Health Impacts of Ionizing Radiation Pertaining to Nuclear Weapons
Scientific and Technical Basics

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Preface

This report addresses the scientific basics of the impact of ionizing radiation on health in the context of nuclear weapons and power. It is not meant to be an analysis or even a compendium of the actual health impacts. There is a voluminous literature about health impacts of nuclear weapons production and testing, including three major works jointly produced by the International Physicians for the Prevention of Nuclear War and the Institute for Energy and Environmental Research (IPPNW and IEER 1991, IPPNW and IEER 1992, and IPPNW and IEER 2000). There are also eleven reports, one for each major nuclear weapons test site, produced by IEER for the International Campaign to Abolish Nuclear Weapons.[1] Of course, there is also a great deal of other literature, including by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and in peer-reviewed journals.

The aim of this report is to provide a succinct, basic scientific resource on the topic. It is focused on low-dose ionizing radiation, and therefore primarily on stochastic effects. The report also explores some issues that have been understudied even though they have major implications for understanding and evaluating the health impacts of ionizing radiation. The issues related to high dose exposure are well established and not revisited here. Internal references are omitted in the quotations.

This report was produced for the Nuclear Truth Project. This is a companion report on remediation of nuclear contamination (Makhijani 2026a) and one on multigenerational impacts of ionizing radiation (Makhijani 2026), both also prepared for the Nuclear Truth Project.

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[1] The eleven briefs, three by Dr. Tilman Ruff and seven by the author of this report, and one co-authored by him with Dr. Ruff, can be downloaded at this IEER link.

Summary

This report provides basic scientific and technical data about ionizing radiation and its impacts. It is focused on the radionuclides related to nuclear weapons production and testing. It also discusses risks that are understudied and relatively neglected in regulation and public health protection. The study summarizes the evolution of radiation protection standards and their tightening over time. It points to areas in which standards are inadequate and the scientific reasons for considering risk factors that are not yet a part of regulation and public health protection. Finally, it discusses the principles of (i) "justification," which requires those who are subjected to radiation exposure benefit more than the harm caused and (ii) optimization, which requires that exposures be kept "as low as reasonably achievable" below regulatory limits and the protection of the environment.

Findings

1. Exposure to low-dose ionizing radiation increases cancer risk, with substantial evidence that the risk of cancer has no threshold and increases with exposure. The risks are higher for females and children, being highest for female infants.
2. There is increased risk of cardiovascular disease at doses received by Hiroshima/Nagasaki survivors or in medical radiation treatment.
3. Many health risks are relatively neglected despite evidence that they exist. They include
    a. non-cancer thyroid diseases;
    b. diseases and risks resulting from cytoplasmic oxidative stress, mitochondrial DNA damage, and mitochondrial dysfunction;
    c. harm to other living beings, who share the same mitochondrial system at the core of the energy system of animals, plants, and fungi.
    d. adverse pregnancy outcomes, including teratogenic impacts;
    e. a variety of "devastating consequences" (Phillips 2008) due to disruption of and errors in DNA methylation.
4. Radiation protection standards take no account of the specific potential risks and harms to the embryo and fetus, especially in the first trimester. They treat pregnant members of the public as any other members of the public with no special consideration for the protection of the embryo/fetus.
5. The principle of justification of exposure when cross-border risks are created by nuclear weapons activities is not yet taken into account, though it is by now a well-established principle.

Recommendations

1. Maximum contaminant limits of radionuclides in drinking water and food should be tightened as a precautionary measure to protect the embryo/fetus and ecosystems. This is necessary due to the large and persistent gaps in radiation protection resulting from the neglect of key issues, despite efforts to have official science and regulation include them.
2. The TPNW process should include the justification principle when it considers issues related to cross-border exposure and risk in non-nuclear weapons states due to activities of nuclear-weapons states, and specifically due to atmospheric nuclear weapons testing. The justification principle should become part of deliberations involving Articles 6 and 7 of the TPNW.
3. Substantial investments should be made to remedy the gaps in knowledge of non-cancer impacts of radiation exposure, including those created by oxidative stresses by water ionization in the cytoplasm of human cells and those of other eukaryotes.

1. Basics of ionizing radiation

a. Radionuclide basics

Ionizing radiation consists of particles that are energetic enough to spilt molecules apart, creating electrically charged ions. The ionizing radiation of principal concern as it relates to nuclear weapons and nuclear power is emitted by unstable nuclei of atoms called "radionuclides." Elements can, and generally do have many unstable isotopes. Most elements have one or more unstable isotopes.

With just one exception, all elements and their isotopes have nuclei that contain protons (positively charged particles) and neutrons (electrically neutral particles). The exception is ordinary hydrogen (H-1), which is the hydrogen in ordinary water. Its nucleus consists of just one proton. Hydrogen has two other isotopes. Deuterium (D or H-2), one proton and one neutron, is not radioactive. Tritium (T or H-3), one proton and two neutrons, is radioactive. The number of protons determines the chemical properties of an element. Isotopes of an element have basically the same chemical properties, though their different masses give them somewhat different physical properties. Both deuterium and tritium are important in nuclear weapons. The D-T fusion reaction gives "hydrogen bombs" their name.

The number after the element symbol denotes the mass number, the total number of protons and neutrons in the nucleus. The total number of protons is called the atomic number. The total mass number remains the same when the mass numbers of the initial and final products are added up. For instance

U-238 → Th-234 + He-4;

Deuterium (H-2) + tritium (H-3) → He-4 + n +17.6 MeV (fusion reaction)

The mass of the electron being much smaller than a neutron or a proton does not figure in the mass number, which does not represent an exact atomic mass.

b. Alpha, beta, gamma radiation[2]

Alpha, beta, and gamma radiation were labeled with Greek letters of the alphabet because their nature was not well understood at the times of their discovery. The particles emitted in the course of radioactive decay have energies ranging from a few kiloelectron volts (keV) to several megaelectron volts (MeV). An electron volt (eV) is the energy gained by an electron accelerated through a one volt potential difference. It is a suitable measure of energy in the chemical and biological context because chemical reactions typically involve a few electron volts of energy. For instance the energy of formation of one molecule of carbon dioxide from carbon and oxygen ($C + O_2 \rightarrow CO_2$) is slightly more than 4 eV. As another example, it takes 12.6 eV to ionize water. The fact that decay particle energies are between hundreds of times and a million times greater than typical chemical reaction energies is important to understanding why ionizing radiation from radioactive decay is biologically disruptive.

- **Alpha particles** are energetic helium-4 (He-4) nuclei emitted by the radioactive decay of many heavy element isotopes. The He-4 nucleus contains two protons and two neutrons.:
    - For example: uranium-238 → thorium-234 + helium-4 (the alpha particle).
    - After emitting an alpha particle U-238 becomes thorium-234, which is also radioactive.

[2] Unless otherwise mentioned, the properties of radionuclides in this chapter are from ANL 2007. In this report, we do not show neutrinos or antineutrinos that can be part of energy release during radioactive decay. They have no health implications since they generally pass right through the body without interaction. Proton radiation, used in medicine, is not discussed in this report.

The He-4 will pick up two electrons and become an atom of neutral helium-4 gas.

- Alpha particles typically carry a large amount of kinetic energy when expelled by the nucleus – generally between 4 MeV and 6 MeV. The alpha particle emitted by U-238 carries 4.2 MeV of energy.
- All three natural uranium isotopes, U-234, U-235, and U-238 decay by emitting an alpha particle. Those nuclei become the corresponding isotopes of thorium (Th-230, Th-231, and Th-234, respectively).
- Four of the five most important plutonium isotopes (Pu-238, Pu-239, Pu-240 and Pu-242) decay by emitting an alpha particle (energies 4.9 MeV to 5.5 MeV). The fifth one, Pu-241, decays to americium-241 by emitting a beta particle: Pu-241 → Am-241 + e^- (5.2 keV). Am-241 is an alpha emitter (5.5 MeV alpha particle).
- All elements with atomic number greater than 83 (bismuth) are radioactive – that is, they have no stable isotopes. Bismuth technically has no stable isotope but Bi-209 has such a long half-life (billions of times more than the age of the Earth) that Bi-209 can be considered for practical purposes to be stable.

