INL/MIS-23-73793-Revision-0

Health effects of Radiation and Radioactivity + Historic Nuclear Accidents

August 2023

Changing the World's Energy Future

River Bennett

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-23-73793-Revision-0

Health effects of Radiation and Radioactivity + Historic Nuclear Accidents

River Bennett

August 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Health Effects of Radiation and Radioactivity Plus Historic Nuclear Accidents

July 2023

River Bennett
Idaho National Laboratory

NRIC | INL Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC.

DISCLAIMER

Protecting People and Planet |

Health Effects of Radiation and Radioactivity Plus Historic Nuclear Accidents

The safety of nuclear energy technology goes hand-in-hand with a modern understanding of the health impacts and required precautions associated with radiation. This is because nuclear power plants require fuel sources, like uranium, which is an element that is naturally radioactive.

1. RADIATION IN EVERYDAY LIFE

From the International Atomic Energy Agency (IAEA):[a]

Naturally occurring radioactive materials are present in the Earth's crust, the floors and walls of our homes, schools, or offices, and in the foods and beverages we consume. There are radioactive gases in the air we breathe. Our own bodies—muscles, bones, and tissue—contain naturally occurring radioactive elements.

Since the dawn of humankind, we have been exposed to this radiation on Earth from space in the form of cosmic radiation or cosmic rays. We face significant exposure when we travel by airplane, for example. We also receive exposure from human-made radiation, such as X-rays, disease diagnostics, and cancer therapy. Fallout from nuclear explosives testing, and small quantities of radioactive materials released to the environment from coal and nuclear power plants, are also sources of radiation in the biosphere.

Radioactivity is the term used to describe the disintegration of atoms. The speed at which atoms disintegrate over time remains constant regardless of external influences, such as temperature or pressure. The time it takes for half the radionuclides to disintegrate or decay is called half-life. This differs for each radioelement, ranging from fractions of a second to billions of years. For example, the half-life of iodine-131 is eight days, but for uranium-238, which is present in varying amounts all over the world, it is 4.5 billion years. Potassium-40, found in bananas and representing the main source of radioactivity in our bodies, has a half-life of 1.42 billion years.

On average, our radiation exposure due to all natural sources amounts to about 2.4 millisievert (mSv) a year—though this figure can vary, depending on the geographical location, by several hundred percent. In homes and buildings, there are radioactive elements in the air. These radioactive elements are radon (radon-222), thoron (radon-220), and byproducts formed by the decay of radium (radium-226) and thorium present in many rocks, other building materials, and the soil. By far, the largest source of natural radiation exposure comes from varying amounts of uranium and thorium in the soil around the world.

The radiation exposure due to cosmic rays is dependent on altitude, and slightly on latitude as people who travel by air increase their exposure to radiation.

[a] https://www.iaea.org/Publications/Factsheets/English/radlife#protection

2. RADIATION IMPACTS AND DOSE

From the IAEA and U.S. Centers for Disease Control (CDC):[b]

The term "radiation" is broad and includes such things as light and radio waves. In our context, it refers to "ionizing" radiation, which can cause matter to become electrically charged or ionized. In living tissues, the electrical ions produced by radiation can affect normal biological processes. But as with other types of toxins, “the dose makes the poison.”

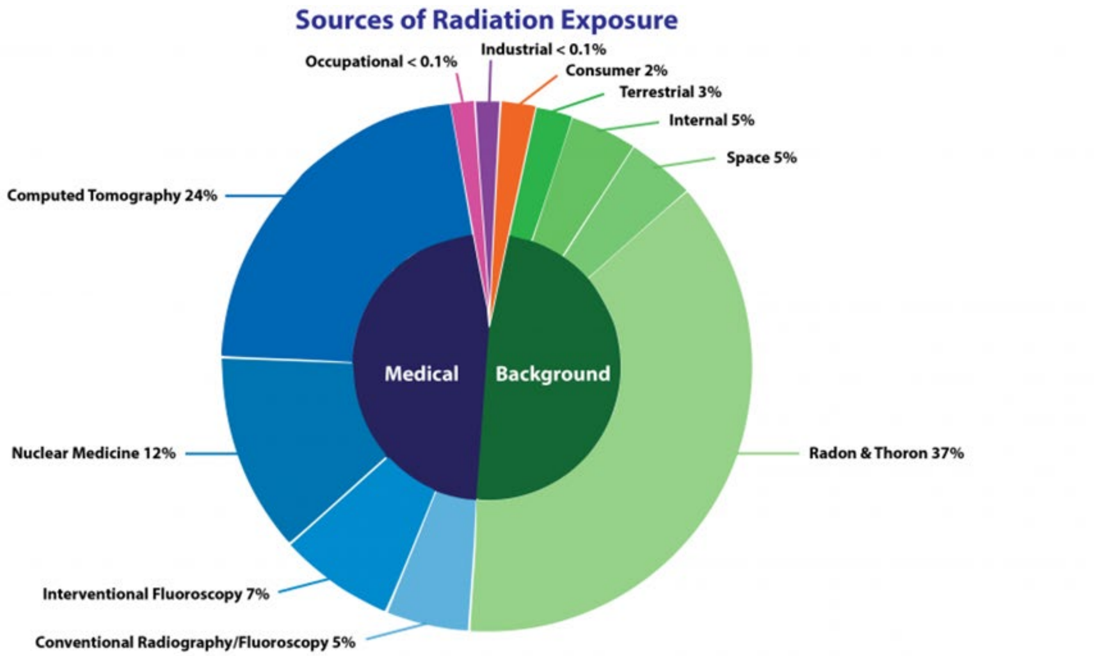
Radiation exposure is one of humanity’s best-understood health hazards. We have been studying the effects of radiation for over 100 years, so we know quite a bit about how radiation interacts with living tissue. It is the radiation dose, or the amount of radiation, which is critical in determining health consequences. It is helpful to put radiation dose in perspective. We receive low doses of radiation from our natural environment. However, we know that radiation at high doses can be lethal. We know that radiation can cause cancer, and we also know radiation can be harmful to a fetus at various stages of development. And, although we haven’t seen it in humans, radiation can cause abnormal hereditary effects in lab animals.

