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Occupational Exposure to Ionizing Radiation for Crews of Suborbital Spacecraft: Questions & Answers

Kyle Copeland
Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

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16. Abstract

Crewmembers on future suborbital commercial spaceflights will be occupationally exposed to ionizing radiation, principally from galactic cosmic radiation. On infrequent occasions, the sun or thunderstorms may also contribute significantly to the ionizing radiation received during such travel. Altitudes of suborbital spacecraft flights are too low for trapped radiation in the Van Allen belts to be of concern. Ionizing radiation consists of subatomic particles that, on interacting with an atom, can cause the atom to lose one or more orbital electrons or even break apart its nucleus. Such events in body tissues may lead to health problems.

For suborbital spaceflight crews and their children irradiated in utero, the principal health concern from occupational radiation exposure is a small increase in the lifetime risk of fatal cancer. Both of these groups also risk passing genetic defects to future generations.

Other health risks are also associated with exposure to low levels of ionizing radiation. The FAA recommends occupational ionizing radiation exposure limits for crewmembers and is developing computer software for estimating the amount of ionizing radiation received on a flight.

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Occupational Exposure to Ionizing Radiation for Crews of Suborbital Spacecraft: Questions & Answers

INTRODUCTION

In 1994, the Federal Aviation Administration (FAA) formally recognized that air-carrier aircrews are occupationally exposed to ionizing radiation and recommended that they be informed about their radiation exposure and associated health risks and that they be assisted in making informed decisions with regard to their work environment (1). Crews on commercial spaceflights will be occupationally exposed to ionizing radiation from the same sources and incur the same risks. In fact, depending on the flight profile, for most of the flight they will likely be acting as aircrew members. The following questions and answers address subjects that suborbital flight crews should be familiar with concerning their occupational exposure to ionizing radiation.

1. What is ionizing radiation?

Ionizing radiation refers to subatomic particles that, on interacting with an atom, can directly or indirectly cause the atom to lose an electron or even break apart its nucleus. Such occurrences in tissues and organs may lead to health problems. Examples of ionizing radiation are neutrons, protons, electrons, positrons, and photons (X-rays and gamma rays). Ionizing radiation is a normal part of our environment (Table 1). Substances that emit ionizing radiation are present in every cell in the body. We are exposed to ionizing radiation emanating from the ground and building materials.

2. How is ionizing radiation measured?

Harm from ionizing radiation is called a *stochastic effect* if the probability (risk)—but not the severity of the effect—is a function of the *effective dose* (see question 3). It is generally accepted that there is no minimum dose required (called a *threshold dose*) to induce a stochastic effect (3). This is because the mechanism for stochastic effects is cells repairing themselves incorrectly. For example, a single badly repaired cell can eventually lead to cancer. Stochastic effects also include 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 initiated by other causes, and it cannot be predicted which individuals in an irradiated group will develop cancer (4). Regardless of when in a person's lifetime the causative dose is received, radiation-induced tumors tend to appear when tumors of the same type occur in the un-irradiated population (3).

Table 1. Average Annual Doses of Ionizing Radiation From Background Sources Received by a Member of the Population of the United States (2).

Source	Effective dose, millisieverts (% of total)
Cosmic radiation	0.33 (11%)
Radioactive material in the ground	0.21 (7%)
Inhaled radon (and thoron)	2.28 (73%)
Radioactive material in body tissues	0.29 (9%)
Total from background sources	3.11 (100%)

When considering potential harmful health consequences for individuals exposed to low levels of ionizing radiation, radiation dose is expressed in terms of effective dose (3). If the radiation is to a *conceptus* (any stage of prenatal development from the fertilized egg to birth), dose is expressed in terms of *equivalent dose* (3). The unit of both effective dose and equivalent dose is the *sievert* (Sv), which is a measure of potential harm from ionizing radiation. The *rem* is an older unit sometimes used to express potential harm from ionizing radiation.

1 sievert (Sv) = 1000 millisieverts (mSv) = 100 rem

1 millisievert (mSv) = 1000 microsieverts (μSv) =100 millirem (mrem)

Harm from ionizing radiation is called *deterministic* if the harm increases with radiation dose above a threshold dose (5). For deterministic effects, the dose is measured in *gray-equivalent* (Gy-Eq; for many radiations 1 Gy-Eq = 1 Sv, but because of the different factors used to modify the *absorbed dose* (mean energy deposited per unit mass), effective dose and equivalent dose are always greater than gray-equivalent). Unlike stochastic effects, which result from cells being repaired improperly, this type of harm is based on cell deaths. It requires a much larger dose to generate a significant effect, since 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. The symptoms and time to onset of symptoms, and their severity and duration, generally depend on the total dose and the rate of exposure. The threshold dose will usually be higher if the exposure time required to reach the dose is more than a few hours (6). Also, there are significant differences among individuals in resistance to effects.

