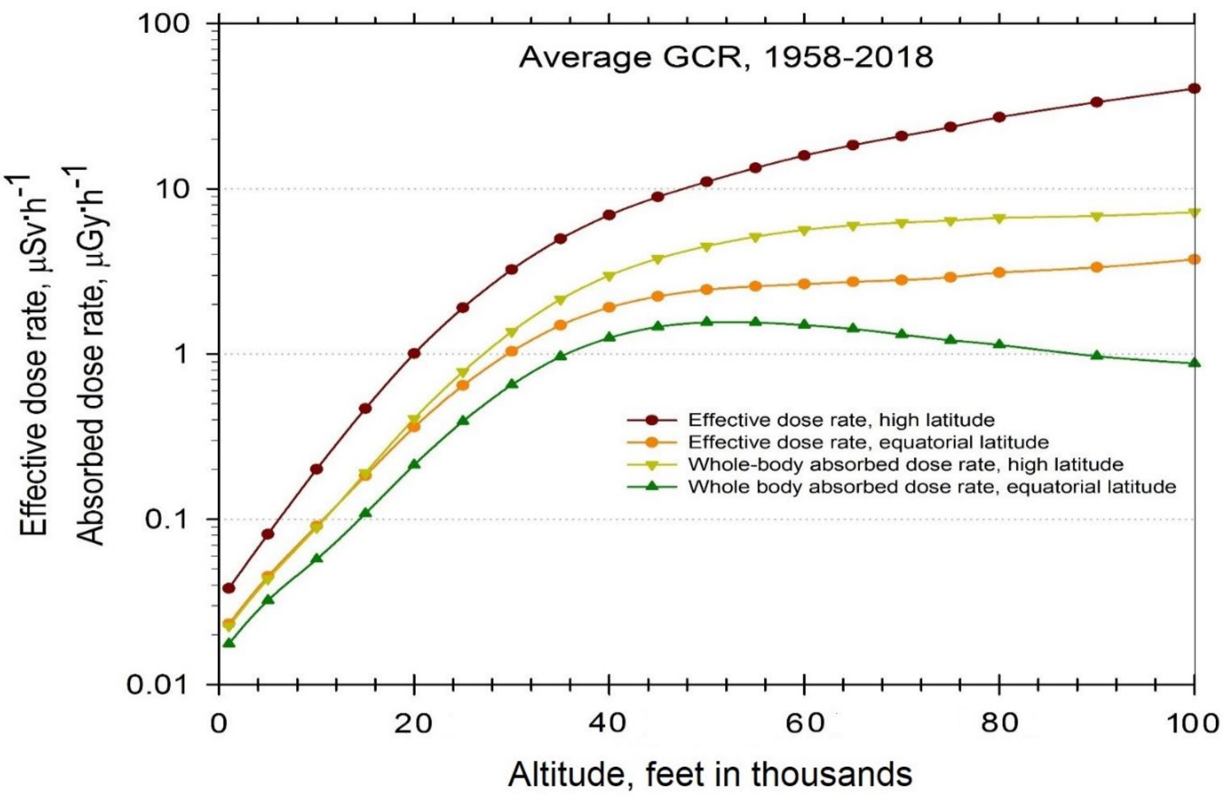
(B)



Note. GCR = galactic cosmic radiation.

With increasing depth in the atmosphere, absorbed dose rates from particles that enter the atmosphere (primary particles) decrease, whereas the absorbed dose rate from particles created in the atmosphere (secondary particles) increases. Thus, a local maximum in absorbed dose rate can occur at an altitude well above the surface of the Earth. It is often referred to as the *Pfotzer maximum* or *Pfotzer dose maximum.* Initially, the term referred specifically to a maximum in atmospheric ionization, but it is now applied to dose rates and particle fluxes where similar physics is the cause. Above this altitude, which can vary due to several factors, the absorbed dose rate (or other quantity) can decrease continuously up to space (where it may begin increasing again). Unlike absorbed dose rates, effective dose rates increase as altitude increases at all altitudes because of the presence and high values of the radiation weighting factors of the heavy ions (Figure 6).

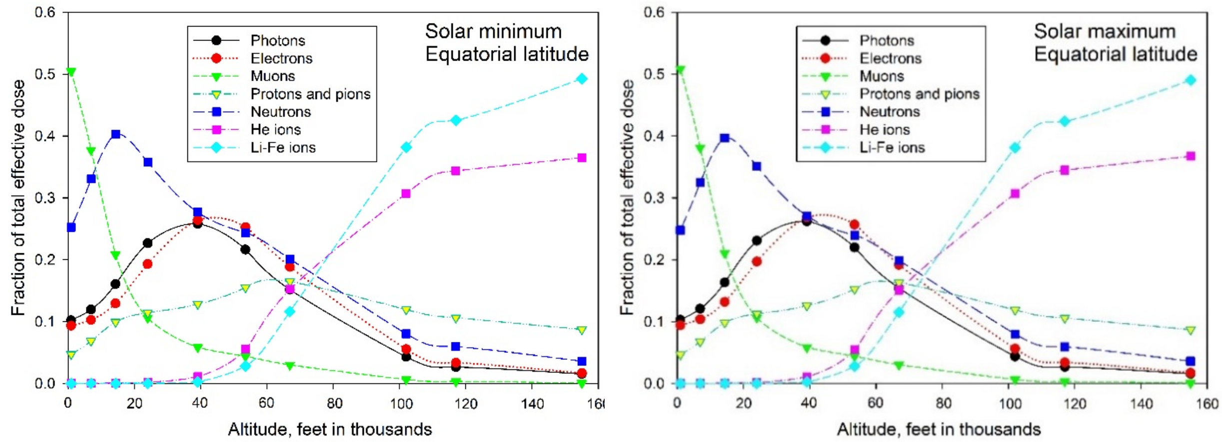
Figure 6. *Average Effective and Absorbed Dose Rates from GCR in the Atmosphere during Recent Solar Activity Cycles*



Note. GCR = galactic cosmic radiation.

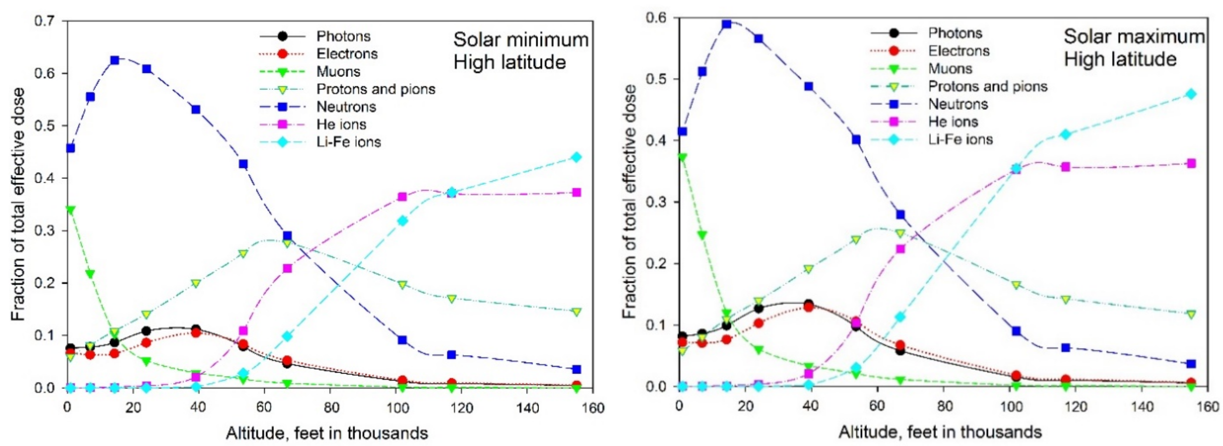
Figures 7 and 8 (p. 26) show the proportional contribution to the mean effective dose rate of each of the principal types of cosmic radiation particles as related to altitude, at the equatorial and high-latitude locations, for solar activity conditions near solar minimum (January 1998) and solar maximum (January 2002) for solar cycle 23. At extreme altitudes, alpha particles and heavier ions are dominant contributors to the dose (about 80%). As these slow down and break up in collisions, neutrons and protons rise in importance. Below about 70,000 feet, neutrons become the most important particles. Lower in the atmosphere, at 20,000 to 40,000 feet where subsonic air-carrier aircraft commonly cruise, neutrons, and electromagnetic shower components are most important. Near sea level, muons and neutrons are the most important particles, combining for about 75% of the total doses.