- **Beta particles** are electrons or positrons, the latter being identical to electrons except that they have a positive electrical charge. They are often written as e^- and e^+ to distinguish them from one another. (In this context, an electron is sometimes referred to as a "negatron.") A large number of radioisotopes are characterized by beta decay, including the most important fission products connected to nuclear weapons testing contamination and radiation doses.[3] When an electron is emitted from the nucleus, the net effect is that one of the neutrons in the nucleus becomes a proton, increasing the atomic number of the resulting element by one. (An electron is so light relative to a proton or neutron that the mass number is not changed by beta particle emission.) The reverse occurs when the beta particle is a positron. Some important radionuclides with beta decay in the nuclear weapons and nuclear power (notably in accident contexts) include:

  - Tritium: H-3 → He-3 + beta particle (e^-). Range of beta particle energies 0 to 18.6 kiloelectron-volts (keV). The average beta particle energy is 5.7 keV – that is roughly seven hundred times less than the U-238 alpha particle. Still, the average tritium beta particle has enough energy to split apart 450 molecules of water when inside a human cell (which is mostly water).
  - Carbon-14: C-14 → N-14 + e^-**,** with an average beta particle energy of 49 keV.
  - Iodine-131 : I-131 → Xe-131 + e^-, with an average beta particle energy of 190 keV.
  - Strontium-90: Sr-90 → Y-90 + e^- (200 keV) → Zr-90 + e^- (940 keV). In effect, strontium-90 decay has two steps, each involving the emission of a beta particle. The first is emitted by strontium-90 and the second by yttrium-90. The latter is far more energetic.
  - Cesium-137: Cs-137 → Ba-137m + e- → Ba-137 + 661 keV gamma ray (photon).[4]

- **Gamma radiation**: Many radioactive nuclei also emit photons, which are particles or packets of electromagnetic radiation.[5] Photons emitted in the process of radioactive decay do not change

[3] In order of cumulative radiation dose due to atmospheric testing over the long-term, the top eight radionuclides are all beta emitters: carbon-14, cesium-137, zirconium-95, strontium-90, ruthenium-106, hydrogen-3 (tritium), cerium-144, and iodine-131. Plutonium-239, an alpha emitter, is next. (IPPNW and IEER 1991, Table 3.)

[4] The "m" in Ba-137m denotes a nuclear "metastable state"; it becomes stable Ba-137 by the emission of a photon, a "particle" of light. The photon emitted by Ba-137m has an energy of 661 keV. This kind of decay is "called an isomeric transition" (Connor 2019).

[5] Photons were first postulated by Max Planck in 1900 to explain black body radiation. They were famously written about as a basic physical property of light as quantized electromagnetic radiation by Einstein in 1905.

the atomic number or mass number, since they carry no charge or mass.[6] But they do carry away a large amount of energy, typically in the hundreds of keV – as illustrated by the isomeric transition of Ba-137m to Ba-137, discussed above. Many alpha and beta decays of radionuclides are accompanied by the emission of an energetic photon, or gamma ray. Two examples of radionuclides that are important in the weapons and power scheme of things (in addition to the cesium-137 decay scheme discussed above) are:

- Iodine-131: Along with the 190 keV beta particle, iodine-131 decay also emits a 380 keV photon. I-131 is copiously produced in the fission process.
- Americium-241: Plutonium isotopes do not have copious amounts of photons in their decay schemes. As a result, pure metallic plutonium can be handled (with gloves, normally). The same is true of the three natural uranium isotopes. However, Pu-241 decays into Am-241, an alpha-emitter that emits a 33 keV photon. Some Pu-241 is normally produced as part pf plutonium production schemes in reactors. When separated, Am-241 builds up in the plutonium and it becomes more difficult to handle – for instance to fabricate reactor fuel.

The above list provides simplified versions of the decay of radionuclides. Radionuclides have decay *schemes* that consist of different modes of decay that occur with different probabilities. For instance, in the simplified version cobalt-60 decay to nickel can be represented thus:

Co-60 → Ni-60 +e^- (97 keV) + photon (2,500 keV) – as described in ANL 2007.

The actual decay scheme is more complex. There are actually two photons in the high probability branch, 1,174 keV and 1,332 keV that add up to 2,506 keV total for the photon energy, which is shown, rounded in the simplified form. Over 99% of Co-60 decays occur in this way. But there are other very low probability (<1%) decays that result in other photons being emitted as well (Lamarsh 1983, p. 21). We omit these complexities in the main discussion in this report because in most cases they are not important to health-related considerations. What is critical in the case of Co-60, for instance, is that the photons are of very high energy, making it extremely dangerous to handle; it can only be handled remotely and must be stored in lead containers.[7]

c. Neutrons[8]

Neutrons, as noted, are electrically neutral and can pass right through spaces with electromagnetic fields without interaction. However, they can collide with nuclei, which case, indirect ionizing radiation can result:

- Neutrons can collide with a hydrogen nucleus by elastic scattering (like billiard ball collisions). A neutron colliding with a hydrogen atom nucleus – that is, a single proton – will transfer energy to it. The proton then becomes a source of ionizing radiation.

[6] A mass can be imputed to a photon via Einstein's famous $E = mc^2$. A very energetic 1 MeV photon has an imputed mass 150 million times less than an electron, which in turn is 1,836 times lighter than a proton. Neutrons have a slightly higher mass than a proton.

[7] There are also other decay modes. In "electron capture" an unstable nucleus captures one of the electrons orbiting round it; this converting a proton in the nucleus into a neutron. A new element is formed with the same mass number but one lower atomic number. This is accompanied by photon emission. What is important for health is the fact of the emission of radiation and the type of radiation rather than the nuclear mechanism by which that radiation is produced.

[8] NRC 2011 is a good basic guide for interactions of neutrons with matter.

- Inelastic scattering occurs when a part of the neutron energy is converted to kinetic energy and a part into excitation energy of the nucleus, which then releases that energy by emitting one or more photons (gamma radiation).
- Neutrons can be absorbed into the nucleus of a stable element, making it unstable, and hence radioactive. For instance, a neutron captured by a stable gold nucleus (Au-197) become unstable Au-198, which decays into mercury by emitting a beta particle.
- An important radionuclide related to nuclear testing, sodium-24 (Na-24), is created by neutron absorption by ordinary sodium. Underwater tests, like Test Baker at Bikini on 26 July 1946 of the Nagasaki-design bomb, created vast amounts of sodium-24 in Bikini lagoon due to neutron absorption by the ordinary non-radioactive sodium (Na-23) in sea salt. Na-24 is intensely radioactive – emitting powerful beta and gamma radiation. It is also very short-lived, with a half-life of about 15 hours. It would have impacted the armed forces personnel, especially naval personnel who came into contact with Bikini lagoon water or spray in the days immediately after the test.

The term "indirectly ionizing radiation" is also applied to gamma rays that knock off an electron from an atom or molecule. That energetic electron then acts much like a beta particle emitted by a radioactive material, causing ionizations of nearby molecules (National Research Council 2006).

d. Half-life and specific activity

Unstable nuclides decay with a characteristic time. One common way to described that time is to define the half-life of the radionuclide. This is the amount of time in which half a given amount of radionuclide will decay. For instance, cesium-137 has a half-life of 30.1 years. In that amount of time, half of it becomes barium-137 (via Ba-137m).[9] The other half is still Cs-137.[10] Half of that will decay in the next30.1 years, leaving one-fourth of the initial amount after 60.2 years. Ten half-lives is often used as a rule of thumb for the time for the radioactivity of a given amount of material to become very small – a little less than one-thousandth of its initial amount. Of course, if the initial amount is extremely large, then decay to a negligible amount will take longer.

Radionuclides are more or less radioactive. *Specific activity* denotes the number of nuclear decay events per second per gram of a radioactive material. If the material is in a waste or otherwise mixed with non-radioactive material, for alloying purposes for instance, specific activity is defined in terms of the decay properties of the composite material. The specific activity of a radionuclide is inversely proportional to its half-life. The longer the half-life, the fewer the number of decays of nuclei per unit time (for a given amount of the radionuclide). Thus, iodine-131 with a half-life of 8.1 days is 700 million times more radioactive than iodine-129, which has a half-life of 15.7 million years. Iodine-131 does its damage in days, weeks, and months. After three or four months essentially all of it has decayed into non-radioactive xenon-131 gas. During that period the damage is intense, as for instance, when children drank milk contaminated with iodine-131 from atmospheric nuclear tests deposited on grass, which was then eaten by grazing cows and sheep. In contrast, iodine-129 decays very slowly – that is the probability of emission of a beta particle in a given time – is low. So the dose delivered when a certain mass is ingested is far lower than iodine-131 of the same amount. Almost all the iodine-129 that is ingested is excreted; it then cycles through the biosphere repeatedly, irradiating people and biota

[9] Ba-137m transitions to Ba-137 with a half-life of 2.55 minutes.