Deterministic effects can occur soon (sometimes minutes) after radiation exposure, if the dose is sufficiently high and delivered at a high rate.

Early deterministic effects of ionizing radiation are called *Acute Radiation Syndrome* (ARS). Nausea, fatigue, vomiting, and diarrhea occur within minutes to days after exposure; they may come and go for several days, unless the dose is totally incapacitating or lethal before then. The irradiated individual usually also looks and feels healthy for short periods of time. During the next stage, the seriously-ill stage, there may be a loss of appetite, nausea, fatigue, vomiting, diarrhea, fever, seizures, and coma. This may last from a few hours to several months and end with death from infection and/or internal bleeding. Some late deterministic effects are cataracts and a decrease in germ cells. To date, cataract formation is the only deterministic effect associated with exposure to ionizing radiation in space (7). Excess cataracts have been seen in former astronauts who received less than 2 Gy of high *lineal energy transfer* (called high-LET [3]) radiation (8).

Table 2 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 (9).

3. What are the most important occupational sources of ionizing radiation for crewmembers?

The principal ionizing radiation to which air and space crewmembers are exposed is *galactic cosmic radiation* (GCR). This source provides a small but continuous background that varies with altitude, latitude, and solar activity level. For aircrew members, doses can be as high as 6 millisieverts per year but are usually much less. Spacecraft crewmembers will probably have somewhat lower doses of GCR until flight hours for crewmembers become similar to those of commercial aviation crewmembers or flights include low-Earth orbit missions.

Some medical procedures using ionizing radiation may be required for a pilot to receive a special medical issuance. Doses vary greatly among procedures, and for the same procedure doses can vary among laboratories, depending on age of equipment, techniques used, etc.

Thunderstorm lightning can produce small amounts of soft X-rays. Thunderstorms also occasionally produce upwardly directed bursts of gamma rays and relativistic electrons (called a *terrestrial gamma-ray flash* (TGF) or "dark lightning"). The worst case dose from a single TGF is estimated to be about 30 millisieverts (14).

The Sun can produce ionizing radiation as a result of interactions of the solar magnetic field with plasma in the solar atmosphere and solar wind. These events can result in doses high enough to cause radiation sickness (Table 2) for those who are very lightly shielded from radiation and not within the protection of the Earth's magnetic field (15).

Table 2. Deterministic Effects in Young Adults From a Whole-Body Gy-Eq of Ionizing Radiation Received in Less Than One Day.

Gy-Eq	Effects
0.15	Threshold dose for temporary sterility in males (6).
0.35	Within a few hours, some suffer nausea, weakness, and loss of appetite. Symptoms disappear a few hours after appearing (6).
1-2	After 2-3 hours, nausea and vomiting in 33-50% (9).
1.5	Threshold dose for mortality (10).
2	Permanent sterility in premenopausal females (3). Minimum cataract dose (11).
2-4	Mild headache in about 50%. Almost constant nausea and vomiting in 70-90% (12). There may be initial granulocytosis, with pancytopenia 20-30 days after irradiation. Possible later effects are infections, hemorrhage, and impaired healing (12). The latent period for cataracts is normally about 8 years, after 2.5-6.5 Gy (3).
3.5-6	Threshold dose for permanent sterility in males (13).
4	About 50% die within 60 days from hematopoetic failure (13). It has been reported for adult males, that shielding 10% of the active (red) bone marrow will result in almost 100% survival (9). Locations and percent of total bone marrow in adults are in Table 15.
5-7	Up to 100% vomit within 2 days (10). Mortality about 90% within 60 days (13).
>8	Within minutes, there may be severe nausea, vomiting, and watery diarrhea. After 1-2 hours, there is almost constant severe headache. There may be renal failure and cardiovascular collapse. Mortality 100%, usually within 8-14 days (12).
>20	Often, burning sensation within minutes. Nausea and vomiting within 1 hour, followed by prostration, ataxia, and confusion. Mortality 100%, usually within 24-48 hours (12).