Figure 7. *Contribution of the Principal GCR Particles to the Mean Effective Dose Rate Near the Geomagnetic Equator as Related to Altitude, for Solar Minimum (Left Panel) and Solar Maximum (Right Panel) conditions*



Note. GCR = galactic cosmic radiation.

Figure 8. *The Contribution of the Principal GCR Particles to the Mean Effective Dose Rate at a High Geographic Latitude as Related to Altitude, for Solar Minimum (Left Panel) and Solar Maximum (Right Panel) Conditions*



Note. GCR = galactic cosmic radiation.

6.4. Summary

Key points:

- GCR is composed of ions accelerated to extreme energies at supernovae and other high-energy astronomical sources.
- GCR includes every naturally occurring element, and its composition changes as it passes through the atmosphere.
- GCR levels in Earth's atmosphere vary with latitude (because of Earth's magnetic properties), with altitude (because of Earth's atmosphere), and with solar activity.

7. THE SUN AND ITS EMISSIONS

7.1. Introduction

The Sun is both a source of protection from GCR and a potentially intense source of ionizing radiation. Earth's space weather, both ionizing radiation storms and other kinds, is the result of solar events. This section presents information on the solar atmosphere, sunspots, solar wind, solar flares, coronal mass ejections, and solar particle events.

7.2. Layers of the Sun's Atmosphere

The photosphere is the Sun's atmospheric layer visible in white light. Above the photosphere is the chromosphere, a significant source of UV radiation. Above the chromosphere is the corona, a region of very hot gas.

7.3. Sunspots

A sunspot is an area on the photosphere seen as a dark spot in contrast with its surroundings. Sunspots appear dark because the area is cooler than the surrounding photosphere.

Sunspots occur where areas of the Sun's magnetic field loop up from the surface of the Sun and disrupt convection of hot gases from below. The sunspot number is an index of solar activity. The sunspot number is calculated from the number of sunspots and groups of sunspots visible on the Sun (Smart and Shea, 1997). For the last 280 years, the sunspot cycle has been about 11 years, with solar activity increasing for approximately 4.8 years and decreasing for approximately 6.2 years.

The Sun initiates disturbances in Earth's geomagnetic field, and disturbances are more common and more intense when sunspots can be seen. However, intense geomagnetic disturbances have occurred when no sunspots were observed, and a low level of geomagnetic disturbances has sometimes been accompanied by high sunspot numbers (Parkinson, 1983).

7.4. Solar Wind

The solar wind boils continuously off the Sun, producing an interplanetary magnetic field. The mass of the solar wind is about 80% protons, 18% alpha particles, and traces of heavier charged particles (Burch, 2001). Discontinuities in the magnetic field carried by the solar wind (called *scattering centers*) deflect away from Earth some low-energy GCR particles that might otherwise enter the atmosphere (Wilson, 1976). This effect on GCR is known as *solar modulation*. During the active phase of the Sun's activity cycle, the solar wind is at its most intense, and this reduces GCR in Earth's atmosphere to its lowest levels. At its highest intensity, the solar wind can adversely affect telecommunication systems, but particle energies are too low to increase ionizing radiation levels at aircraft flight altitudes (Friedberg et al., 1992). Any environmental effect from the increased intensity of charged particles from the Sun is called *space weather*.

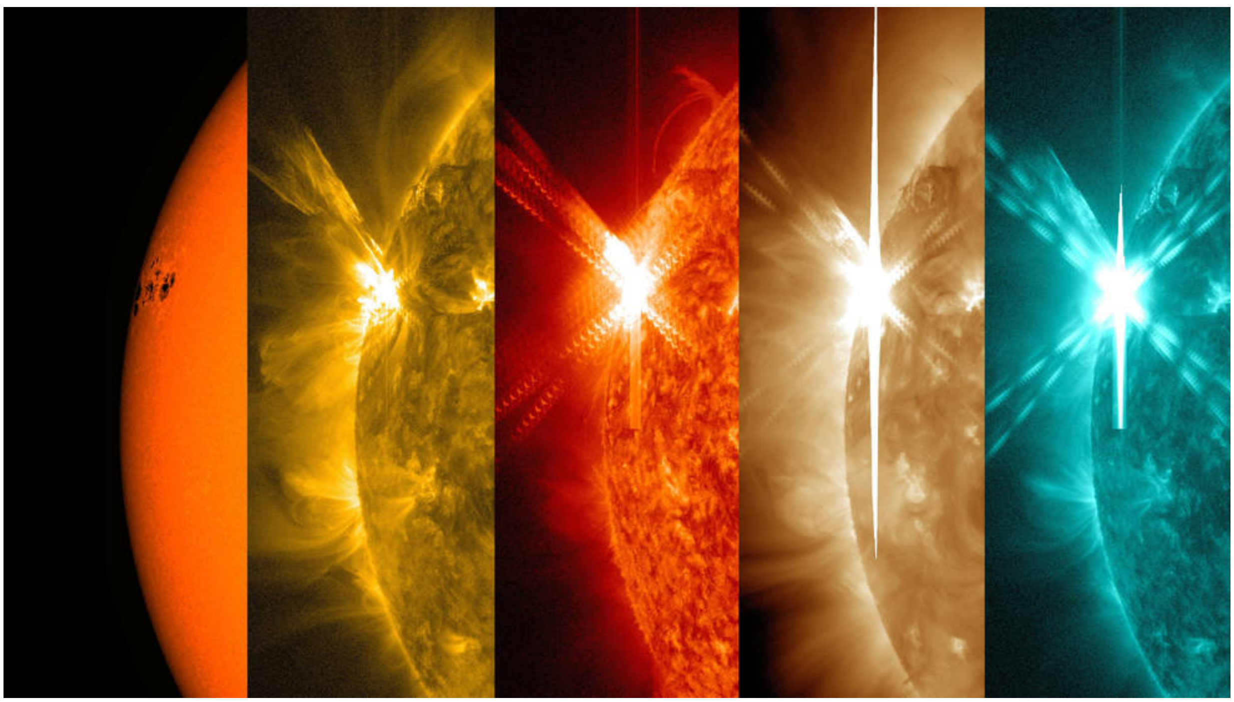
7.5. Coronal Mass Ejections and Solar Flares

Occasionally a magnetic disturbance in the Sun results in an explosive ejection of vast amounts of matter and embedded magnetic fields from the solar corona, and this is called a *coronal mass ejection* (CME). A CME usually originates in a magnetically active region around a visible sunspot group. A large CME can blast billions of tons of charged particles into space at speeds of 1,700 km/second (Burch, 2001). When a fast CME plows through the slower moving solar wind, it produces interplanetary shock waves, which are responsible for showers of high-energy particles impacting Earth's atmosphere (Smart and Shea, 1997).

Because the interplanetary magnetic field and geomagnetic field bend the trajectories of these particles, they enter the atmosphere from all directions (flying at night is no benefit), and they interact with air atoms in the same way as GCR particles.

The term *solar flare* refers to the electromagnetic energy and particles released suddenly from a relatively small volume of the Sun (Smart and Shea, 1997). Figure 9 shows images of a solar flare taken in five different wavelengths of light. Solar flares and CMEs have often been associated, but the relationship between them, if any, is currently unknown. The amount of energy and matter released during a solar flare is relatively small compared to the amount released during a CME. Most CMEs and solar flares are not directed at the Earth. Particles associated with a solar flare may not have enough energy to increase radiation levels in Earth's atmosphere. Photons from a solar flare begin arriving about 8 minutes after departing the Sun. The most energetic charged particles from a CME or a solar flare reach Earth in 15 to 20 minutes. The difference in arrival time between photons and charged particles is due to the longer path the particles must follow to reach Earth.

