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What Aircrews Should Know About Their Occupational Exposure to Ionizing Radiation, 2026 Edition

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12. Abstract

Through advisory materials such as this report, AC 120-61 and its successors, resources offered from its Radiobiology Services website, and other related work, the FAA assists and advises those seeking to understand and minimize the hazards associated with ionizing radiation sources encountered in aviation, including recommendation of occupational exposure limits for aircrews and providing computer software for estimating the amounts of solar and galactic cosmic radiation received on flights. This report updates report DOT/FAA/AM-03/16 and is intended as an introductory briefing on the topic of occupational exposure to in-flight ionizing radiation in the form of a series of questions and answers. Air carrier crewmembers and others who regularly fly, while not classified in the U.S. as radiation workers, are considered occupationally exposed to ionizing radiation. The occupational exposures come from both natural and technological sources. The most consistent source of this exposure is naturally occurring galactic cosmic radiation, which increases as altitude increases and with increasing proximity to either geomagnetic pole. On very infrequent occasions, the Sun and other sources also contribute significantly to the ionizing radiation received during air travel. At the low doses and dose rates typically encountered in aviation, the principal health concern is not acute radiation induced injury but rather is the small increases in lifetime risks of radiation-induced diseases such as cancers and genetic defects in future generations.

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List of Abbreviations

Acronym	Abbreviation Explained
AC	Advisory Circular
ACGIH	American Conference of Governmental Industrial Hygienists
CAMI	Civil Aerospace Medical Institute
CARI	Civil Aeromedical Research Institute (an older acronym for CAMI) and also the name of cosmic radiation flight dose calculation software originally developed by FAA scientists working at CAMI and their collaborators.
FTE	Full time employee
FAA	Federal Aviation Administration
GCR	Galactic cosmic radiation
NCRP	National Council on Radiation Protection and Measurements
NOAA	National Oceanic and Atmospheric Administration
TGF	Transient gamma-ray flash
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

Executive Summary

Aircrews and others who regularly fly, while not classified in the U.S. as radiation workers, are formally recognized as being occupationally exposed to ionizing radiation. In a 1987 presidential document, Radiation Protection Guidance to Federal Agencies for Occupational Exposure, it is recommended that individuals who are occupationally exposed to ionizing radiation and their managers receive instruction on possible health effects associated with such exposure and on basic ionizing radiation protection principles (1). The National Academies of Science Engineering and Medicine repeated this recommendation in their 2026 report (2). In 1994, the Federal Aviation Administration (FAA) formally recognized that aircrews are occupationally exposed to ionizing radiation, recommended that crewmembers be informed about their radiation exposure and associated health risks, and that crewmembers be assisted in making informed decisions regarding their work environment (3).

This report updates DOT/FAA/AM-03/16, an introductory briefing on occupational exposure to in-flight ionizing radiation (4). The briefing addresses the radiation safety-related topics recommended in AC 120-61 (3) using a series of questions and answers, providing introductory information for each of the recommended topics:

a. Types and amounts of ionizing radiation received during air travel, as well as comparisons with other sources, such as radon exposure in the home and medical x-rays;

b. Variables affecting the amount of ionizing radiation exposure in flight (such as altitude, latitude, and solar flares);

c. Guidelines regarding exposure to ionizing radiation, including recommended limits for workers and the general public;

d. The risks to crewmembers and fetuses associated with exposure to ionizing cosmic radiation. These should include: (1) The health effects of ionizing radiation at air carrier flight altitudes (expressed in likelihood of health problems such as cancer, genetic defects, or birth defects); (2) Uncertainties about effects of low doses of radiation; and (3) Comparison of health risks from galactic radiation exposure with other health risks.

e. Special considerations during pregnancy, including: (1) the importance of early recognition and prompt reporting of a pregnancy to management; (2) the voluntary nature of this disclosure; and (3) employee and management responsibility to ensure that exposure of the unborn child does not exceed recommended limits;

f. Risk management, including: (1) How changes in amount or type of flight assignments alters estimated risk; (2) How changes in amount or type of flight assignments can affect proximity to recommended limits; and (3) How crewmembers may obtain estimates of the amounts of cosmic radiation received during flight segments, such as appropriate monitoring devices and/or a computer program;

g. Radioactive material shipments as sources of ionizing radiation exposure;

h. Any other subjects which the air carrier believes would improve crewmembers' knowledge of exposure to ionizing radiation.