4. Where does galactic and solar cosmic radiation come from?

There is good evidence that the main source of galactic cosmic radiation (GCR) is supernovae (exploding stars) within our galaxy. Charged particles in interstellar space are accelerated to near the speed of light by shock fronts produced by supernova explosions. These particles then travel twisted paths ordered by the magnetic fields of our galaxy until they arrive in our solar system, where the magnetic fields generated by the Sun are dominant. Thus, we do not know the points of origin for these particles. The highest-energy GCR particles are believed to come from nearby galaxies with central black holes. The black holes eject jets of plasma (a gas with a portion of its components ionized) into intergalactic space (16).

Occasionally, a magnetic disturbance in the Sun's atmosphere accelerates a surge of particles to high energy, forming a shock front that moves at supersonic speeds through the solar wind in interplanetary space. These eruptions, called *solar flares* and *coronal mass ejections* (CMEs), accelerate particles in the solar wind to near light speed and can significantly increase radiation levels in Earth's atmosphere and in low-Earth orbit for a few hours or, at most, a few days. This radiation is called *solar cosmic radiation* (SCR). Because solar eruptions are not nearly as powerful as supernovae, the accelerated particles are not as penetrating as GCR, and dose rates drop significantly faster with decreasing latitudes than they do for GCR.

Outside the earth's atmosphere, these radiations consists mostly of fast-moving protons (hydrogen nuclei) and alpha particles (helium nuclei), with small quantities of heavier atomic nuclei, electrons, photons, and neutrons. On entering the atmosphere, these particles collide with the nuclei of nitrogen, oxygen, and other air atoms, generating additional ionizing radiation particles. At aircraft flight altitudes, the dose of galactic cosmic radiation received by air travelers is mainly from neutrons, protons, electrons, positrons, and photons. Protons and neutrons dominate at higher altitudes.

5. How can a crewmember find out the effective dose of radiation received on a flight?

As a conservative estimate of the effective dose from GCR for a flight, one can use the FAA computer programs CARI-6M or CARI-6W. These programs can be used to calculate the effective dose of GCR received by a crewmember flying any route up to internal altitude limits (60,000 ft to 87,000 ft) by means of entering waypoints. The maximum altitude in CARI is above the altitude of maximum dose rate at most U.S. launch locations. Above the altitude of maximum dose rate, sometimes called the *Pfotzer maximum* (academically, the term refers to the altitude of maximum ionization), dose rates decrease as altitude increases until the Van Allen Belts begin to contribute to the dose rates. As long as the Van Allen radiation belts are not an issue and latitude is somewhat equator-ward of the latitude of the *cosmic ray knee* (latitude at which GCR rates stop increasing significantly as one moves towards one of the poles), flight doses can be safely assumed to be below the amount calculated using the maximum allowable altitude to estimate dose rates at all higher altitudes. It is important to note that transitory effects on the dose rates such as solar particle events and *Forbush decreases* (sudden reductions in GCR dose rate that sometimes result when a coronal mass ejection passes near Earth) are not included in CARI-6M or CARI-6W.

Programs such as AVIDOS, EPCARD.NET, PARMA, and PCAIRE can also be used for this purpose, while the NASA NAIRAS program offers a global view of the radiation environment at multiple altitudes updated on a regular basis (17-21).

6. What sort of radiation doses can be expected during commercial space travel?

Commercial space flights, in the next decade or so, are expected to be limited to suborbital flights and trips to the International Space Station, with suborbital flights far more common. It is expected that the suborbital flights will be primarily like that of SpaceShipOne, a rocket carried aloft and launched at high altitude from a carrier aircraft, or else something like the early ballistic flights of the Mercury program. These kinds of flights usually spend 15 minutes or less at high altitudes and in space. GCR should be the primary source of ionizing radiation exposure. The flight path can be chosen to avoid the trapped radiation of the South Atlantic Anomaly and the timing selected to avoid SCR hazards. Doses to vehicle occupants are expected to be quite low during the rocket-powered and freefall portions of the flight. For example, the effective dose (calculated with LUINNCRP [22] from the flight profile) to Alan Shepard on the Mercury 3 mission was 0.00031 millisievert.

For tourists going to the International Space Station, the trip is typically 7-10 days, and doses will be considerably higher than on suborbital flights. The trapped radiation of the South Atlantic Anomaly cannot be avoided. Also, the orbit of the International Space Station is at a high inclination, so for part of each orbit, it is outside latitudes well-protected by Earth's magnetic field, and International Space Station occupants receive little protection from GCR. While of low probability, SCR is also a possible radiation hazard. An example of a trip to the International Space Station 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 (23).