Figure 9. *A Solar Flare Observed in Five Different Wavelengths of Light*



Note. NASA's Solar Dynamics Observatory captured these images of a solar flare—as seen in the bright flash on the left edge of the Sun—on May 5, 2015. From "NASA's SDO observes 'Cinco de Mayo' solar flare," by National Aeronautics and Space Administration, 2015. https://www.nasa.gov/feature/goddard/nasas-sdo-observes-cinco-de-mayo-solar-flare.

7.6. Solar Proton Events

A surge of subatomic particles from the Sun is defined as a *solar proton event* (SPE) by the Space Weather Prediction Center of the U.S. National Oceanic and Atmospheric Administration (NOAA) if instruments on a Geosynchronous Operational Environmental Satellite (GOES) measure in three consecutive 5-minute periods an average solar proton flux $\geq$ 10 particles/(cm^2·steradian·second) with all proton energies >10 MeV (NOAA, 2019). A particle surge that meets these characteristics is most likely the result of a CME.

7.7. Summary

Key points:

- The solar wind boils continuously off the Sun, producing an interplanetary magnetic field.
- The magnetic fields in the solar wind deflect GCR.
- CMEs and solar flares that lead to SPEs are rare events; particles are usually directed away from Earth.
- The most energetic charged particles from a CME or a solar flare reach Earth in 15 to 20 minutes.
- An SPE increases ionizing radiation in the vicinity of the Earth, but an SPE may not have enough energetic particles to increase radiation levels at aviation altitudes.

8. AIR AND SPACE TRAVEL

8.1. Introduction

Air and space travel expose travelers to ionizing radiation. This section discusses doses to travelers from GCR, SPEs, and other sources, including calculations of GCR flight doses and career dose estimates, doses from radioactive cargo shipments, doses from terrestrial weather sources, and the particular case of space travel.

8.2. Cosmic Radiation

The FAA freely provides software (CARI-6 and CARI-7) to the public for calculation of the effective dose of GCR to an adult on an aircraft flight between commercial airports at its Radiobiology Website:

https://www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology/

CARI-6 variants are suitable for flights below 60,000 feet requiring ICRP Publication 60 dosimetry methods,[7] while CARI-7 variants can be used for flights at any altitude and can calculate several additional kinds of doses, such as effective dose from ICRP Publication 103 dosimetry methods or ambient dose equivalent, H*(10). For direct airport-to-airport flights, the information needed for calculations with either program is as follows:

(1) Date of flight;
(2) International Civil Aviation Organization (ICAO) code of origin airport;
(3) ICAO code of destination airport;
(4) Number of en route altitudes;
(5) Minutes climbing to first en route altitude;
(6) First en route altitude, in feet;
(7) Minutes cruising at first en route altitude;
(8) Additional en route altitudes (if any), in feet;
(9) For each en route altitude (if any) after the first: Minutes changing to the en route altitude plus minutes cruising at the en route altitude;
(10) Minutes descending to the destination airport.

[7] In aviation and space, ICRP Publication 60 effective dose is higher than ICRP Publication 103 effective dose, primarily because both the high-energy proton and neutron radiation weighting factors are much lower.

Waypoint based flights and point only calculations can also be done. Table 14 shows the effective dose (sieverts) from GCR received on single nonstop one-way air carrier flights calculated with CARI-7. Flight dose data, such as in Table 14, when combined with risk coefficients in Tables 10-12 (p. 11–12), can be used to estimate cancer risk and genetic effects from GCR exposure during a flying career.

Table 14. *Flight Data and Effective Dose Based on ICRP Pub 60 and ICRP Pub 103 Recommendations Calculated with CARI-7A on Single Nonstop One-Way Air Carrier Flights*

Origin – Destination	Highest alt. (kft)	In-air hours	Block[a] hours	Effective dose (mSv) ICRP Pub. 103	Effective dose (mSv) ICRP Pub. 60
		Solar Maximum (January 2002)			
Houston TX – Austin TX	20	0.5	0.6	1.4×10^{-4}	1.7×10^{-4}
Miami FL – Tampa FL	24	0.6	0.8	3.3×10^{-4}	4.1×10^{-4}
St. Louis MO – Tulsa OK	35	0.9	1.1	1.3×10^{-3}	1.7×10^{-3}
London UK – Los Angeles CA	39	10.5	11.0	4.5×10^{-2}	5.8×10^{-2}
Chicago IL – London UK	37	7.3	7.7	3.1×10^{-2}	4.1×10^{-2}
London UK – Chicago IL	39	7.8	8.3	3.4×10^{-2}	4.5×10^{-2}
Athens Greece – New York NY	41	9.4	9.7	4.6×10^{-2}	6.0×10^{-2}
		Average Solar Activity in 61 years (1958-2018)			
Houston TX – Austin TX	20	0.5	0.6	1.6×10^{-4}	1.9×10^{-4}
Miami FL – Tampa FL	24	0.6	0.8	3.7×10^{-4}	4.6×10^{-4}
St. Louis MO – Tulsa OK	35	0.9	1.1	1.6×10^{-3}	2.0×10^{-3}
London UK – Los Angeles CA	39	10.5	11.0	5.4×10^{-2}	7.1×10^{-2}
Chicago IL – London UK	37	7.3	7.7	3.8×10^{-2}	4.9×10^{-2}
London UK – Chicago IL	39	7.8	8.3	4.2×10^{-2}	5.5×10^{-2}
Athens Greece – New York NY	41	9.4	9.7	5.5×10^{-2}	7.2×10^{-2}
		Solar Minimum (January 1998)			
Houston TX – Austin TX	20	0.5	0.6	1.7×10^{-4}	2.0×10^{-4}
Miami FL – Tampa FL	24	0.6	0.8	3.9×10^{-4}	4.8×10^{-4}
St. Louis MO – Tulsa OK	35	0.9	1.1	1.7×10^{-3}	2.2×10^{-3}
London UK – Los Angeles CA	39	10.5	11.	6.1×10^{-2}	8.0×10^{-2}
Chicago IL – London UK	37	7.3	7.7	4.3×10^{-2}	5.6×10^{-2}
London UK – Chicago IL	39	7.8	8.3	4.7×10^{-2}	6.2×10^{-2}
Athens Greece – New York NY	41	9.4	9.7	6.0×10^{-2}	8.0×10^{-2}

Note. ICRP = International Commission on Radiological Protection.

[a] Block hours start before takeoff from the origin airport, after the aircraft door is closed and the brake is released. Block hours end after landing at the destination airport, the last time the brake is set before the aircraft door is opened.

Example 1 A crewmember worked 700 block hours per year for 25 years flying between Athens, Greece and New York, NY. Assuming average solar activity for each flight, estimate the crewmember's increased lifetime risk of fatal cancer using flight data in Table 14, particle dose contribution data from Figures 7 and 8, and risk coefficients for fatal cancer from Table 10.

Risk from low-LET radiation (using ICRP Pub 103 effective doses)

700 block hours per year x 25 years = 17,500 block hours in 25 years

Low LET dose fraction estimate = 0.055 mSv total dose × 0.27 = 0.015 mSv

0.015 mSv per flight / 9.7 block hours per flight = 0.00155 mSv per block hour

0.00155 mSv per block hour x 17,500 block hours in 25 years = 27.1 mSv in 25 years

Fatal cancer risk = 3.1 in 100,000 per mSv x 27.1 mSv in 25 years = 84 in 100,000

Risk from high-LET radiation

High-LET flight dose = 0.055-0.015 = 0.040 mSv

0.040 mSv per flight / 9.7 block hours per flight = 0.0041 mSv per block hour

0.0041 mSv per block hour x 17,500 block hours in 25 years = 71.8 mSv in 25 years

Fatal cancer risk = 6.3 in 100,000 per mSv x 71.8 mSv = 452 in 100,000

Total risk

Risk from low-LET radiation + high-LET radiation =

84 in 100,000 + 452 in 100,000 = 536 in 100,000 = **1 in 190**

Example 2 Before conceiving children, one parent worked 700 block hours per year for 5 years flying between Athens, Greece, and New York, NY. Assuming average solar activity for each flight, what is the risk of genetic defects in the first 2 successive generations from this exposure? (Flight data are in Table 9. Risk coefficients for genetic defects are in Table 11.)