Multiple questions are used to address more complex topics. Further information on these topics is offered elsewhere by the FAA in other resources and advisory materials such as the offerings from the FAA Radiobiology Services Website (5) and related works. The questions and answers in this document address the topics in an introductory manner, with some examples where it could be helpful without adding significant length.

Questions and Answers

Q1. What is ionizing radiation?

Ionizing radiation refers to electromagnetic radiations and subatomic particles that, when interacting with an atom, can directly or indirectly cause an atom to lose an electron or disrupt its nucleus. Examples of ionizing radiation are X-rays, gamma rays, neutrons, protons, electrons, and positrons. Ionizing radiation is a normal part of our natural environment and there are many natural sources such as radiation from decay of naturally radioactive atoms, nuclear reactions, thunderstorms, solar storms, and supernova explosions, among others.

Table 1 shows average annual doses of ionizing radiation from natural sources for someone living in the United States. We are exposed to natural ionizing radiation from the ground and building materials, from the air we breathe, and even from outer space. In the late 19th century we began to learn how to create and manipulate ionizing radiation. Now, over 100 years later, we commonly use ionizing radiation in diagnostic and therapeutic medicine, as well as a wide variety of other industries.

Table 1
*Average Annual Doses of Ionizing Radiation from Natural Sources Received by a Member of the Population of the United States (**6**).*

Source	Effective dose, millisieverts (% of total)
COSMIC RADIATION [1]	0.33 (11%)
RADIOACTIVE ATOMS THAT DECAY IN THE GROUND [2]	0.21 (7%)
RADIOACTIVE ATOMS THAT DECAY IN THE BODY [3]	0.29 (9%)
RADIOACTIVE ATOMS THAT DECAY IN THE AIR [4]	2.28 (73%)
TOTAL	**3.11 (100%)**
[1] Almost entirely galactic cosmic radiation from supernovae and other energetic astronomical sources. This includes 0.1 millisievert from air travel. [2] Primarily the decay of naturally present uranium and thorium. [3] Primarily the decay of natural abundant radioactive potassium. [4] Radon gas and its decay products (a gaseous byproduct of uranium and thorium decay).	

Natural sources are essentially everywhere. A radioactive atom is one that will, at a random time in the future, naturally emit ionizing radiation. There are many naturally occurring radioactive versions of common elements such as carbon, potassium, iodine, etc. These common elements are part of life's chemistry. Thus, radioactive substances are always present throughout the body. They surround us and are part of us (see also: https://www.epa.gov/radiation/radiation-sources-and-doses).

Q2. How is ionizing radiation measured?

The basic measurement unit of ionizing radiation exposure is the absorbed dose. For any given volume, it is the energy deposited in the volume by the radiation divided by the mass of that volume (body, heart, tumor, etc.). In the international "SI" system (metric system), the name of the unit is the gray (Gy). An older unit that is still sometimes used is the rad (1 gray = 100 rad).

Doses typically encountered in aviation (millionths to thousandths of 1 gray per year) are too small to cause the effects commonly known as radiation sickness. The greatest concern is future health effects from improperly repaired, non-lethal cellular damage. The effects cannot be accurately estimated just from the absorbed dose because of the biological complexity. Living matter is a highly organized collection of chemicals and the chemistry of life includes self-repairing systems. Different kinds of ionizing radiation cause different damage patterns. Different tissues respond to those damages in different ways. Even cell maturity and rate of irradiation matter. Thus, dose calculation techniques have been developed for use in radiation protection that include adjustments for many of these biological factors. When considering potential harmful health consequences from exposure to ionizing radiation, radiation dose is usually expressed in terms of effective dose in units called sieverts (Sv) (7-9). Effective dose calculations are weighted to allow comparisons of estimated harm from different exposures. When specific targets (or health outcomes) are considered such as a specific organ or a conceptus (any stage of prenatal development from the fertilized egg to birth) the weighted absorbed dose is given other names such as equivalent dose, dose equivalent, or gray-equivalent depending on the outcome being modeled and the methods used to weight the absorbed dose used in the calculation. Many of these also use sievert as the unit name.