[10] "Decay time" is also used in the literature to describe the exponential decay characteristic of radionuclides. It is the time in which the number of atoms is reduced by decay to about 36.8% of its original value. The number 0.368 is one divided by "e" the base of natural logarithms (e = 2.718, approximately). The symbol T is often used for decay time.

essentially forever, with very small individual doses to very large numbers of people and biota.

Specific activity is also inversely proportional to mass number. A low mass number radionuclide, carbon-14 has far more atoms per gram of material than a radionuclide like radium-226 with a high mass number. As a result, even though the half-life of carbon-14 is 3.6 times longer than radium-226, carbon-14 has 4.5 times the specific activity of radium. A simple, though slightly approximate way,[11] to calculate specific activity is to remember that a gram of radium-226 has specific activity equal to one curie, a unit named after the discoverer, Marie Curie, and a half-life of 1,600 years.

Specific activity, S, in curies per gram of a radionuclide with half-life H in years and mass number M can be calculated thus:

S = (1600*226)/(H*M)

Table 1-1 shows the specific activities of several important radionuclides calculated in this way in both curies per gram and in gigabecquerels per gram, rounded as indicated.

Table 1-1: Specific activities of some radionuclides

Radionuclide	GBq/gram	curies/gram
tritium (hydrogen-3)	362,600	9,800
carbon-14	167	4.5
strontium-90	5,198	140
cesium-137	3,244	88
radium-226	**37**	**1**
thorium-230	0.77	0.021
uranium-234	0.23	0.006
Uranium-235	0.000081	0.0000022
uranium-238	0.000013	0.00000034
plutonium-239	2.3	0.063
americium-241	128	3.5

GBq = gigabecquerels = one billion becquerels.
1 curie = 37 GBq

[11] It is slightly approximate because mass number, which is an integer, does not exactly represent the mass of the atom. But the specific activity calculation is accurate for all practical purposes relevant to health impacts.

e. Measures of damage due to ionizing radiation

The basic measure of energy deposition in standard international (metric) units is the "gray" – one gray is equal to one joule of energy deposited in one kilogram of matter.[12]

Human beings are mostly water – 55% to 60% for adults, more for infants, with variation among individuals (Helmenstine 2026). The starting point for developing a metric for health impacts has been to treat the body like a bag of water. For instance, the distribution of ionizations in the body is determined by experiments on a phantom in human form filled with water.

In one basic respect, treating the body as a bag of water is a reasonable starting point, because the amount of energy deposited determines the number of ionizations, which are the source of unwanted biochemical reactions and of DNA damage. At the same time, a physical-science-based approach must acknowledge human bodies – and the bodies of other living beings – are highly differentiated, finely-tuned bio-chemical structures. In that light, it would be much more accurate to model a living being as a highly ordered, complex information system that reproduces itself via environmental interactions, like eating and excreting (homeostasis). Poking ionizing radiation into it is a little like poking a clock's finely-tuned mechanism at random with a screwdriver. Of course, a critical difference is that living beings have biochemical repair mechanisms.

Another complication relates to the fact that different types of ionizing radiation create damage differently. Alpha particles are rather big, on an atomic scale of things; they consist of two neutrons and two protons. Being large, they cannot penetrate a thin layer of paper or the outer dead layer on skin on our bodies. Therefore alpha particles do no damage when emitted by a radionuclide that is outside the body. Indeed, a few centimeters of air will slow down an alpha particle; it then becomes just another atom of helium gas in the atmosphere.

It is a very different story inside the body. Being massive, an alpha particle collides with nearby molecules and deposits a large amount of energy in a small volume. Because of this characteristic, alpha radiation is called high linear energy transfer radiation ("high-LET" radiation).[13]

Because of the density of alpha-particle-created ionizations is high, the damage *per unit energy deposited* is much greater than the same amount of energy deposited over long distances (on a cellular scale). High energy gamma rays do not interact frequently with matter in cells and deposit their energy over long tracks with a low density of ionization – called "low LET" radiation. The bag-of-water model does not capture these realities. Very energetic gamma rays deposit only part of their energy in the body and exit at the other end with some residual energy; they fall into the "low-LET" radiation category.

Beta particles have energies from a few keV to hundreds of keV. In a few cases beta energies approach 1 MeV or more. The lowest energy beta particles, like those emitted by tritium, do not penetrate the dead layer of the skin. A 2 MeV beta particle will penetrate soft tissue to a depth of about one centimeter.

Figure 1-1 shows a schematic of the penetration capacities of alpha, beta and gamma radiation. X-rays and neutrons are also shown. X-rays are electromagnetic radiation, like gamma ray photons, but lower energy. They are most familiar in a medical context where they are generated by accelerated electrons

[12] The United States uses the centimeter-gram system for deposited energy. In that system, 1 rad = 100 ergs of energy deposited in one gram of matter. the conversion is 100 rad = 1 gray. "rad" stands for "radiation absorbed dose."

[13] Linear energy transfer is measured in the amount of energy in kiloelectron volts deposited per micrometer (keV/µm). Living cells are of varying sizes, a few microns to a few tens of microns is typical. LET is discussed at length in ICRP 2003.

striking a target material. (The "x" in "x-ray" arose because the nature of the radiation was not clear at the time of discovery.) Medical x-rays are in the tens of keV and sometimes 100 keV or more, depending on the specific medical application. As shown in Figure 1-1, they are less penetrating than gamma rays, most of which are over 100 keV and are often several hundred keV or more. (Photons of visible light are in the single digit eV range: about 1.6 eV to 3.1 eV).

Figure 1-1 also shows neutron radiation. Neutrons, being neutral, do not interact with the electrons in an atom or molecule – most of the space in an atoms has no particles in it. That is why an atom is sometimes compared to the solar system – a core with distance particles circling around and vast (notionally) empty distances. Neutron interactions are with nuclei, which occupy a very small volume of an atom. As a result, neutrons can go through a lot of material without collisions but the collisions have a large impact when they occur. In other words, neutron radiation is penetrating and damaging. Neutron damage depends on the energy of the neutron, which can range from very low (small fraction of an eV) to very high as when created by fission or fusion reactions in a bomb explosion (many MeV). The latter are the source of tritium and carbon-14 induced radioactivity created by neutrons produced by atmospheric nuclear explosions.