Risk from low-LET radiation

700 block hours per year x 5 years = 3,500 block hours

Low-LET dose per block hour same as **Example I** = 0.00155 mSv per block hour

0.00155 mSv per block hour x 3,500 block hours in 5 years = 5.425 mSv in 5 years

Genetic risk = 1.2 in 1,000,000 per mSv x 5.425 mSv in 5 years = 6.51 in 1,000,000

Risk from high-LET radiation

0.040 mSv per flight / 9.7 block hours per flight = 0.0041 mSv per block hour

0.0041 mSv per block hour x 3,500 block hours in 5 years = 14.35 mSv in 5 years

Genetic risk = 2.4 in 1,000,000 per mSv x 14.35 mSv = 34.44 in 1,000,000

Total Risk

Low-LET radiation + high-LET radiation = 6.51 + 34.4 = 41 in 1,000,000 = **1 in 24,000**

From January 1, 1986, through January 1, 2008, there were 170 solar proton events. During 169 of these events, Copeland et al. (2008) estimated doses of SCR and GCR received on simulated high-latitude aircraft flights. To estimate SCR, they used GOES measurements, near sea-level neutron-monitor data, and MCNPX. For GCR, they used CARI-6P, with w_R(protons) = 2.

For each event, they calculated the highest combined GCR + mean SCR dose received by an adult and the highest received by a < 3-month-old conceptus, in 1, 3, 5, and 10 hours, at altitudes of 30, 40, 50, and 60 kft. Thus, for each of the 169 events, there were 16 adult categories and 16 conceptus categories. The highest value for each of the 32 categories (shown in Table 15) occurred either during the September 29, 1989 event or the January 16, 2005 event. No larger solar particle events have occurred in the years since this analysis (NOAA, 2019).

The combined GCR and mean SCR dose to an adult was always < 20 mSv, the annual occupational limit (a 5-year average) recommended by the ICRP (2007) and the FAA. During 10 of the 169 events, in one or more of the 16 categories for the conceptus, the combined GCR and mean SCR dose exceeded the 0.5-mSv monthly limit recommended by the NCRP (1993) and the FAA.

Table 15. *Highest Combined GCR and Mean SCR Effective Doses to an Adult and <3-month-old Conceptus on Simulated High-Latitude Aircraft Flights during 169 Solar Proton Events at R_{vc} = 0.01 GV at Selected Altitudes*

Altitude,	Effective dose[b] to an adult (Equivalent dose to a conceptus), mSv			
ft. in 1000s	1 h[a]	3 h	5 h	10 h
		29 September 1989 event		
30	---	0.098 (0.11)	0.14 (0.16)	0.20 (0.22)
40	---	0.27 (0.30)	0.39 (0.43)	0.57 (0.63)
50	---	---	0.84 (0.90)	1.3 (1.4)
60	---	---	---	2.6 (2.4)
		16 January 2005 event		
30	0.048 (0.050)	---	---	---
40	0.16 (0.17)	---	---	---
50	0.42 (0.44)	0.68 (0.72)	---	---
60	0.90 (0.83)	1.5 (1.4)	1.8 (1.7)	---

Note. From “Cosmic radiation exposure of aircraft occupants on simulated high-latitude flights during solar proton events from 1 January 1986 through 1 January 2008,” by K. Copeland, H. H. Sauer, F. E. Duke, and W. Friedberg 2008, *Advances in Space Research*, 42, p. 1008-29. GCR = galactic cosmic radiation; SCR = solar cosmic radiation.

[a] These effective doses are somewhat overestimated by modern standards because of changes to recommended values for neutron radiation weighting factors in the ICRP 2007 recommendations.

[b] 1, 3, 5, or 10 hours of continuous exposure

The ground-level event (GLE) of February 23, 1956 (GLE 5) remains the largest SPE of the neutron monitor era in terms of its influence on count rates at monitors near sea level. Copeland and Atwell (2018) calculated event doses at a high-latitude location at selected altitudes for this event, which are shown in Table 16 (p. 35) and Figure 10 (p. 36). During this event, the count rate was increased by as much as 4760% (15-minute average) at the Leeds monitor relative to the count rate from GCR. For locations of low geomagnetic cutoff rigidity, effective doses calculated with CARI-7A using SCR models are very high when compared with GCR and can exceed recommended exposure limits. Both GLE spectra exhibit a much stronger dependence on cutoff rigidity than GCR and a larger fraction of the dose from neutrons.

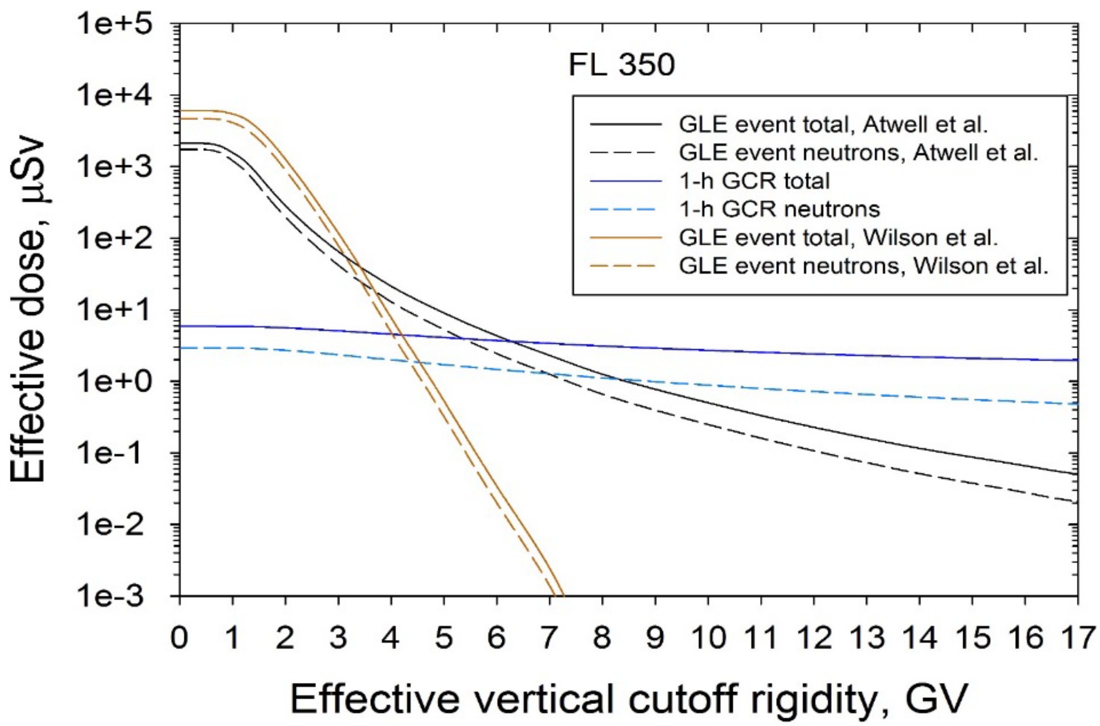
Table 16. *Event Total Effective Doses at R_{vc} = 0.01 GV at Selected Altitudes*

Altitude, feet (km)	Effective dose, mSv		
	Wilson, et al. (1991) model	Atwell, et al. (2011) model	GCR, 1 hour
35,000 (10.7)	6.1	2.1	5.8×10^{-3}
43,000 (13.1)	1.3×10^{1}	4.7	9.4×10^{-3}
51,000 (15.5)	2.3×10^{1}	9.4	1.2×10^{-2}
60,000 (18.3)	4.2×10^{1}	2.0×10^{1}	1.8×10^{-2}

Note. From (Copeland and Atwell, 2018)

Figure 10 illustrates the change in event doses for the February 1956 event calculated for different levels of geomagnetic shielding from polar latitudes (0 GV) to near the geomagnetic equator (17 GV) along with the GCR hourly dose rates at the same locations, at FL 350. The modeled GLE effective doses are smaller than the GCR hourly dose at locations with cutoff rigidities above 4.2 and 6.4 GV, respectively. At locations with cutoff rigidities above about 4 GV, GCR was the dominant source of exposure in ≤ 10 hours at all altitudes examined. This suggests that if a similar event occurs in the future, low- and mid-latitude flights at modern jet flight altitudes could be well-protected by Earth's magnetic field.