1 sievert = 1000 millisieverts (mSv) = 1,000,000 microsieverts

The rem is an older unit sometimes encountered in regulations and guidance documents. Like the sievert, it is used to express potential harm from ionizing radiation.

100 rem = 1 sievert

Depending on the type of radiation and target, a one gray exposure could be less than one sievert or be many sieverts (for further information on dose definitions see Ref. 8).

Q3. How uncertain are the calculations of health effects from measured doses?

Our knowledge of population-level future health effects is based on long-term studies following exposed survivor populations of events such as the atomic bombs dropped in World War Two, nuclear plant accidents, cancer radiotherapy, and other sources such as studies on animals. The data at high doses (at and above a few hundred millisieverts) has very good statistical power and health effect projections are very reliable. At doses below 100 mSv, there is still considerable debate as to how to best account for the influences of dose rate and radiation type on many disease outcomes. Expert committees consistently suggest using a reducing factor of 1.5 or 2 to adjust for the added cellular self-repair and immune system boost that is observed in very low dose and dose rate exposures when extrapolating effects from the results of studies in which the dose or dose rate was high, rather than simple linear extrapolation or other models (9-13). Accordingly, the risk coefficients used to estimate cardiovascular and cancer-related risks incurred from accumulated flight doses in this report have been reduced by a factor of 2 prior to use in calculations. Researchers hope to improve this uncertainty with new data from ongoing and planned studies of larger populations at lower doses and dose rates.

Q4. What are the recommended limits of occupational exposure to ionizing radiation for aircrews?

The FAA-recommended limit for an aircrew member is a 5-year average effective dose of 20 millisieverts per year, with no more than 50 mSv in a single year. For pregnant crewmembers, a limit of 1 mSv for the pregnancy (once declared to the employer) and no more than 0.5 mSv in any month are recommended to protect the developing conceptus. These limits are consistent with national and international guidance published by expert panels such as the U.S. National Council on Radiation Protection and Measurements (NCRP), the American Conference of Governmental Industrial Hygienists (ACGIH), and the International Commission on Radiological Protection (ICRP) (9,11,12). A deeper discussion of the limits recommended during pregnancy can be found in the answer to Question 12.

Q5. What types and amounts of ionizing radiation are received during air travel?

The ionizing radiation environment at commercial jet cruising altitudes (and higher) is significantly different from the environment at and near the surface of the Earth. Just as more radon is present in an environment rich in uranium or thorium, such as an underground mine, air travel takes place in an environment naturally rich in cosmic radiation. In a 2022 publication, The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated that crewmembers are one of the most occupationally exposed employee groups, receiving about 2.7 mSv per year on average (13).

Galactic cosmic radiation: This is the only significant occupational source of ionizing radiation for crew and passengers on almost every flight. The gases of Earth's atmosphere absorb much of the radiation from outer space before it can reach the ground. This shielding effect depends primarily on how much atmosphere is above the aircraft. At 30,000 ft. about 30% of the shield is above the aircraft. At today's passenger and business jet cruising altitudes, galactic cosmic radiation is almost always the most significant source of ionizing radiation (more on galactic cosmic radiation at:

https://www.swpc.noaa.gov/phenomena/galactic-cosmic-rays).

Other sources can significantly contribute to the annual dose, but this is very rare. The most likely of these intermittent sources are: solar cosmic radiation, charge movements in thunder clouds, radioactive cargoes, and nuclear contamination (accidental or deliberate). On average, these sources each contribute less than 1% of the expected annual galactic cosmic radiation dose to a crewmember, but (very rarely) they may contribute more than a typical annual dose from galactic cosmic radiation in a single flight.