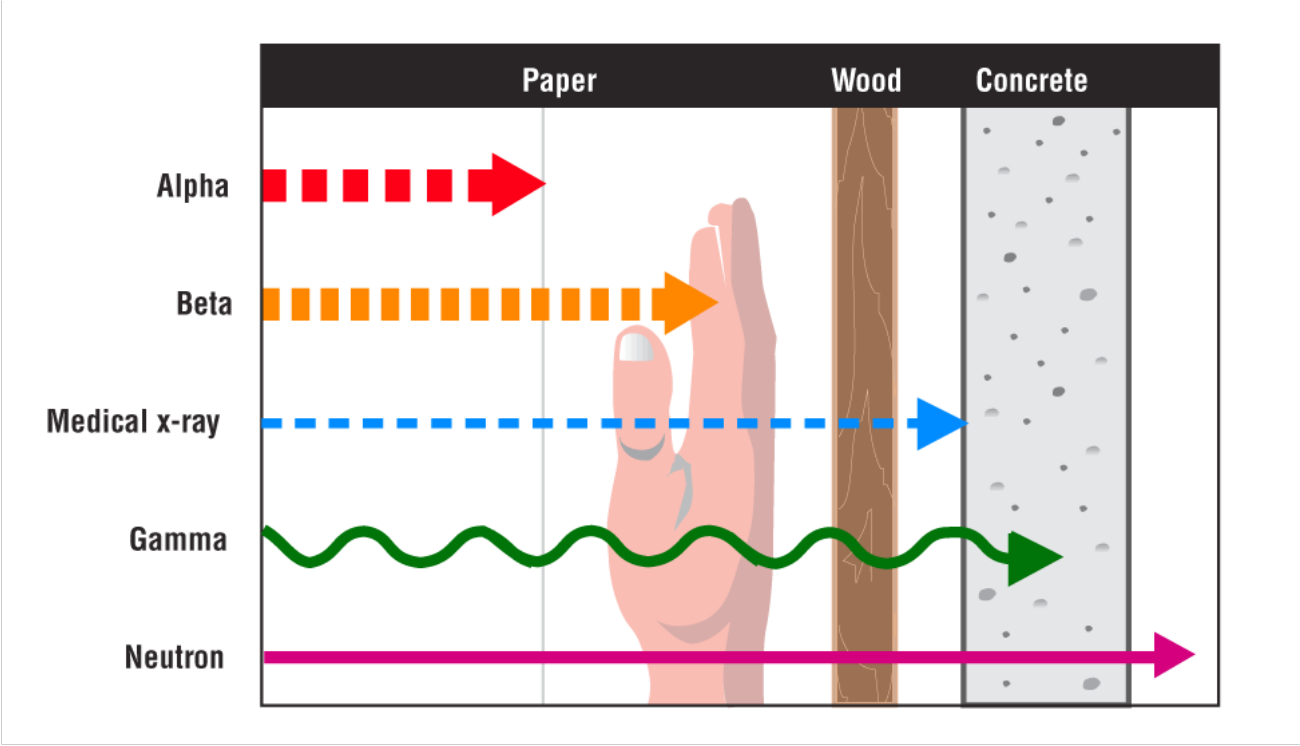

Figure 1-1: Penetration characteristics of different types of ionizing radiation types
Source: NRC 2023

i. RBE, grays and sieverts

A dimensionless factor called "relative biological effectiveness" (RBE) was developed to take account of the different amounts of biological damage by high-LET and low-LET radiation. This allows for estimation of biological damage – and therefore health risk— more accurately than deposited energy alone. Deposited energy, in grays, is multiplied by the RBE to get an estimate of harm, measured in sieverts.

RBEs can be developed for different organs and different types of biological harm. This is a scientifically appropriate way to look at health risk from radiation exposure – both by the type of radiation and by the type of health impact being considered. However, that is not how radiation protection has been approached. Fixed weighting factors for different types of radiation have been developed for regulatory purposes in order to adjust the amount of deposited energy to better reflect risk. In effect, the focus of this approach is on cancer risk as the health endpoint of concern.

Weighting factors are RBEs frozen for purposes for radiation protection standards and enforcement. The weighting factors proposed by the International Commission on Radiation Protection (ICRP 2003) are as follows:

- Gamma radiation: 1;
- Beta radiation: 1
- Alpha radiation: 20.
- Neutrons: 2.5 to 20 depending on energy. The weighting factor at low energies and at very high energies is 2.5. The peak weighting factor is 20 at about 1 MeV neutron energy.

Weighting factors, used with cancer risk estimates, developed for instance the U.S. National Academies committee's most recent report on the impacts of low-level ionizing radiation (the "BEIR VII" report) are a reasonable way to estimate population impacts so far as cancer is concerned, with due attention to age and sex dependence of cancer risk per unit of exposure.

Yet, this picture does not adequately represent the risk of low energy beta particles, such as those emitted during the decay of tritium. Their energies are far lower than alpha particles but they also deposit their energy in a small volume. Moreover, in the form of tritiated water (HTO or T_2O), tritium becomes part of the cytosol in the cytoplasm and ionizes water molecules there. A single tritium beta particle can created hundreds of water molecule ionizations in the cytoplasm of a single cell.

The formation of highly reactive hydroxyl radicals creates oxidative stress in the cytoplasm potentially damaging mitochondrial DNA. That is the DNA of the organelles that at the core the human energy system. Remarkably, it is the same energy system in all multicellular living beings, whether plants, animals, or fungi. Yet, mitochondrial DNA is not even mentioned in the ICRP report on RBE (ICRP 2003). It has not been a significant factor in consideration protecting the public in terms of cancer risk limitation, not to speak of other health and ecosystem risks (see below).

Since RBE is an index of biological harm, other end points than cancer also need to be considered. This is especially important to internal radiation, notably that from alpha-emitting radionuclides, radionuclides that target particular organs, and harm to embryos and fetuses during various stages of pregnancy. Implicit alpha particle RBE can be in the thousands for certain genetic endpoints. Alpha radiation has also been shown to produce "bystander" effects, where cells near the radiated cell are adversely impacted though they did not directly suffer ionization.[14] Excess ROS, created for instance by tritium beta particles ionization of cytoplasm water, can also create bystander effects (Bondareva Kudryasheva, Tananaev 2022).

[14] These RBE-related issues are discussed in Makhijani 2023; references are provided there.

2. Nuclear weapons and health impacts

a. Cancer

Ionizing radiation is a carcinogen. The matter has been studied for decades. The longest-running effort has been based on the Hiroshima-Nagasaki survivors, a group known as the "Life Span Study" (LSS) cohort. The impact of low-level exposures that do not produce immediate, discernible somatic effects down to 0.1 sievert (100 mSv, which is the same as 100 mGy for low-LET radiation) have been shown to increase cancer risk, with the risk being proportional to exposure for solid cancers. The linearity of the risk down to 0.1 Sv and laboratory data lead to a conclusion that the Hiroshima Nagasaki data can be linearly back-extrapolated and that there is no threshold of radiation exposure below which cancer risk is zero (National Research Council 2006).[15]

A number of epidemiological studies of populations whose average exposure at or considerably lower than 0.1 Sv (100 mSv) also point to the validity of risk with no threshold below which it is zero:

- Excess leukemia risk in children do to mother's exposure to diagnostic x-rays when pregnant at exposures of 10 mSv, or ten times less than the 100 mSv of the LSS cohort (National Research Council 2006, p. 6; see also Stewart et at. 1956);
- A vast study of over 300,000 workers with median exposure of 4.1 mGy and average exposures of 20.9 mGy, about 24 times less and almost five times less respectively than the 100 mSv of LSS cohort indicated "a linear increase in the rate of cancer with increasing radiation exposure…" (Richardson et al. 2015);
- A large Australian study with a 10.9 million person cohort, including 680,211 people exposed to CT scans, found an excess cancer risks among those who received the CT scans, with an average dose of 4.5 mGy, 22 times lower than the 100 mSv of those among whom excess cancers were found in the LSS cohort (Mathews et al. 2013).
- A meta study of low dose ionizing radiation cancer risk that restricted its review to average cumulative exposure to less than 100 mGy and mainly low-LET radiation exposure found broad agreement with the finding of positive cancer risk at low doses, generally of the same magnitude as the BEIR VII analysis of Hiroshima-Nagasaki data (Hauptmann et al. 2020).

Figure 2-1 shows the cancer risk per unit of exposure, based on the risks arrived at in the BEIR VII report, the most recent comprehensive report on cancer risk of low-level radiation by the U.S. National Academies. That report also examined hypotheses that the risks of low-level radiation could be lower or higher than those shown in the figure. Table 2-1 shows the risk for specific cancers by age and sex. The data are from the National Academies 2006 report. Similar values are used for purposes of radiation protection, enforcement and compensation in the United States and around the world.

The risks change dramatically with age. Risks to infants are several times risks to adults for the same exposure. And risks to females are generally higher, being almost double for female infants compared to male infants. While that is true when all cancers are taken into account, there are some cancers, such as colon cancer and leukemia, where risks to males are higher. In the most extreme case the risk of thyroid

[15] The Hiroshima- Nagasaki cohort was formed in 1950, about five years after the atomic bombings of those cities. Many affected people who had died were thereby excluded. A further issue was created by the fact that only permanent resident of the cities at the time of cohort formation were included. These factors may have significantly impacted the analysis. Two papers by Alice Stewart and her colleagues discussed these issues (Stewart and Kneale 1993 and Stewart and Kneale 2000. The work of these well-recognized readers has often been cited, including for instance in National Research Council 2006. Yet, these specific papers and the issues they have raised have neither been cited or addressed by those same authorities. (See Makhijani 2025 for further discussion.)

cancer for a female infant is almost 60 times higher than for an adult male, starkly illustrating the differential risks to which atmospheric nuclear weapons testing exposed children, especially female children.