Figure 10. *Relationship Between Vertical Cutoff Rigidities and Total and Neutron Effective Doses at 10.7 km (35,000 ft) for the February 23, 1956, Solar Proton Event and GCR During Solar Minimum for 1 Hour Calculated Using CARI-7A*



Note. From "Flight safety implications of the extreme solar proton event of 23 February 1956," by K. Copeland and W. Atwell, 2018, *Advances in Space Research*, 63, 665–671. The Wilson et al. event proton spectra are from Singleterry et al. (2010), the Band fit of the 23 Feb. 1956 GLE is from Atwell et al. (2011), and the GCR spectrum is the 2011 update to the 2010 Badhwar and O'Neill (O'Neill, 2010) model run for January 1998 (near solar minimum). GCR = galactic cosmic radiation; GLE = ground-level event.

The most severe solar proton event for which a record is available occurred in 1859 (Odenwald and Green, 2008). While significant information about particle fluxes is unknown, recorded data indicate the most powerful geomagnetic storm occurred in 1859. Magnetic compasses were useless, telegraph systems failed, and auroras were seen as far south as the Caribbean in the Americas. If the 1859 storm were to happen in a modern, high-technology environment, the high levels of SCR would damage electronics on spacecraft, disable radio communications, and cause widespread electrical blackouts. Intense solar activity can heat the atmosphere, causing it to expand. For a satellite in LEO, such an atmospheric change would increase the drag on the satellite, causing it to slow down and change its orbit to a lower altitude.

8.3. Cargo Shipping

The most common radioactive cargos on passenger-carrying aircraft are isotopes used for medical diagnosis or treatment. These are often shipped by air because of the short lifetimes of the isotopes. Other shipments of radioactive material are isotopes used for research or commercial purposes. Regardless of the material, packaging and shipping of radioactive materials is strictly regulated to limit the doses to all persons on board the aircraft and limit the possibility of a spill. A Nuclear Regulatory Commission (NRC) (1977) study of passenger-carrying aircraft in the United States during 1975 estimated the mean annual ionizing radiation dose from radioactive cargo was 0.06 mSv for cabin crew and 0.01 mSv for flight deck crewmembers. For aircrew working only on flights out of airports serving major radiopharmaceutical producers, they estimated annual exposures up to 0.13 mSv for cabin crew and 0.025 mSv for flight deck crewmembers. Combined 1981-1983 surveys by Javitz et al. (1985) indicated a slight decrease in the number of packages of radioactive material transported by air when compared with 1975 figures. More recently, a survey of the cabin and flight-deck doses from radioactive cargo on flights based in the United Kingdom resulted in estimates of average annual doses of ≤ 0.064 mSv to the flight deck and cabin crew (Warner et al., 2003). Most recently, a 2012 survey by the Centre for Radiation, Chemical and Environmental Hazards of Public Health England in the United Kingdom found that the highest average annual doses to flight deck crew, cabin crew, and passengers from radioactive shipments were very low: 0.024, 0.073 and 0.073 mSv, respectively (Harvey et al., 2014). The doses reported in these surveys are quite low—no more than the GCR received on a single intercontinental flight (see Table 14 [p. 31]), and would make only a small contribution to the annual flight doses from GCR received by crewmembers flying between most city pairs.

8.4. Other Radioactive Contaminations

Historically, regions of the atmosphere have sometimes temporarily become contaminated with radioactive gases and particles released during nuclear reactor accidents and detonations of nuclear weapons. Also, atmospheric contamination may be a possible consequence of a terrorist attack or a dirty bomb detonation. These radioactive contaminants may travel long distances in the wind. Radioiodines, effective at causing thyroid cancers, are the chief gaseous isotopes of concern after nuclear explosions, and inhalation problems with fission products other than iodine are minor (NCRP, 1974). For example, in Belarus (formerly part of the Soviet Union), in the 10 years before the Chernobyl reactor accident, 1,342 adult and 7 childhood thyroid cancers were diagnosed, whereas, during the 9 years after the accident, 4,006 adult and 508 childhood thyroid cancers were reported (NCRP, 2008). Other airborne radioactive substances are not as hazardous as inhalants but can contaminate exposed surfaces. Exposure risks will be specific to the event.

8.5. Lightning and Terrestrial Gamma-Ray Flashes

Each commercial aircraft is struck by lightning about once every 3,000 flight hours, on average. Soft X-rays and gamma rays (ionizing radiation photons) are emitted by thunderclouds and are associated with lightning. Soft X-ray spectra associated with lightning have been measured, and doses can be neglected when compared with GCR. Also, thousands of bursts of gamma rays emanating from our atmosphere (i.e., *TGFs*), have been observed by spacecraft since 1994. TGFs have also been observed very infrequently within the last few years using ground and aircraft-based instruments (Bowers et al., 2017; Wada et al., 2019a). The photon spectra are consistent with production by electron bremsstrahlung. However, there are many unknowns, including the occurrence rate of TGFs relative to lightning (estimated from satellite measurements at 1:19,100 [Fabro et al., 2015]), whether an aircraft can trigger a TGF or associated lightning, whether a TGF can occur without lightning and required conditions for TGF electron acceleration regions in thunderstorms.

The estimated upper limit of the effective dose received by an individual in an aircraft struck by TGF is about 30 mSv (Dwyer et al., 2010). This dose falls exponentially with intervening atmosphere. For instance, Wada et al. (2019b) measure doses of about 1 μGy at about 0.5 km from a TGF during a winter thunderstorm in the vicinity of the Kashiwazaki-Kariwa Nuclear Power Station in Japan. Thus, while a significant number of aircraft occupants could receive a large radiation dose when a TGF occurs, very close proximity to the event would be required. Aircraft are rarely flown into regions thought to be capable of producing a TGF.

8.6. Space Travel

Commercial space flights, in the next decade or so, could include suborbital flights, trips to the ISS, and even trips into deep space. Persons on these flights may be exposed to trapped radiation, GCR, and SCR.

It is expected that the suborbital flights will be primarily like SpaceShipOne, a rocket carried aloft and launched at high altitude from a carrier aircraft or something like the early ballistic flights of the Mercury program. These kinds of flights usually spend ≤ 15 minutes at high altitudes and in space. GCR should be the primary source of ionizing radiation exposure if the flight path is chosen to avoid the trapped radiation of the South Atlantic Anomaly, and the timing is selected to avoid SCR events. Doses to vehicle occupants are expected to be quite low during the rocket-powered and freefall portions of the flight. For example, Friedberg and Copeland (2011) estimated an effective dose of 0.00031 mSv for Alan Shepard's Mercury 3 mission. The highest doses could be incurred during the longer pre-ballistic climb portion of the flight (e.g., SpaceShipTwo before release by White Knight Two).

For any tourists visiting the ISS, the trip is typically 7 to 10 days, and doses will be considerably higher than on suborbital flights. The trapped radiation of the South Atlantic Anomaly[8] cannot be avoided. Also, the orbit of the ISS is at a high inclination, so for part of each orbit, it is at higher latitudes than those well-protected by Earth's magnetic field, and ISS occupants receive little protection from GCR. While of low probability, SCR is also a possible radiation hazard.

An example of a trip to the ISS orbit is STS-91, a 9.8-day space shuttle mission, during which the effective dose equivalent to the astronauts, based on in-flight measurements, was 4.1 mSv (Yasuda et al., 2000).