Solar cosmic radiation: Occasionally a disturbance in the Sun's atmosphere (solar flare, coronal mass ejection) leads to a surge of ionizing radiation moving away from the Sun with sufficient energy to penetrate the Earth's magnetic field and enter the atmosphere. The particles are called solar cosmic radiation. Solar cosmic radiation interacts with our atmosphere in the same way as galactic cosmic radiation. The result is that for varying amounts of time air travelers are exposed to both ionizing radiation from the Sun and galactic cosmic radiation. See Question 6 for more information on solar cosmic radiation.

Rapid charge movements around thunderstorms: Charge movements within and around thunderstorms can generate ionizing radiation in the form of X-rays, gamma-ray glows, neutron glows and terrestrial gamma-ray flashes (TGFs). While aircraft avoid direct flight through thunderstorms when possible, a commercial aircraft is struck by lightning about once every 3000 flight hours, on average. Lightning is sometimes preceded by gamma-ray glows. The ionizing radiation spectra associated with these have been measured, and dose estimates are in the nanosievert (1 billionth of a sievert) to microsievert range because of the short durations of these phenomena. They can be safely neglected when compared with galactic cosmic radiation. TGFs are possible exceptions. Exposure to a single TGF near its origin could result in a dose of tens of millisieverts at close range, but dose falls rapidly as distance increases from the source region and doses that large remain theoretical (14). However, TGFs are rare (the current estimate is an average of per thunderstorm on average, but many thunderstorms do not produce them at all, while others produce multiple TGFs, making study difficult). TGF frequency is poorly known with estimates at 1000 to 20,000 times lower than lightning.

Irradiated passengers and cargo shipments: Persons who have recently received radiotherapy can be a source of exposure to others nearby, depending on the type of treatment. Under current federal regulations, clinicians are required to provide patients who are given those treatments with guidance on how to limit doses to bystanders (15). Aircraft sometimes carry shipments of radioactive cargo. U.S. and U.K. based studies suggest 0.13 mSv per year or less from radioactive cargo, even for crewmembers based in cities that regularly ship radiopharmaceuticals (16-19). Cargo shipping incidents with doses to crewmembers that exceed recommended limits have not occurred since regulations and practices were significantly improved following an incident in 1974 (20).

Contamination: Nuclear power plant accidents and nuclear weapons detonations can release radioactive atoms into the atmosphere. Once released, radioactive gases and dust travel downwind and can contaminate large areas to some degree. Aircraft flying through the airborne radioactive material become contaminated and occupants are exposed. Most of these materials decay within days into non-radioactive forms, but some remain radioactive for decades. Doses to crew and passengers are unique to each aircraft and event, and while flying directly through a bomb plume can lead to doses over 200 mSv, calculated passenger doses on commercial aircraft flying through dispersed plumes from tests in the south pacific were estimated to be negligible in comparison to galactic cosmic radiation on those flights (21). In the absence of any recent above-ground nuclear weapons detonations or any recent nuclear power plant accidents, this source can be safely neglected when calculating dose estimates for crewmembers.

Q6. How can an airline minimize the risk of aircraft occupants being exposed to excessive amounts of ionizing radiation from the Sun?

The FAA operates a solar radiation alert system (22). Alert messages are transmitted to subscribers of the NOAA Weather Wire Service. This system provides regular updates of calculated solar radiation dose rates during periods of unusually intense solar cosmic radiation once solar radiation dose rates for 3 consecutive 5-minute periods exceed 20 mSv per hour at 70,000 ft. at any location worldwide. Accompanying an alert is a message with estimates of radiation levels at altitudes from 20,000 ft to 70,000 ft, at specified high latitudes (see map at:

www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology.)

For both solar and galactic cosmic radiation, there are 3 basic dose reduction strategies: fly faster, fly at lower altitude, and fly closer to the equator. The best choice for any particular event depends on the incoming solar cosmic radiation, aircraft type, location, and available alternative flight-routing options. In polar regions, altitude reduction is the quickest way to reduce dose rates. However, a slower airspeed at the reduced altitude may result in a similar (or higher) total flight dose. Travelling at lower geomagnetic latitudes reduces solar cosmic radiation dose rates more than galactic cosmic radiation dose rates and can significantly reduce dose rates. Under normal geomagnetic conditions, flights at middle and low latitudes are well protected from solar energetic particles by Earth's magnetic field.