7. If the crewmember is pregnant, how can she find out the equivalent dose of radiation received by the conceptus?

Because of the very penetrating nature of galactic and solar cosmic radiations, the effective dose to a pregnant woman is a reliable estimate of the equivalent dose received by the conceptus (24).

8. If the crewmember is pregnant, should she fly?

With regard to occupational exposure to radiation during pregnancy, the FAA recommends that a pregnant crewmember and her management work together to ensure that exposure of the conceptus will not exceed recommended limits.

There are many dangers involved in spaceflight besides exposure to ionizing radiation, including medical issues that could affect her and/or her conceptus. She should take into account the advice of her physician when considering flight duties while pregnant, both to limit the cumulative radiation doses to herself and her conceptus and for other safety reasons.

Under U.S. law, however, 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.

9. What are the recommended occupational radiation exposure limits for crewmembers?

The FAA accepts the recommendations of the American Conference of Government Industrial Hygienists (25, 26). The current FAA recommended limit for a crewmember is a 5-year average effective dose of 20 millisieverts per year, with no more than 50 millisieverts in a single year (24). For a pregnant crewmember, starting when she reports her pregnancy to management, the recommended limit for the conceptus is an equivalent dose of 1 millisievert, with no more than 0.5 millisievert in any month (24).

10. What health concerns are associated with occupational exposure to radiation?

At the radiation doses likely to be received by crewmembers, an increased risk of fatal cancer is the principal health concern (24). This risk is estimated to be four fatal cancers per 100,000 persons exposed to 1 millisievert (i.e., 4% per Sv). In the general population of the United States in 1998, about 24% of adult deaths were from cancer (24). Individual resistance to radiation can vary considerably, depending on age, sex, and personal genetics, so for an individual, a risk estimate should be considered a rough approximation.

Genetic defects passed on to future generations are another possible consequence of exposure to radiation (24). Radiation exposures of both parents prior to conception should be included. The estimated risk is 4 in 1,000,000 per millisieverts (i.e., 0.4% per Sv) for radiation-induced severe genetic defects in first-generation offspring. Thus, the risk from a combined parental dose of 14 millisieverts is approximately (0.0004% x 14 millisieverts =) 0.006%. In the general population, 2-3% of liveborn children have one or more severe abnormalities at birth (24).

Cardiovascular damage from ionizing radiation was first noted in 1899 (7). Risk coefficients based on studies in atomic bomb survivors, Chernobyl workers, and cancer treatment survivors are shown in Table 3.

Although one cannot exclude the possibility of harm from occupational exposure to radiation at the doses likely to be received during a career of flying, it would be impossible to establish that an abnormality or disease in a particular individual resulted from such exposure.

11. How can a crewmember reduce the amount of radiation received without working fewer hours?

Some basic ways to keep the dose as low as possible include:

- Minimize flight time at high altitudes during a solar particle event, particularly if your flight will pass through polar latitudes.
- Fly at the lowest possible latitudes.
- Descend as quickly as possible to aviation altitudes once the sub-orbital portion of the flight is done.
- Avoid going over or through thunderstorms.

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, the radiation received on the lower-latitude flight will usually be the lower because of the greater amount of radiation shielding provided by the Earth's magnetic field. This shielding is greatest near the equator

Table 3. Excess Relative Risk (ERR) Coefficients for Cardiovascular Diseases (7).

Disease	ERR per gray*
Cardiovascular (arteries, veins, and capillaries)	0.54
Ischemic heart	0.41
Essential hypertension	0.36
Cerebrovascular	0.45

* For low-LET radiation, 1 gray (Gy) is equivalent to 1 sievert (Sv).

and gradually decreases to zero as one goes north or south. For example, during the period January 1958 through December 2001, at an altitude of 30,000 feet, the average galactic cosmic radiation level over Reykjavik, Iceland (64° N, 22° W), was approximately twice that over Lima, Peru (12° S, 77° W).

12. If a crewmember works during pregnancy, what are the health consequences for her conceptus?

For a conceptus irradiated *in utero* (in the uterus), major potential risks are structural abnormalities, mental retardation, pre-term death, and fatal cancer (24). The available data indicate that even if the dose to the conceptus is as high as 20 millisieverts — which might occur during an unusually large solar-proton event or as a result of a TGF — no radiation-induced structural abnormalities or mental retardation would be observed. However, irradiation of the conceptus during the first day of development, even with a dose less than 20 millisieverts, could result in an increased risk of prenatal death. The risk would depend on the stage of development of the conceptus at the time of irradiation and the radiation dose. If death did occur, the conceptus would most likely be aborted before the pregnancy was recognized. After the first day or two, 20 millisieverts to the conceptus would not affect prenatal survival. A dose less than 100 milligray to a conceptus is not considered a justification for terminating a pregnancy (9).