Trips into deep space, such as proposed commercial human-crewed lunar missions and trips to Mars, can result in much larger doses. Table 17 (p.36) shows CARI-7A doses of GCR calculated at the most extreme

[8] A region above Earth's atmosphere where geomagnetically trapped radiation is unusually close to the Earth because Earth's magnetic field axis is tilted and offset from its axis of rotation.

solar modulation conditions since January 1958 for deep space at 1 A.U.[9] Calculations at several different possible shielding configurations are shown. Most of the time, during this kind of space travel, there will be no protective effect from Earth's magnetic field. The weak fields of Mars and the Moon are both insignificant in comparison. Also, deep space travelers will not benefit from the shielding provided by the mass of large planetary bodies such as Earth. GCR dose rates beyond LEO can be as high as a few millisieverts per day, depending on spacecraft shielding and solar activity (Rietz et al. 2012).

Table 17. *Extreme GCR Effective Doses in Deep Space at 1 A.U.*

	ICRP Publication 103 effective dose, mSv per day				
Activity	Al, 0 g•cm^{-2}	Al, 1 g•cm^{-2}	Al, 5 g•cm^{-2}	Al, 10 g•cm^{-2}	Al, 20 g•cm^{-2}
Deepest Solar Minimum (Dec. 2009)	5.33	4.44	3.48	2.95	2.26
Greatest Solar Maximum (Jun. 1991)	1.01	0.95	0.79	0.71	0.58

Note. GCR = galactic cosmic radiation; ICRP = International Commission on Radiological Protection.

In addition to higher GCR, SCR from solar proton events can be particularly hazardous during space travel. Table 18 shows SCR doses calculated using CARI-7A for the event of 29 September 1989, one of the more significant events of the last 50 years. Whole-body absorbed doses and ICRP publication 103 effective doses at altitudes of 3, 12, 20, 100, and 500,000 km altitudes are shown with four levels of spacecraft or aircraft shielding of occupants: 0, 1, 5, and 20 g/cm^2 of aircraft aluminum alloy. In space, dose rates exceed 500 mSv and 250 mGy with no shielding—enough to result in ARS symptoms (see Section 3.2 *Deterministic Effects [Nonstochastic Effects, Tissue Reactions]*). Doses are significantly reduced to < 80 mSv and < 40 mGy by even the lightest shield considered (1 g•cm^{-2} of Al alloy). With the heaviest shield (20 g•cm^{-2} of Al alloy), deep space SCR doses are reduced to 16 mSv and 6.5 mGy. Doses are much lower in the atmosphere, and taking the shielding of the vehicle into account is much less important. Without shielding at a 20-km altitude, the doses are a few mSv and mGy. At a 12-km altitude, the lowest dose at high latitude is nearly 0.5 mSv, while equatorial latitudes are well protected.

Table 18. *Influence of Vehicle Shielding on Event Cumulative SCR Doses During the Large Solar Proton Event of September 29, 1989 at Selected Altitudes*

	Vehicle shielding of occupants							
	Al, 0 g×cm^{-2}		Al, 1 g•cm^{-2}		Al, 5 g•cm^{-2}		Al, 20 g•cm^{-2}	
	Effective cutoff rigidity at altitude of 20 km							
Altitude, km	0 GV	16 GV	0 GV	16 GV	0 GV	16 GV	0 GV	16 GV
	Whole-body absorbed dose, mGy							
3	$1.18 \cdot 10^{-3}$	$3.03 \cdot 10^{-5}$	$1.14 \cdot 10^{-3}$	$3.02 \cdot 10^{-5}$	$1.01 \cdot 10^{-3}$	$2.98 \cdot 10^{-5}$	$9.68 \cdot 10^{-4}$	$2.83 \cdot 10^{-5}$
12	$1.42 \cdot 10^{-1}$	$5.50 \cdot 10^{-4}$	$1.40 \cdot 10^{-1}$	$5.48 \cdot 10^{-4}$	$1.35 \cdot 10^{-1}$	$5.40 \cdot 10^{-4}$	$1.21 \cdot 10^{-1}$	$5.08 \cdot 10^{-4}$
20	1.42	$7.78 \cdot 10^{-4}$	1.40	$7.78 \cdot 10^{-4}$	1.32	$7.86 \cdot 10^{-4}$	1.02	$8.09 \cdot 10^{-4}$
100	$1.47 \cdot 10^{2}$	$4.37 \cdot 10^{-4}$	$2.28 \cdot 10^{1}$	$4.51 \cdot 10^{-4}$	$1.03 \cdot 10^{1}$	$5.28 \cdot 10^{-4}$	3.85	$7.44 \cdot 10^{-4}$
500,000	$2.50 \cdot 10^{2}$	$2.50 \cdot 10^{2}$	$3.88 \cdot 10^{1}$	$3.88 \cdot 10^{1}$	$1.75 \cdot 10^{1}$	$1.75 \cdot 10^{1}$	6.55	6.55

[9] An astronomical distance unit equal to the average distance from the Earth to the Sun. Solar modulation decreases with distance from the Sun, so GCR dose rates on a trip to Mars will be somewhat higher than in the Earth's vicinity.

Altitude, km	Vehicle shielding of occupants							
	Al, 0 g×cm^{-2}		Al, 1 g·cm^{-2}		Al, 5 g·cm^{-2}		Al, 20 g·cm^{-2}	
	Effective cutoff rigidity at altitude of 20 km							
	0 GV	16 GV	0 GV	16 GV	0 GV	16 GV	0 GV	16 GV
	ICRP Publication 103 effective dose, mSv							
3	$5.87 \cdot 10^{-3}$	$5.37 \cdot 10^{-5}$	$5.78 \cdot 10^{-3}$	$5.36 \cdot 10^{-5}$	$5.44 \cdot 10^{-3}$	$5.30 \cdot 10^{-5}$	$4.95 \cdot 10^{-3}$	$5.03 \cdot 10^{-5}$
12	$5.60 \cdot 10^{-1}$	$9.21 \cdot 10^{-4}$	$5.55 \cdot 10^{-1}$	$9.20 \cdot 10^{-4}$	$5.39 \cdot 10^{-1}$	$9.11 \cdot 10^{-4}$	$4.92 \cdot 10^{-1}$	$8.75 \cdot 10^{-4}$
20	3.86	$1.29 \cdot 10^{-3}$	3.82	$1.29 \cdot 10^{-3}$	3.65	$1.30 \cdot 10^{-3}$	2.94	$1.35 \cdot 10^{-3}$
100	$2.97 \cdot 10^{2}$	$8.86 \cdot 10^{-2}$	$4.65 \cdot 10^{1}$	$8.90 \cdot 10^{-4}$	$2.20 \cdot 10^{1}$	$1.02 \cdot 10^{-3}$	9.50	$1.36 \cdot 10^{-3}$
500,000	$5.05 \cdot 10^{2}$	$5.05 \cdot 10^{2}$	$7.91 \cdot 10^{1}$	$7.91 \cdot 10^{1}$	$3.75 \cdot 10^{1}$	$3.75 \cdot 10^{1}$	$1.62 \cdot 10^{1}$	$1.62 \cdot 10^{1}$

Note. SCR, solar cosmic radiation; ICRP, International Commission on Radiological Protection.

8.7. Summary

Key points:

- FAA makes flight dose calculation software, CARI-7, freely available to researchers and the public.
- During an SPE, flight doses can be many times higher than normal.
- Radioiodines are the chief gaseous isotopes of concern after nuclear explosions.
- Flying in or above a thunderstorm increases the risk of exposure to X-rays and gamma radiation from TGF.
- While the dose from a TGF could be large, exposure is considered very rare.
- The doses reported in surveys of flights carrying radiopharmaceuticals are quite low—no more than the GCR doses received on a single intercontinental flight.
- Doses to vehicle occupants are expected to be quite low during the rocket-powered and freefall portions of a suborbital space flight.
- GCR doses for space missions are highly dependent on shielding.
- The dose from a single day in deep space can exceed the dose accumulated during a year of commercial flight.

9. COUNTERMEASURES

9.1. Introduction

Basic strategies for radiation protection include limiting time exposed, separation from sources, and use of shielding. These strategies can all be applied in different ways depending on the specific source. Radiation exposure in air and space comes from both external and internal sources. This section discusses the basic strategies for limiting doses during air and space travel.