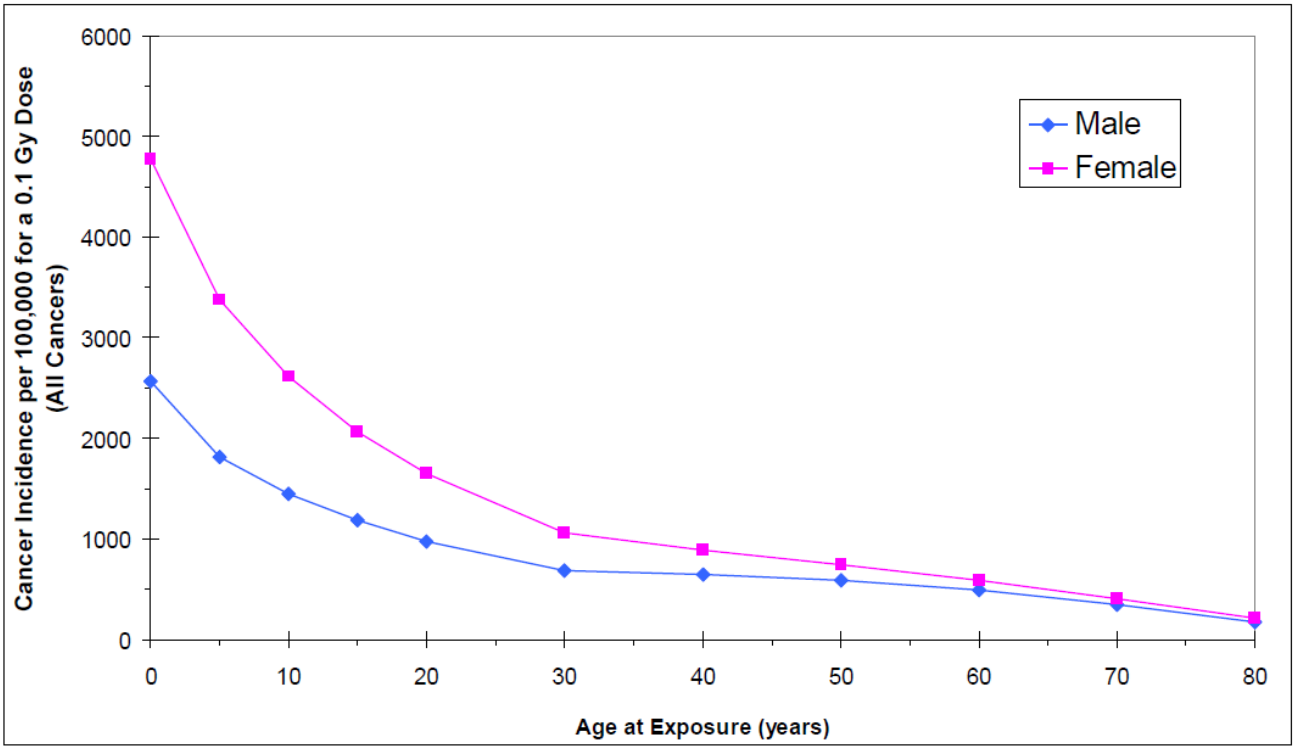

Figure 2-1: Cancer incidence per 10,000 Gy population dose by age at exposure and sex.
Source: Makhijani, Smith and Thorne, 2006, p. 38, based on risk estimates in National Research Council 2006

Cancer risks for several cancer types by age and sex are shown in Table 2-2.

Table 2-1: Cancer risks for selected cancers, by age and sex, for 10,000 person-gray population dose

	Infant		Age 5 Yrs		Age 30 Yrs		Ratio infant:30 yrs	Ratio infant:30 yrs
	Male	Female	Male	Female	Male	Female	Male	Female
Colon	336	220	285	187	125	82	2.69	2.68
Lung	314	733	261	608	105	242	2.99	3.03
Breast	N/A	1171	N/A	914	N/A	253	N/A	4.63
Thyroid	115	634	76	419	9	41	12.78	15.46
leukemia	237	185	149	112	84	63	2.82	2.94
All solid	2326	4592	1667	3265	602	1002	3.86	4.58
All cancers	2563	4777	1816	3377	686	1065	3.74	4.49

Source: National Research Council 2006 as published in Makhijani, Smith, and Thorne 2006, p. 38.

The female-male cancer risk ratio for all cancers combined and some selected cancers is shown in in Figure 2-2. The overall ratio of cancer risks experienced by females declines from almost 2 at infancy to 1.19 at age 70 years. The risk ratio for many cancers such as lung (greater than one for females) or colon

(greater for males than females) stays about the same throughout life; that is not true of all cancers.

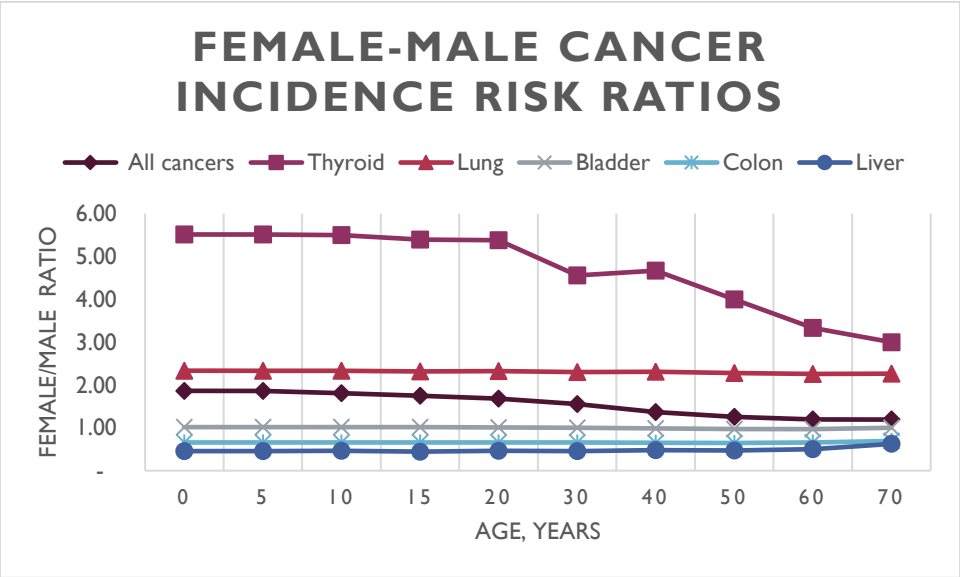

Figure 2-2: Female-to-male cancer incidence risk ratios
Source: National Research Councill 2006, Table 12D-1, p. 311

Among the cancers shown in Figure 2-2, the decline in the female/male ratio is dominated by thyroid cancer. Biegon, Cohen and Franceschi (2022) provide evidence that this is related to hormonal factors:

> "Available data on cancer secondary to ionizing radiation consistently show an excess (2-fold amount) of radiation-attributable solid tumors in women relative to men. This excess risk varies by organ and age, with the largest sex differences (6- to more than 10-fold) found in female thyroid and breasts exposed between birth until menopause (~50 years old) relative to age-matched males. Studies in humans and animals also show large changes in cell proliferation rates, radiotracer accumulation and target density in female reproductive organs, breast, thyroid and brain in conjunction with physiological changes in gonadal hormones during the menstrual cycle, puberty, lactation and menopause."

b. Atmospheric testing-related radionuclides and radiation doses[16]

Among the radionuclides listed below, only carbon-14 and tritium occur in significant quantities in nature. The tritium injected into the atmosphere by atmospheric testing far exceeded accumulated natural amounts. While natural amounts of C-14 are greater, most reside outside the atmosphere. The atmospheric injection of C-14 by testing was greater than the natural accumulated C-14. All other radionuclides either do no occur in nature or, like plutonium, are present in very trace quantities.