Q7. What else about radiation from the Sun is of interest to aircrews?

Much of the ionizing radiation that leaves the Sun to eventually arrive at Earth does not follow a straight path from the Sun to the Earth but rather is guided by interplanetary magnetic fields. When these particles reach the vicinity of Earth their paths are further bent and twisted in Earth's magnetic field. Thus, the ionizing radiation particles from the Sun that penetrate the Earth's atmosphere can enter coming from many directions. Even when the ionizing radiation levels on the day and night sides of the Earth start out appreciably different, they become practically the same after a few hours.

Long-distance communications are sometimes disrupted because of increased ionization of the Earth's upper atmosphere by X-rays, ultraviolet radiation, or protons from the Sun. This often occurs without affecting ionizing radiation levels at flight altitudes.

The Aurora Borealis and Aurora Australis (northern and southern lights) are colorful displays resulting from interaction of charged particles with air in the upper atmosphere. They are not a hazard to air travelers.

Q8. How can aircrew members reduce their occupational exposure to ionizing radiation without working fewer hours?

As mentioned previously, for both solar and galactic cosmic radiation, there are 3 basic dose reduction strategies: fly faster, fly at lower altitude, and fly closer to the equator. Flying short flights at low latitudes takes advantage of two of these strategies. Short flights are flown at lower altitudes than long-distance flights, hence there is more radiation shielding during short flights because of the greater amount of air above the aircraft. If two flights are flown at the same altitude for the same length of time, but at different geographic latitudes, less radiation will usually be received on the lower-latitude flight because of the greater amount of radiation shielding provided by the Earth's magnetic field. This shielding is maximum along the geomagnetic equator (close to the geographic equator) and gradually decreases to zero as one goes north or south (7). For example, at an altitude of 35,000 ft., the galactic cosmic radiation level over Anchorage, AK is about double that over Miami, FL and roughly triple that over Guam.

Q9. How can an aircrew member find out the effective dose of ionizing radiation received on a flight?

An FAA-developed web-based flight dose calculator can be reached by a link from the FAA Radiobiology Services website:

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

The calculator requires no download and as of July 2026 is based on CARI-6 software. It calculates the effective dose of galactic cosmic radiation received by a crewmember while flying the most direct route (the shortest distance, i.e., a "great-circle" route) between two airports.

Four versions of the CARI program, CARI-6, CARI-6M, and the newer CARI-7 and CARI-7A are available for download from the Radiobiology Services website (see Question 6). These downloadable versions of CARI provide more options than the interactive version, including allowing the user to store and process multiple flights, add airports, use custom flight paths (except for CARI-6), and calculate dose rates at user-specified locations in the atmosphere. CARI-7 is recommended for most users as it will run on most modern personal computers and will look most familiar to users of earlier versions of CARI.

Q10. What health concerns are associated with occupational exposures to ionizing radiation?

At the radiation doses received by aircrews, an increased risk of cancer is the most common health concern (7). The dose and dose rate adjusted risk of radiation-induced cancers following exposure in a working age population is estimated to be 12 in 100,000 per mSv. Thus, the risk of cancer associated with a 30-year career of exposure at 3 mSv per year (90 mSv total career dose) would be:

90 mSv x 12 in 100,000 / mSv = 1080 in 100,000 = 1.1 in 100 (i.e., 1.1%).

In the U.S. population, about 23% of deaths per year are from cancers and the number of new cases is approximately 3 times the number of fatalities (www.cdc.gov/cancer/data/index.html).

Another concern is the possibility of genetic defects in future offspring after exposure to ionizing radiation. The estimated risk of serious defects appearing in the next two generations is 1.2 in 1,000,000 per mSv. Thus, after 5 years, a crewmember's occupational exposure to ionizing radiation, again assuming occupational exposure at the rate of 3 mSv per year, would be estimated to lead to a risk in the next 2 generations of descendants of:

5 years x 3 mSv per year x 1.2 in 1,000,000 per mSv = 18 in 1,000,000 (i.e., 0.0018%).