9.2. Reducing doses from external sources

In aviation and aerospace operations, most exposure comes from external sources (e.g., cargo and GCR). Improving local shielding or moving to a location with better shielding can be effective ways to reduce doses from these sources. Exposures for aircrews are controllable via route optimization, cargo placement, airspeed, and flight timing. Because SPEs cause only short-term increases in dose rates, the timing of a flight is the best way to minimize flight doses from SCR. Careful packing of cargo minimizes dose rates from this source if present. Radiation from lightning and TGFs is minimized by avoiding thunderstorms.

Clouds of radioactive materials, such as those from a reactor leak during a nuclear power plant accident, should also be avoided when possible, both to avoid immediate exposure and eliminate the risk of contamination of the aircraft. While GCR exposure is unavoidable, the total dose can be minimized by optimizing the route selection regarding speed, altitude, and geomagnetic latitude. When optimizing a route to minimize the dose from any or all external sources, speed is an important consideration, given that high speed reduces exposure time. Flying at higher altitude (i.e., reduced shielding from Earth's atmosphere) or higher latitude (i.e., reduced shielding from Earth's magnetic field) can increase GCR and SCR dose rates along the route, but does not always increase flight dose because travel time can be significantly reduced.

Except for suborbital flights, speed is not usually a consideration during space flight mission planning. Doses for astronauts are usually controlled using shielding (as with vehicle design), altitude and latitude control, and mission timing. For suborbital missions and missions in Earth orbit, altitude and latitude selection minimize dosing from GCR, SCR, and trapped radiation in the Van Allen radiation belts. Shielding on human-crewed missions is restricted by mission mass limits, while launch windows restrict mission timing. For multi-year missions such as a trip to Mars, mission planners must consider the possibility of physically debilitating doses from SCR and may choose to accept the risks from increased doses of GCR during solar minimum to offset this risk (Friedberg et al., 2005).

9.3. Reducing doses from internal sources

If an aircraft flies through a cloud of radioactive gasses and/or particles from a reactor accident or nuclear weapon test, or there is a cargo spill, passengers and aircrew may internalize radioactive elements in addition to receiving radiation emanating emitted from the cloud. These elements can enter the body through the skin, via contaminated food, or as inhaled contaminated particles in the air. When radioactive elements enter the body, they can be deposited in tissues or circulate in the blood. This results in doses to tissues as the radioactive elements decay. Doses from this kind of exposure can often be mitigated by proper administration of medicines designed to either speed up the natural removal of the radioactive element from the body or limit its uptake into the most at-risk tissues.

Potassium iodide (KI) blocks iodine uptake by the thyroid gland. It should be taken daily at the doses recommended in Table 19 (p. 39) at the first warning of the possible release of radioactive iodine until the risk of significant inhalation or ingestion of radioactive iodine no longer exists. Potassium iodide protects the thyroid gland for approximately 24 hours. Zanzanico and Becker (2000) indicate treatment is most effective if it begins between 2 days before and approximately 8 hours after inhalation or ingestion of radioactive iodine while starting treatment 16 or more hours after radioactive iodine exposure provides little protection. It probably should not be taken for more than 10 days. After leaving a contaminated area, potassium iodide should be taken for at least another day to allow the kidneys time to eliminate radioactive iodine that is in the blood.

For persons younger than age 20, the risk of thyroid cancer decreases with increase in age at the time of irradiation. There is little risk of thyroid cancer after age 40 (NCRP, 2008). However, if the dose to the thyroid is 200 to 300 Gy or more, the thyroid parenchyma (functional tissue) will be destroyed (FDA, 2001). A person older than age 40 should take potassium iodide only if the predicted dose is >5 Gy to prevent hypothyroidism. Children are much more at risk of exposure than adults. The risk to a child is significant if the dose to the thyroid is ≥ 0.05 Gy.

Table 19. *Recommended Daily Dose of Potassium Iodide, If Radioactive Iodine Has Been Released into the Atmosphere*

Persons at risk	Daily dose of potassium iodide, mg
Pregnant or breastfeeding	130
Age >18 years	130
Age >12 years through 18 years and weight ≥70 kg	130
Age >12 years through 18 years and weight <70 kg	65
Age >3 years through 12 years	65
Age >1 month through 3 years	32
Age newborn through 1 month	16

Note. Adapted from "Risk to the thyroid from ionizing radiation (NCRP Report No. 159)," by the National Council on Radiation Protection and Measurements, 2008.

Radioactive iodine easily crosses the placenta, and the fetal thyroid begins to accumulate iodine at approximately 10 weeks of gestational age (Gusev et al., 2001). After 8 weeks post-conception, administering 60 to 130 mg potassium iodide to the mother within 12 hours of radioactive iodine intake will reduce the uptake of radioactive iodine by the fetal thyroid. Health risks from stable iodine, a component of potassium iodide, include sialadenitis (inflammation of the salivary gland), gastrointestinal disturbances, allergic reactions, and minor rashes. Persons with iodine sensitivity should avoid potassium iodide, as should individuals with dermatitis herpetiformis and hypocomplementemia vasculitis—rare conditions associated with increased risk of iodine hypersensitivity (NCRP, 2008). Because radioactive iodine has a physical half-life of 8.04 days, food affected by radioactive iodine fallout poses a minimal risk if stored 2 months or longer.

Other possibly important radioactive substances that could be released into the atmosphere from a nuclear reactor, detonated nuclear weapon, or dirty bomb, along with the annual allowable levels of intake (ALIs) for U.S. radiation workers, are listed in Table 20.

Table 20. *Nuclear Regulatory Commission Annual ALI[a,b] for Selected Radionuclides*

Isotope	Ingestion, μCi [c]			Inhalation, μCi [c]		
	<10 d	10-100 d	>100 d	<10 d	10-100 d	>100 d
Americium-241		0.8			0.006	
Cesium-137		100			200	
Cobalt-60	----	500	200	----	200	30
Iodine-125		40			60	
Iodine-131		30			50	
Iridium-192		900		300	400	200
Palladium-103		6,000		6,000	4,000	4,000
Phosphorus-32		600		900	400	----
Plutonium-239		0.8		----	0.006	0.02
Radium-226		2			0.6	
Strontium-90		30		20	----	4
Tritium (hydrogen-3)		80,000			80,000	

Isotope	Ingestion, µCi [c]			Inhalation, µCi [c]		
	<10 d	10-100 d	>100 d	<10 d	10-100 d	>100 d
Uranium-233		10		1	0.7	0.04
Uranium-234		10		1	0.7	0.04
Uranium-235		10		1	0.8	0.04
Yttrium-90		400		----	700	600

Note. ALI = allowable levels of intake; d = day.
[a] One ALI gives an effective dose of about 50 mSv. The radiation worker is assumed to be doing light labor while wearing no protective gear.
[b] If more than one isotope is involved, the procedure to find whether the exposure exceeds the intake limit is to divide each intake by its respective ALI and calculate the sum of the resulting fractions. If the sum is >1, the ALI has been exceeded.
[c] The various compounds incorporating these isotopes have different lifetimes in the body. In this table, allowable levels of intake for these isotopes are subdivided into three groups, based on their retention times in the body: < 10 days; 10-100 days; and > 100 days. If there is no specified lifetime, then the allowable level of intake is applicable to all compounds that incorporate that isotope, whatever their lifetime in the body.

Some possible therapies are listed in Table 21 The ALI for each isotope is the intake of that isotope resulting in a committed effective dose approximately equal to 50 mSv, the Nuclear Regulatory Commission annual limit for radiation workers and the FAA recommended limit for any one year (Energy, 2018).