Carbon-14, a beta-emitter, was produced in copious quantities due to the interaction of neutrons from the explosions with atmospheric nitrogen. The estimated 220 PBq produced was quickly oxidized into carbon-14 dioxide, and became part of the food chain. Equilibrium in human tissue with non-radioactive carbon took just 1.4 years. Its long half-life (5,730 years) means that it will repeatedly circulate through ecosystems and living beings for tens of thousands of years, producing small individual doses but large

[16] This section is based on UNSCEAR 1982, Annex E, unless otherwise stated.

cumulative effects.[17]

The organ most affected is the bone marrow; cumulative doses are estimated at 53 million person-gray.[18] Bone lining cells are next, at 49 million person-gray. The committed dose equivalent over time is estimated to be 26 million person-sieverts, almost all due to the ingestion pathway. A population of 10 billion is assumed for evaluating global dose.

Cesium-137, half-life 30.1 years, is a chemical analog of potassium, an essential element in diet. As a result, almost the entire population dose is via the food pathway – 2.2 million person-sieverts. Cesium-137 "becomes relatively uniformly distributed in soft tissues"; there is little in the bones or fat. The "representative retention assumptions for the adult are that 10% is excreted with a half-time of 2 d[ays] and 90% with a half-time of 110 d[ays]." (UNSCEAR 1982, Annex E, p. 221). In other words, once ingested essentially all of it will be excreted in two to three years. An estimated 960 PBq was injected into the stratosphere as a result of atmospheric testing and then redeposited all over the world, mainly in the northern hemisphere.

Strontium-90, half-life 28.6 years, is a bone seeker; it is a calcium analog. Sr-90 and its decay product yttrium-90 are powerful beta emitters. The global ingestion dose to a population of 4 billion is estimated at 440,000 person-sieverts. The main target organs are the bone marrow and the cells of the bone lining. About 600 PBq were produced.

Tritium,[19] half-life 12.3 years, was produced in the largest amounts by atmospheric of all long-lived radionuclides. Like carbon-14, it is a product of the interaction of the interactions of neutrons from bomb tests with atmospheric nitrogen. The total amount of tritium so produced was 100 million TBq. While about seven times less than iodine-131, a substantial amount, 5 million TBq still remained in the environment by the end of 2025, while iodine-131 decayed away about three months after it was created.

Tritium is also routinely emitted to the atmosphere and discharged into waterways or oceans by nuclear power plants. Since it is radioactive hydrogen, it combines with oxygen to form radioactive water (HTO or T_2O), which is chemically indistinguishable from ordinary water, the staff and stuff of life. One teaspoon of HTO (five grams) is enough to contaminate 400 billion liters of water to the U.S. drinking water limit.

The cumulative tritium dose from atmospheric testing is estimated at 190,000 person-sieverts, mainly from ingestion of drinking water but also from food. There is essentially no external dose associated with tritium.

Iodine-131, is extremely radioactive (beta and gamma radiation) due to its short half-life (8.1 days). The amount injected into the atmosphere, 700 million terabecquerels, was more than one thousand times the amount of strontium-90. It is the main cause of the increase in thyroid cancer risk. Other thyroid ill-effects, such as nodules, also occur (Zupunski et al. 2019). The global collective thyroid dose was estimated to be 3.5 million person-gray. As noted, children, and especially female infants would have been most impacted.

In addition to cancer impact, disruption of thyroid functioning in pregnant women creates risks for the

[17] The natural annual production rate of carbon-14 in the atmosphere is about 1 PBq. The amount naturally accumulated over the eons is 8,500 PBq. The natural atmospheric inventory is estimated at 140 PBq (UNSCEAR 1982, Annex B).
[18] UNSCEAR 1982 cites doses from beta emitters like C-14 in gray; the assumed weighting factor being 1, this is equivalent to dose in sieverts.
[19] Refer to Makhijani 2023 for extensive discussion on the health impacts of tritium.

fetus (Makhijani 2026). This risks have not yet been taken into systematic account in considering the damage that atmospheric testing did to people all over the world, disproportionally in the countries and areas where testing occurred, but also likely in hot spots. For instance, the 1954 series of U.S. tests in the Marshall Islands created hot spots thousands of miles from the test sites in that country, including in Mexico City and Colombo (Sri Lanka). (See maps in List 1955, pdf pp.20-21.)

Estimates of thyroid doses are quite variable. For instance, official estimates of thyroid doses in the more affected parts of the Marshall Islands made by the US government scientists have varied over time (Makhijani 2025, p. 25). The gap between independent estimates and the government estimates is large, as can be seen in Table 2-2.

Table 2-2: U.S. Department of Energy and Sanford Cohen & Associates (SC&A) estimates of Utirik thyroid doses.

Thyroid dose (mGy)	DOE	SC&A	Ratio SC&A/DOE
Adult	1,550	27,000	17.4
Child	3,200	34,000	10.6
Infant	6,600	59,000	8.9

Source: As compiled in Makhijani 2025, Table 4-4, p. 26

Zirconium-95, ruthenium-106 and cerium-144 are relatively short-lived radionuclides. Those created by atmospheric testing have completely decayed away. During the years of atmospheric testing and immediately after their main impact was via external dose (due to gamma radiation) and via inhalation of radioactive particles. The total global dose was a little over one million person-sieverts.

Plutonium-239, half-life 24,110 years, was dispersed all over the world. Only a fraction was consumed during nuclear weapons explosions. The rest remained un-fissioned and was dispersed all over the world. Some plutonium was also created by neutron bombardment of the uranium-238 in the tertiary part of thermonuclear weapons. About 4,000 kilograms of plutonium-239 were dispersed. Weapons-grade plutonium contains a few percent plutonium-240 and a smaller amount of plutonium-241, which is a short-lived beta emitter that decays into alpha-emitting americium-241.

The bone surface and bone marrow are the most targeted organs, followed by gonads and lungs. The impact is mainly via inhalation, since plutonium is not easily taken up from the gut. The global dose is estimated at 220,000 person-sieverts.

c. Non-cancer health impacts

i. Cardiovascular disease

The BEIR VII assessment concluded that an elevated risk of cardiovascular disease has been shown at doses experienced by Hiroshima -Nagasaki survivors and patients exposed to radiation for therapeutic purposes (National Research Council 2006, p. 8):

> "In addition to cancer, radiation exposure has been demonstrated to increase the risk of other diseases, particularly cardiovascular disease, in persons exposed to high therapeutic doses and also in A-bomb survivors exposed to more modest doses. However, there is no direct evidence

of increased risk of noncancer diseases at low doses, and data are inadequate to quantify this risk if it exists."

As to the specifics, the BEIR VII report noted that (National Research Council 2006, pp. 185-186):

> "Both animal and human studies have identified intimal thickening, lipid deposition, and adventitial fibroses of the vascular system following irradiation. These changes are associated with atherosclerosis and the normal aging process, although irradiation may accelerate the development of these conditions."

ii. Thyroid diseases other than cancer

Despite the well-known prominence of thyroid exposure, including in children, the BEIR VII report noted in 2006 that "relatively little has been published regarding thyroid outcomes other than thyroid cancer, although one study has reported an elevated risk of benign thyroid tumors" (National Research Council 2006, p. 225). Almost two decades later, this problem continued, though the evidence for thyroid dysfunction due to low-dose radiation exposure has mounted. We quote in full the conclusions of a 2025 systematic review in this regard (Colaprico et al. 2025, italics added):

> "Studies present different results regarding the correlation between exposure to LDIR [low dose ionizing radiation] and thyroid dysfunction. From our review, it emerges that in the literature there are few studies relating to the correlation between LDIR and thyroid function, and these studies present data that are sometimes conflicting with each other. *It is clear, however, that even at low doses, it negatively affects the activities of the thyroid*. In this regard, it is necessary to collect more documentation, carry out new studies in order to delve deeper and define this topic, and, consequently, outline useful measures with the aim of ensuring the protection of workers in contact with this particular physical agent."

iii. Major birth defects and multigenerational impacts

The problem of major birth defects due to exposure to nuclear testing fallout was identified early on as a major issue. There was extensive discussion, in official reports and other literature of the problem, including an assertion in the California Engineer, a 1960 University of California alumni magazine estimate that there would be "an additional 6,000 babies born with major birth defects" worldwide due to U.S. nuclear weapons testing but that this risk should be weighed against "the demonstrated need of the United States for a nuclear arsenal" and specifically for tactical nuclear weapons to fight "brushfire wars" like the Korean War (California Engineer 1990)

In 1958, double Nobel-Prize winner Linus Pauling (Chemistry and Peace) wrote about genetic defects from nuclear testing, and specifically carbon-14 exposure, in *Science*, the premier U.S. peer-reviewed scientific journal (Pauling 1958). Despite this early recognition of the risks, major gaps remain, especially in regard to internal radiation due to radionuclides that cross the placenta and multigenerational impacts. In 1999, the Institute for Energy and Environmental research explicitly asked the BEIR VII Committee to consider this issue; the committee, in its 2006 report, punted it to a future date by saying that "this issue be addressed as part of a larger review of maternal exposures in humans that may affect the fetus" (National Research Council 2006, Appendix C). In letter to another National Academies committee in 2022, this author noted that that larger review had still not been done (Makhijani 2022).