Future cardiovascular disease may also be an issue, though data are more limited. The evidence from breast cancer radiotherapy patients suggests a risk of 3.7% per gray (adjusted for low dose rate as discussed in Q3) (23). Assuming a 1:1 conversion from gray to sievert as a rough estimate and an exposure of 90 mSv (30 years at 3 mSv per year) as in the earlier example, we can estimate risk from occupational exposure to ionizing radiation as an aircrew member after a 30-year career as:

90 mSv x 3.7 in 100 per Gy x 1 Gy per Sv x 1 Sv / 1000 mSv (i.e., 0.33%).

It is important to note that these risks estimates come from studies of populations. Their use as individual estimates is not likely to be accurate.

Q11. How does ionizing radiation encountered in aviation compare with other sources, such as radon exposure in the home and medical x-rays?

The ionizing radiation dose to a passenger or crewmember of an aircraft over the course of a flight can vary enormously. Flight doses of galactic cosmic radiation vary from less than 0.2 microsievert for a commuter flight between close airports such as Houston, TX to Austin, TX to more than 100 microsieverts for some transcontinental flights such as New York, NY, U.S.A. to Tokyo, Japan. Table 2 shows estimated annual average effective doses for crewmembers using U.S. population averages for other sources. Medically related (excluding cancer treatments) and radon exposures vary considerably depending on life events and location. The data shown are population level estimates.

Table 2

*Average Annual Doses of Ionizing Radiation from Natural and Medical Sources Received by U.S. Aircrew Members (**6, 13**).*

Source	Effective dose, millisieverts
DECAY OF NATURALLY OCCURRING RADIOACTIVE ATOMS IN THE GROUND AND IN THE BODY [1]	0.5
DECAY OF RADIOACTIVE GASES [2]	2.3
CREWMEMBER OCCUPATIONAL RADIATION EXPOSURE [3]	2.7
MEDICAL IMAGING AND NUCLEAR MEDICINE [4,5]	3.0
TOTAL	**8.5**
[1] Primarily from decay of radioactive isotopes of uranium, thorium and potassium. [2] Almost entirely radon and its decay products (radon is a gaseous byproduct of uranium and thorium decay). [3] Almost entirely galactic cosmic radiation. From supernovae and other energetic astronomical sources. [4] Radiography, fluoroscopy, CT. [5] Excludes cancer treatments.	

Q12. Are there any special considerations during pregnancy?

Risks: The risk of radiation-induced harm is greater for a child during prenatal development than during later stages of life—e.g., fatal cancer risk is estimated at 1 in 10,000 (0.01%) per millisievert during prenatal development. The risks depend on the precise stage of development at the time of irradiation and the radiation dose (8). During the first three weeks of pregnancy, before cells specialize, cell killing is an important risk—on day one, before there are multiple cells, the passing of a single ionizing radiation particle through the cell in the wrong way can result in prenatal death (like bullets hitting an adult, only some hits are fatal). The risk of this kind of death has been estimated at 8 in 10,000 per millisievert and declines extremely rapidly as the cell population increases, such that after the first couple of days, the probability of a low dose of radiation killing every cell is insignificant (24). However, there is some evidence for a notable risk of spontaneous abortion correlated with cosmic radiation exposure during pregnancy, which could be spontaneous abortion from a known or unknown (if early enough) pregnancy, as well as some evidence of risk of preterm birth (25-29).

For exposures before organ specialization starts, even a dose as high as 20 millisieverts has not been found to result in radiation-induced structural abnormalities or mental retardation (8). Studies of irradiation after specialization begins have found evidence of DNA damage, chromosomal aberrations, growth deformities, and cognitive defects. While DNA and chromosome damage can occur at any dose, deformities and cognitive defects could not be attributed to radiation exposure at equivalent doses below 100 mSv.