Table 21. *Drugs Used to Treat Persons Contaminated with Radioactive Materials*

Drug	Action
Ammonium chloride	This salt acidifies the patient's blood and is useful for the removal of strontium, especially when combined with intravenous calcium gluconate. Ammonium chloride is given orally, 1 to 2 g, four times per day, for up to 6 consecutive days. While best results occur if given quickly after intake, some effect is seen if used up to two weeks afterward. If used promptly with calcium gluconate, strontium levels can diminish by 40% to 75%. Nausea, vomiting, and gastric irritation are common. Avoid in patients with severe liver disease.
Calcium (oral)	Many oral calcium supplements are available (e.g., Tums®). Generous doses of oral calcium should be beneficial because calcium can interfere with the absorption of the other alkaline earths, such as strontium, barium, and radium and compete with their deposition in bone.
Ca-DTPA (also Zn-DTPA)	This is a powerful and stable chelating agent, used primarily to remove plutonium and americium. It chelates transuranic (Z>92) metals (e.g., plutonium, americium, curium, californium, and neptunium), rare earths (e.g., cerium, yttrium, lanthanum, promethium, and scandium), and some transition metals (e.g., zirconium and niobium). In typical, healthy, nonpregnant adults with healthy bone marrow and renal function, the dose to use is 1 g in 250 ml normal saline or 5% dextrose in water, intravenously over 1 hour. One dose per day should be used, and the dose should *not* be fractionated. Use for several days to one week is safe in most cases. Toxicity is due to the chelation of needed metals, such as Zn and Mn. Toxic effects include nausea, vomiting, chills, diarrhea, fever, pruritus, muscle cramps, and anosmia. In pregnant patients or

Drug	Action
	after a couple of doses, the less toxic Zn-DTPA should be used instead, with the same dose strength and schedule. These agents are best used as quickly as possible after internal contamination. They are effective if given later, but therapy may continue for months or years. These agents are only effective if the metals one wishes to chelate are in ionic form. They are useless for highly insoluble compounds.
Calcium gluconate	Intravenous calcium gluconate is indicated for Sr-90 contamination, and probably Ra-226 contamination. Five ampoules, each containing approximately 500 mg calcium, may be administered in 0.5-L 5% dextrose solution over a 4-hour period daily for 6 consecutive days. It is contraindicated in patients who have a very slow heart rate and those on digoxin preparations or quinidine.
Dimercaprol (British antilewisite, BAL)	This agent effectively chelates mercury, lead, arsenic, gold, bismuth, chromium, and nickel. It is toxic, and about 50% of patients given 6 mg/kg intramuscular injections develop reactions. These include systolic and diastolic hypertension, tachycardia, nausea, vomiting, chest pain, headache, and sterile abscess at the injection site. The dose is ≤ 2.5 mg/kg every 4 hours for 2 days, then twice daily for 1 day, and then every day for day 5 to day 10. It is available in 300-mg vials for deep intramuscular injection use, suspended in peanut oil. Use caution if the patient has a penicillin allergy.
D-Penicillamine	This drug chelates copper, iron, mercury, lead, gold, and possibly other heavy metals. The chelated metals are excreted in the urine. While this drug is relatively nontoxic, it probably has only limited usefulness for radionuclide decorporation, preventing perhaps only 1/3 of the total radiation absorbed dose that would have occurred without treatment. The adult dose is oral 250 mg daily between meals and at bedtime. The dose may be increased to 4 or 5 g daily in divided doses. Use caution if the patient has a penicillin allergy.
Potassium iodide	Useful for blocking radioiodine uptake by the thyroid but needs to be administered within 8 hours of intake for best effectiveness. See Table 19 (p. 41) for dosing information.
Potassium phosphate (and sodium phosphate)	Used to block uptake of radioactive phosphate. K-Phos® Neutral contains 250 mg phosphorus per tablet. Usual adult dose is 1 to 2 tabs, orally 4 times per day, with full glass of water each time, with meals and at bedtime. Pediatric dose (patients aged >4 years) is 1 tab 4 times per day. Contraindicated in patients with hyperphosphatemia, renal insufficiency, and infected phosphate stones.
Propyl-thiouracil	This drug is useful to decrease the thyroid's retention of radioiodine and may be considered if the efficacy window for KI has passed. The adult dose is two 50-mg tabs taken orally 3 times per day for 8 days.
Prussian blue	This drug is indicated for decorporation of cesium, thallium, and rubidium and is highly effective for Cs-137 contamination. It is benign, except for causing occasional constipation. Turns stool blue. Usual dose starts at two 0.5-g capsules taken orally, 3 times per day for up to 3 weeks or longer as required. Doses up to 10 to 12 g/day for significantly contaminated adults may be used.

Drug	Action
Sodium alginate	Oral alginates efficiently bind strontium in the gastrointestinal tract, preventing absorption. The dose is a 10-g powder in a 30 cc vial, administered orally by ingesting the suspension in water.
Sodium bicarbonate	Used to protect kidneys from uranium deposition after uranium intake. It can be administered orally or intravenously, as needed to maintain alkaline urine. The intravenous formulation is 8.9% in 100 or 200 cc vials.
Sodium phosphate	See potassium phosphate. Also used for radioactive phosphate decorporation.
Zn-DTPA	See Ca-DTPA.

Note. Adapted from "Administration of decorporation drugs to treat internal radionuclide contamination: medical emergency response to radiologic incidents" by C. S. Marcus, 2004, *RSO Magazine*, 9(5), pp. 9-15.

As was done by the Japanese government during the Fukushima Daiichi reactor incident, aircraft not performing emergency-related flights should be re-routed around highly contaminated airspaces to the extent possible while considering other safety concerns. Flying through radioactively contaminated air space should be minimized. If crewmembers are exposed to multiple isotopes, the ALI for each isotope should be reduced to keep the total committed effective dose at or below the FAA-recommended limit (50 mSv from all occupational sources in any one year, with a 5-year average of 20 mSv per year) from all occupational sources. A pregnant crewmember should avoid any exposure that results in the dose to the conceptus exceeding recommended limits (0.5 mSv in any month and 1 mSv total during her declared pregnancy).

As previously noted, federal shipping regulations require the maximum dose rate from radioactive materials on board the aircraft not exceed 0.02 mSv per hour in any occupied space. Additionally, an aircraft contaminated or suspected of contamination with radioactive materials must be removed from service, and it cannot be returned to service until the dose rate from radioactive contaminants at every accessible surface is <0.005 mSv per hour and there is no significant removable surface contamination.

9.4. Summary

Key points:

- In aviation and aerospace operations, most exposure comes from external sources.
- The timing of a flight is the best way to minimize the dose from SCR.
- Careful packing of cargo minimizes dose rates from this source if present.
- Radiation from lightning and TGFs is minimized by avoiding thunderstorms.
- GCR exposure is unavoidable but controllable.
- Total flight doses can be minimized by optimizing the route selection factoring for speed, altitude, geomagnetic latitude, and flight timing.
- Doses for astronauts are usually controlled using shielding (vehicle design), altitude and latitude control, and mission timing.
- Shielding in aerospace vehicles is restricted by mass limits.
- Space mission timing is restricted by launch windows.
- Flying through radioactively contaminated air space should be minimized.

- Avoiding clouds of radioactive materials reduces the total flight dose and eliminates the risk of contamination of the aircraft.
- Doses from internal exposures can often be reduced by proper dosing of medicines.

10. CONCLUSION

Ionizing radiation is a known carcinogen and can be lethal at sufficiently high exposure levels. Relative to terrestrial travelers, those in aerospace vehicles may face increased exposure to ionizing radiation because of the environments in which their vehicles operate. At doses likely to be incurred working in aerospace environments, control of occupational exposures can reduce risks, leading to longer and better-quality lives for aircrews (and passengers). GCR exposure can be controlled by optimizing flight paths (altitude and location). Flying higher and at higher latitude does not always increase exposure because travel time can be significantly reduced. SCR exposures, while currently still unpredictable, can be reduced by remaining aware of space weather. The most effective means of avoiding SCR are altitude reduction, route selections (closer to the geomagnetic equator), and delaying flights until dose rates during events have at least peaked. Risks can be attenuated by minimizing exposures when possible. Accidents like cargo spills (or events like those at Chernobyl), and natural disasters (e.g., Fukushima Daiichi) can lead to unexpected exposure situations. Efforts should focus on reducing the occurrence of accidents and the potential impacts when accidents occur. The hazards of flying through and near thunderstorms are well known; possible exposure to ionizing radiation from a TGF is just one more reason to avoid flying in these conditions when possible.

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