More detail on teratogenic and multigenerational impacts is provided in Makhijani 2026.

iv. Mitochondrial damage and oxidative stress

Damage to mitochondria, including to mitochondrial DNA, has also been a surprisingly neglected topic,

notably in regard to non-cancer risks, including birth defects and other reproductive impacts. This gap also has major implications for how the impact of radiation is considered on other living beings. Specifically, mitochondria are core of the energy system of human beings and of all other multicellular beings -- animals, plants, and fungi. Mitochondrial damage and dysfunction creates a variety of risks. It can result when there are excess reactive oxygen species (ROS) in the cytoplasm, as occurs, for instance, when the water there is ionized by ionizing radiation.

BEIR VII discusses nuclear DNA (nDNA) damage by oxidative stress created by the ionization of water by photons (gamma radiation), while noting that "[w]ater molecules make up 70% of human tissue." It specifically cites the reactions that result in the formation of the highly reactive hydroxyl radical (OH•) and the ionization of DNA that may result (National Research Council 2006, p 29):

> "The relatively long-lived (about 10^{-5} s) OH• radical is believed to be the most effective of the reactive species; as an oxidizing agent, it can extract a hydrogen atom from the deoxyribose component of DNA, creating a DNA radical. Early experiments demonstrated that about 70% of the DNA damage can be prevented by the addition of OH• scavengers."

The focus on nDNA, while important especially from the point of view of cancer risk, misses a problem that is at least as important. The water in human tissue is in the cytoplasm, where the mitochondria are located. The main volume of the cytoplasm (and the cell), consists of cytosol, which consists of a variety of substances dissolved in water. Almost all human cell types have hundreds or thousands of mitochondria, which make ATP, the main chemical currency of human energy. Oocytes have many more. Mitochondria are remnants of bacteria with their own DNA.

Mitochondrial DNA (mtDNA) is a relatively simple circular structure; it has about 16,600 base pairs, compared to over 3 billion for nDNA. Moreover, unlike nDNA, mtDNA has very limited capacity for repair. When tritiated water is ingested, it pervades every cell and ionizes water in the cytoplasm, creating excess ROS, including hydroxyl radicals, and oxidative stress that can damage mtDNA and cause mitochondrial dysfunction.

Moreover, the nucleus, while the largest single organelle in the cell, is only roughly 10% of its volume; nDNA, in turn is a small volume within the nucleus. The likelihood of oxidative damage by water ionization is, therefore, far greater in the cytosol, which has a much larger volume and where there are hundreds to thousands of mitochondria. Tritium should be a focus of examining such damage, because when ingested as tritiated water, it pervades the body and its cells.

Despite these realities, The BEIR VII report does not even mention, much less discuss, mtDNA damage and resultant dysfunction due to oxidative stress created by water ionization in the cytosol.[20] There is one passing reference to oxidative mitochondrial damage, but in the context of a criticism of a paper that the authors did not agree with (National Research Council 2006, p. 332). The lack of attention to the problem was still and issue in 2022, as noted in a National Academies report (see Makhijani 2026).

This lack is especially troubling since mitochondria are a basic link between the environment and the nucleus (Castegna, Iacobazzi, and Infantino 2015):

> "Mitochondria represent the machinery by which stimuli from the environment can translate into epigenetic regulation of gene expression. Mitochondrial metabolism controls the levels of key signaling molecules….Therefore, mitochondrial dysfunctions can modify the expression of nuclear genes involved in metabolism, signaling, growth, differentiation, and apoptosis."

[20] Based on a search of the document for the following terms: "mtDNA"; "mitochondrial DNA"; and "mitochondrial."

Stimuli from the environment can be positive and essential. In this context, it Is to be noted that "[t]he bidirectional cross talk between nuclear and mitochondrial DNA is essential for cellular homeostasis and proper functioning" (Castegna, Iacobazzi, and Infantino 2015). But environmental stimuli can also be disruptive, like exposure to external ionizing radiation or ingestion of radionuclides like tritium and iodine-131, as well as non-radioactive toxicants like heavy metals. Among other things, they cause oxidative stress and mtDNA damage leading to dysfunction and disruption of homeostasis.

The issue is also important for multigenerational impacts. The embryo is not homeostatic. Once the ovum is fertilized, the zygote moves towards the uterus; implantation takes a week. The mitochondria from the sperm are stripped; the mitochondrial genetic inheritance is entirely maternal. Cell division and cell differentiation take place rapidly. Most organogenesis occurs in the first trimester.

In particular, mitochondria play a role in nDNA methylation (Laaksonen et al. 2021), a process that turns genes in the nucleus on and off, including during embryogenesis. Disruption and errors in DNA methylation can lead to "devastating consequences" (Phillips 2008):

> "There are many ways that gene expression is controlled in eukaryotes, but methylation of DNA (not to be confused with histone methylation) is a common epigenetic signaling tool that cells use to lock genes in the "off" position. In recent decades, researchers have learned a great deal about DNA methylation, including how it occurs and where it occurs, and they have also discovered that methylation is an important component in numerous cellular processes, including embryonic development, genomic imprinting X-chromosome inactivation, and preservation of chromosome stability. Given the many processes in which methylation plays a part, it is perhaps not surprising that researchers have also linked errors in methylation to a variety of devastating consequences, including several human diseases."

While the evidence is not yet definitive, one of the consequences "epigenetic changes induced by maternal factors during fetal life" may be an increased risk of autoimmune diseases, and specifically of Type 1 diabetes (Barchetta et al. 2021). Epigenetic markers, including those that may be caused by adverse environmental experience, can be inherited for one or more generations. It also occurs in other animals and plants (Horsthemke 2018; Lacal and Ventura 2018).

As problematic as the relative neglect of mtDNA in human health and disease, is a similar pattern in assessing the impact on other living beings and, hence, on ecosystems. All eukaryotes have nuclei and cytoplasm with cytosol, and hence water. They are therefore subject to similar oxidative stress risks resulting from ionization of water and consequent creation of hydroxyl radicals; mtDNA damage is one consequence. Yet, the allowable body burdens of internal radionuclides in non-human creatures is far larger than that of humans.

For instance, consider a great-horned owl found on the property of Los Alamos National Laboratory and reported upon in its 2017 Environmental Report (LANL 2018, p. ES-3):

> "A great-horned owl that was collected at Area G had 14,800 picocuries per milliliter of tritium. The internal tritium dose to the great horned owl from this measured tissue concentration was 0.0043 rad per day. The dose was well below the DOE limit of 0.1 rad per day for animals."[21]

A pocket gopher with more than ten times the tritium concentration was found; the great-horned owl's apex-predator diet was offered as an explanation for its high tritium body burden (LANL 2018, p. 7-26).

[21] Area G of Los Alamos National Laboratory is a 63-acre (25-hectare) radioactive waste disposal and storage area. The Laboratory's description of the site is at the following link: https://n3b-la.com/what-we-do/waste/area-g-tru/

The estimated great-horned owl dose is almost 16 times the maximum human limit of 1 mSv/year. The concentration in the owl's body was 740 times the U.S. standard for tritium in (human) drinking water. The framework essentially ignores the large commonality between human beings and other animals, notably in the role of mitochondria.

There is evidence that reproductive harm can occur at levels of tritium exposure orders of magnitude lower than the concentration in the owl.[22] In fact, it has been shown to occur at tritium concentrations below the U.S. drinking water standard. Two examples – harm to carp eggs (Bondareva, Kudryasheva, and Tananaev 2022) and to goose barnacle molting (Abbot and Mix 2026) – were cited in Makhijani 2026.