Irradiation during prenatal development increases an individual's lifetime risk of fatal cancer. The increased lifetime risk of fatal cancer from 1 millisievert received during prenatal development is 1 in 10,000 (0.01%). In the general population of the United States (all ages) in 2009, approximately 23% of all deaths were from cancer (27). With galactic cosmic radiation, the effective dose to the pregnant crewmember is a reliable estimate of the equivalent dose to the conceptus.

There are other medical risks associated with normal flight and spaceflight. If you are a pregnant crewmember you are strongly urged to consult your physician concerning these risks.

13. What should a crewmember know about radiation from the Sun?

Solar cosmic radiation (SCR) interacts with air atoms in the same way as galactic cosmic radiation particles. Various terms used to indicate that there may be a surge of solar particles entering the Earth's atmosphere (least to greatest intensity) are:

- *Coronal Mass Ejection* (CME) — an ejection of a large mass of solar material from the Sun's corona (outermost layer of the Sun's atmosphere). These happen frequently but are rarely directed towards Earth, large and fast enough to increase radiation levels significantly at aviation altitudes.
- *Solar flare* — Usually used by NOAA to indicate intense X-ray emissions. However, the largest solar flares are often associated with the most powerful CMEs, so they can indicate increased radiation levels.
- *Solar particle event* and *solar cosmic ray even*t — These events are the result of CME driven shocks and indicate above average particle fluxes as measured at various satellites. Radiation levels may or may not be increased significantly above GCR background levels.
- *Solar proton event* (SPE) — An SPE is a solar particle event or solar cosmic ray event that passes specific minimum flux criteria. The minimum flux and energy requirements for declaration of an SPE are such that these events are, at the very least, a concern to spacewalkers. A very large SPE may also be a *ground level event*.
- *Ground level event* (GLE) — These are the most intense at Earth, and are so-called because neutron monitors on Earth's surface see a significant increase in count rates of secondary cosmic ray neutrons.

SCR is unlike GCR in that it typically has many more particles but at much lower energies. Thus, the latitude effect (how much radiation decreases as one move away from the poles, where shielding is weakest) is much stronger for SCR, but SCR doses can temporarily be much greater the GCR doses for locations at high latitudes and at very high altitudes. Flights into space outside the protection of Earth's magnetic field risk the possibility of doses to crewmembers exceeding one sievert, particularly if the spacecraft does not have a built-in radiation storm shelter. For suborbital flights at low- and mid-latitudes, the risk level is greatly reduced, due to limited exposure time and the benefit of strong shielding by the Earth's magnetic field.

SCR cannot be avoided by flying only at night. Although the particles are from the Sun, they do not follow straight paths and soon are entering the atmosphere from all directions because of the spreading effect caused by the interplanetary and earth's magnetic fields. After about 20 minutes to 3 hours from the start of an SPE, radiation levels in the atmosphere on the dark and light sides of the Earth are almost the same.

The solar particle event of February 23, 1956, caused the largest known increase in the radiation at flight altitudes. If satellite data had been available, it probably would have been classified as a solar proton event. Although the dose rates during this event are uncertain, available information indicates that recommended radiation limits for pregnant crewmembers would probably have been exceeded on high-latitude flights at 40,000 feet and higher altitudes. The dose to non-pregnant crewmembers could also have exceeded the recommended limit.

A solar radiation alert system, developed by the FAA and NOAA, provides early warning of a solar proton event that may lead to air travelers being exposed to excessive amounts of ionizing radiation. Solar radiation alerts are transmitted worldwide to the aviation community with weather data.

Long-distance communications may be disrupted because of increased ionization of the Earth's upper atmosphere by solar x-rays, ultraviolet radiation, or protons. However, radio communication problems often occur in the absence of SCR and therefore should not be used as an indicator of excessive ionizing radiation levels at flight altitudes.

14. What research is this information based upon?

In estimating radiation-induced health risks for aircrews and their progeny, this report uses dose-effect relationships recommended by national and international organizations recognized for their expertise in evaluating radiation effects (4-6). However, considerable uncertainty exists in these estimates because the original data is primarily from studies on individuals exposed to radiation at much higher doses and dose rates and generally of lower energy than the galactic cosmic radiation to which aircrews are exposed. Also, controls were often inadequate. These differences are the major reason that epidemiological studies involving aircrews are particularly important and work to improve risk estimates is ongoing.

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