Limits: It is important to recognize that under U.S. law (30-32), an employer may not limit, classify, or segregate an employee in any way that deprives or tends to deprive him or her of employment opportunities or otherwise affects the status of an employee because of sex or pregnancy and her declaration of pregnancy is optional. Once she reports her pregnancy to management, they should work together to limit fetal exposure to an equivalent dose of 1 millisievert, with no more than 0.5 millisievert in any month (7,9,11-12). Because of the highly penetrating nature of galactic cosmic radiation, the effective dose to the mother is a good estimate of the equivalent dose to the developing child (7). The intent of the lower occupational dose limits for the mother during pregnancy is to provide the child developing in utero with protection equivalent to other members of the public.

Q13. How do the risks from radiation exposure compare with other risks in the aircraft and in other industries?

There are other occupational safety concerns for aircrews in addition to radiation safety. Prominent among these are: circadian rhythm disruptions due to irregular hours, jet lag, and long shifts; cabin pressure changes; musculoskeletal issues from lifting, etc.; and disease transmission risks from being confined with passengers and other crewmembers. Radiation and problems from pressure changes are among the best studied. While skin and female breast cancer rates are higher in aircrews, studies are generally inconclusive as to causality (UV, ionizing radiation and circadian disruptions are all known risk factors). Examples of other issues include ear issues from cabin pressure changes, which are commonly reported during the first few years of employment, as well as issues with the unusually dry and thin air in the cabin during the cruise.

While commercial passenger air travel continues to be extremely safe, segments of the aircrew population have shown increased death, illness, and injury rates relative to many other professions. The Bureau of Labor Statistics (www.bls.gov) reports professional pilots and flight engineers (combined Part 121 and 135) consistently as one of its top 10 most dangerous job categories (e.g., 36.7 job-related accidental deaths vs 3.3 per 100,000 FTEs for all private workers in 2024) and also reports flight attendants average many more occurrences of at least one day away from work due to illness and injury per FTE than the national private workforce average (e.g., 486.2 vs 89.7 per 10,000 FTEs in 2018).

We can calculate an approximate increased lifetime risk of fatal cancer from occupational exposure to ionizing radiation using the assumptions for calculations from Question 11. The dose and dose rate adjusted lifetime risk of radiation induced fatal cancers following exposure in a working age population is estimated to be 4 in 100,000 per mSv. Thus, the incurred future risk of cancer from 1 year of occupational radiation exposure can be estimated to be:

3 mSv $\times$ 4 future fatal cancers in 100,000 persons per mSv = 12 per 100,000 (i.e., 0.012%).

For cardiovascular diseases the added lifetime risk estimate would be similar. It is also important to keep in mind that there are large uncertainties in these estimates at very low dose rates such as those encountered in aviation.

Finally, it is important to note that, like other cancer-causing agents, radiation-induced cancers and other effects do not usually occur until many years after the occupational exposures (unless dose rates or doses are high).

Concluding Remarks

For individual crewmembers, one cannot exclude the possibility of harm from occupational exposure to radiation at the doses likely to be received during a career of flying, but it remains very difficult if not impossible to establish that an abnormality or disease in a particular individual resulted from such exposure.

The radiation-induced health risk estimates for aircrews and their progeny used here are derived from dose-effect relationships recommended by national and international organizations recognized for their expertise in evaluating radiation effects. Considerable uncertainty exists in the estimates because the original data are primarily from studies on individuals exposed to ionizing radiation from nuclear and medical sources at much higher doses and dose rates. These radiations are generally of much lower energy than the galactic cosmic radiation components that make up most of a crewmember's exposure. While there has been progress in risk modeling since the publication of DOT/FAA/AM-03/16 (4), the very low dose rates in aviation remain a great source of uncertainty and disease latencies add further complexity to modelling. Thus, epidemiological studies involving large populations of crewmembers are important if future risk estimates for crewmembers are to be improved.

With regard to occupational exposure to radiation during pregnancy, the FAA recommends that a pregnant crewmember and management work together to ensure that exposure of the conceptus does not exceed limits recommended by national and international radiation safety advisory bodies such as the U.S. National Council on Radiation Protection and Measurements, American Conference of Governmental Industrial Hygienists, and the International Commission on Radiological Protection.

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