Bondareva, Kudryasheva, and Tananaev 2022 also studied plants and microorganisms as well as the impact of conversion of free, non-organically-bound tritium into organically-bound tritium. They found that tritium bioaccumulates particularly in the liver of fish, where its biological half-life as long as 550 days. They concluded that "despite the low energy of tritium decay, its influence on living organisms in water environments may be considerable. The activation of microbial functions in natural reservoirs, due to the low content of tritium, may result in unpredictable changes in food chains and an imbalance of natural equilibria."

The facts that reproductive disruption has been shown at contamination levels below the U.S. drinking water standard and that bioaccumulation occurs, for instance in fish liver where is it bound as non-exchangeable tritium with a long half-life (relative to tritiated water), provide evidence of reproductive and ecological risks that should be considered much more seriously and comprehensively than they have been, especially as tritium is the most ubiquitous pollutant associated with both nuclear weapons and nuclear power.

[22] Concentration in the body and rate of tritium ingestion are related through the biological half-life of tritium in the body, which is typically short if it is in the form of water. However, non-exchangeable organically-bound tritium can have a biological half-life that is far longer.

3. Radiation protection standards

Radiation protection guidelines date back over a century to the time when experimenters and medical personnel discovered somatic, non-stochastic harm from exposure. As a result the initial guidelines were very high by today's standards. They were tightened during the Manhattan Project. Cancer, while a known risk early on, became an increasing concern after the atomic bombings of Hiroshima and Nagasaki, though explicit limits for public exposure, distinct from and much lower than worker exposure limits, were only set in the late 1950s.

The table below summarizes the development of guidelines and standards. It is based on Meinhold, Taschner, and Inkret 1995, including the words in quotes, unless explicitly noted.[23]

Table 3-1: Evolution of radiation protection guidelines and standards

Date	Guide or standard	Comments
1902	0.1 Gy/day (30 Gy/year)	Based on visible evidence of dermatitis rather than health protection. Skin dose.
1924	0.7 Sv/y	Recommendation based on one-hundredth of observed x-ray dose causing skin redness (erythema). Skin dose.
1934	0.1 roentgen/day (about 0.3 Gy/year)	The "first formal standard" proposed by the U.S. Advisory Committee on X-ray and Radium Protection.
1941	0.1 microgram radium body burden	Based on observed "devastating experiences of the radium-dial painters" at or above one microgram body burden. The plutonium "tolerance limit" of 5 micrograms (about 0.3 microcuries or 10 kBq), set in 1944 (during the Manhattan Project), was based on the 1941 radium limit. Reduced to 0.06 microcuries (2 kBq) in 1945.
1957	50 mSv/yr for workers	Proposal of the International Commission on Radiation Protection (ICRP).
1958	5 mSv/year individual member of the public	National Council on Radiation Protection and Measurements (NCRP) proposal.
1958	0.17 mSv/year/person average for a population	NCRP proposal.
1989-1990	20 mSv/year (workers) and 1 mSv/year (public individual dose)	20 mSv/year has been widely adopted but not by the United States where 50 mSv/year for workers is the limit.
1970s-2000	0.25 mSv/year nuclear fuel cycle, 0.04 mSv drinking water (man-made radionuclides)	U.S. standards (EPA 2006 and EPA 2000). The 0.25 mSv limit is for the whole body or any organ, except the thyroid, for which the limit is 0.75 mSv/year.

[23] Meinhold, Taschner, and Inkret 1995 uses U.S. units (curies, rad, rem). The table shows the values in Standard International units. The same is the case when U.S. regulations are cited. For radioactivity both units are shown.

The limits in the standards are complemented by two principles to ensure that they do not become a license for exposing the public to radiation up to the limit. The first principle is known as "justification"; the second is "optimization."

a. Justification

The General Safety Guide of the International Agency for Atomic Energy (IAEA) defines "justification" as follows (IAEA 2018, p. 6):

> "For planned exposure situations, justification is the process of determining whether a practice is, overall, beneficial, i.e. whether the expected benefits to individuals and to society from introducing or continuing the practice outweigh the harm (including radiation detriment) resulting from the practice. The benefits apply to individuals and society as a whole, and include benefits to the environment. Radiation detriment may only be a small part of the total harm. Justification thus goes far beyond the scope of radiation protection, and also involves the consideration of economic, societal and environmental factors."

Thus, radiation exposure should not be imposed upon a public that gets no benefit; and when there is a putative benefit, it must be evaluated against the harm. One critical consideration in determining whether an exposure is justified related to cross-border exposure. Specifically, is exposure to the public beyond the borders of the country that is the source of exposure justified?

Within countries where there is a democratic process for determining exposure limits, such as publication of a draft standard with estimated harm that may be inflicted on that country's public, one might say, with some reason that, despite disagreement over the specific limits, there has been consideration of whether the activity resulting in the exposure is justified. The situation is different when the source is in one country and exposures also extend beyond its borders. This has been most demonstrably the case with atmospheric nuclear weapons testing. The entire world was exposed. But any putative security benefits would be to the people of the country testing the weapons, leaving aside the difficult issues of whether there has been a net benefit from nuclear weapons testing to any society, how costs and benefits should be calculated, and over what periods of timey.

Considerations of justification were not current at the time of atmospheric testing. But they have been for decades now; they are therefore important in two critical ways:

- Retrospectively, since the people of non-nuclear weapons states received no benefits, however questionable they may be for the weapons states themselves.
- Prospectively for future generations, since the harms from past exposure and as well as exposures from contamination related to nuclear weapons production and testing will continue for generations.

Both of these points are more poignant and important in the context of Articles 6 and 7 of the Treaty on the Prohibition of Nuclear Weapons (TPNW 2017).

While the TPNW does not include harm from nuclear weapons production processes, there has been harm in non-nuclear countries in the extraction of uranium, especially in colonially-ruled countries, as for example with Congo during Belgian rule. The problem of justification for multigenerational exposure has yet to be substantively addressed, despite the long half-lives of several nuclear-weapons production and testing-related radionuclides.

b. Optimization

If an exposure is justified, it must be optimized. The IAEA safety guide provides a specific definition for optimization IAEA 2018, p. 7, italics added):

> "Optimization of protection and safety is defined as the process for determining what level of protection and safety would result in the magnitude of individual doses, the number of individuals (workers and members of the public) subject to exposure and the likelihood of exposure being *as low as reasonably achievable (ALARA)*, economic and social factors being taken into account. This means that the level of protection would be the best possible under the prevailing circumstances, and will thus not necessarily be the option with the lowest risk or dose. *Protection of the environment should also be considered in the process of optimization* of protection and safety."

There are specific procedures for the implementation of ALARA to ensure its achievement. For instance, the U.S. Nuclear Regulatory Commission even provides a numerical limit of 0.1 mSv/year – well below the 0.25 mSv/year limit in EPA 2006, as its ALARA guide for its nuclear power operations licensees (NRC 2022 at 10 CFR 20.1101(d)).

c. Protecting reproduction

There are no specific standards for protecting the embryo and fetus of pregnant members of the public. They are regarded as any other member of the public without any consideration of the embryo/fetus they are carrying. Radiation exposure limits have generally been set in the context of limiting cancer risks. Adverse pregnancy outcomes notably in terms of early failed pregnancies and teratogenic impacts have received little or no regulatory attention.

The gaps in the knowledge of multigenerational impacts especially resulting from exposure in the first trimester, are large. These are more notable for internal exposure to high-LET radiation and radiation not defined as high-LET, such as tritium beta particles that nonetheless deposit energy is a small volume (Makhijani 2023). In view of this major gap, Makhijani 2026 recommended that drinking water standards be tightened for man-made radionuclides as a precautionary measure and to correspond to the lowest level of cancer risks specified in the U.S. remediation standard for very contaminated sites (popularly called Superfund sites. This implies the specific limits for drinking water for long-lived, man-made radionuclides shown in Table 3-2. See Makhijani 2009 for more discussion.

Table 3-2:Suggested maximum contaminant protective limits for drinking water for some man-made radionuclides in millibecquerels per liter, when one radionuclide is present

Radionuclide	Recommended drinking water limit milliBq/L
Tritium	15,000
Cesium-137	24
Strontium-90	13
Plutonium-239/240, americium-241	6

Corresponding standards should also be set for food. The current standard for uranium in drinking water is 30 micrograms per liter. It should be tightened to 2 micrograms per liter (Makhijani 2026a).

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