How the dose is received will determine its health impacts:

- How fast the dose is received: The dose received within a quantifiable unit of time is known as the dose rate. If a person receives a dose over an extended period of time, the impact on health won’t be as severe as if the same dose were received all at once.
- Where the dose is received: The location of radiation dose is very significant to any occurrence of radiation exposure. Should the dose be received by the vital organs within the trunk of the human body or the head the effects are likely to be much more severe when compared to the body’s extremities like the hands or feet.
- How sensitive the body is to radiation: Individual sensitivity to radiation is also a factor. A developing fetus is the most vulnerable to the effects of radiation. Infants, children, the elderly, pregnant women, and people with compromised immune systems are more vulnerable to health effects than healthy adults.

The biological effects of ionizing radiation vary with the type and energy. Depending on the dose, the effect can range from being negligible to causing cell damage and an increased risk of cancer. A measure of the risk of biological harm is the dose of radiation that the tissues receive. The unit of absorbed radiation dose is the sievert (Sv). Since one sievert is a large quantity, radiation doses normally encountered are expressed in millisievert (mSv) or microsievert (μSv) which are one-thousandth or one millionth of a sievert, respectively. For example, one chest X-ray will give about 0.2 mSv of radiation dose.

[b] https://www.cdc.gov/nceh/radiation/dose.html#how



Average Annual Radiation Dose

Sources	Radon & Thoron	Computed Tomography	Nuclear Medicine	Interventional Fluoroscopy	Space	Conventional Radiography/ Fluoroscopy	Internal	Terrestrial	Consumer	Occupational	Industrial
Units mrem (United States) mSv (International)	228 mrem 2.28 mSv	147 mrem 1.47 mSv	77 mrem 0.77 mSv	43 mrem 0.43 mSv	33 mrem 0.33 mSv	33 mrem 0.33mSv	29 mrem 0.29 mSv	21 mrem 0.21 mSv	13 mrem 0.13 mSv	0.5 mrem 0.005 mSv	0.3 mrem 0.003 mSv

(Source: National Council on Radiation Protection & Measurements, Report No. 160)

Figure 1: Sources of radiation exposure. Source: https://www.epa.gov/radiation/radiation-sources-and-doses

3. RISKS AND BENEFITS[c]

The use of radiation and nuclear techniques in medicine, industry, agriculture, energy, and other scientific and technological fields has brought tremendous benefits to society. The benefits in medicine for diagnosis and treatment—in terms of human lives saved—are enormous. Radiation is a key tool in treating certain kinds of cancer. Three out of every four patients hospitalized in the industrial countries benefit from some form of nuclear medicine. Applications of nuclear techniques in other industries have experienced similar benefits. Examples include non-destructive testing of materials techniques, electronic sensors or detector systems, security imaging or screening technologies, and many more.

[c] https://www.iaea.org/Publications/Factsheets/English/radlife

Table 1: Average annual radiation exposure in the United States.

Occupation	Dose (mSv)	Source
U.S. Citizen	3	U.S. NRC: Biological Effects of Radiation
Interventional Radiologist	4	Radiological Society of North America
Uranium Mine Worker	4–6	NRC (Nuclear Regulatory Commission)
Nuclear Power Plant Worker	4–6	NRC (Nuclear Regulatory Commission)
Airline Crew	5–6	CDC: Aircrew Safety & Health (Centers for Disease Control)
Intl. Space Station Crew (6 months)	80–160	NASA: Space Radiation, v.3.08 (National Aeronautics and Space Administration)

4. WHAT KIND AND HOW MUCH RADIATION IS PRODUCED BY A NUCLEAR POWER PLANT?[d]

An operating nuclear power plant produces very small amounts of radioactive gases and liquids, as well as small amounts of direct radiation. If you lived within 50 miles of a nuclear power plant, you would receive an average radiation dose of about 0.0001 mSv per year. To put this in perspective, the average person in the United States receives an exposure of 3 mSv per year from natural background sources of radiation.

5. RADIATION EXPOSURES FROM THE THREE MILE ISLAND, CHERNOBYL, AND FUKUSHIMA ACCIDENTS

History's three largest civilian nuclear incidents have had varying impacts on the public health of communities and regions surrounding the plants where these incidents took place. However, the differences in impact between these accidents demonstrate the safety improvements of nuclear power over time.

5.1 The Three Mile Island Accident

From the U.S. Nuclear Regulatory Commission (NRC) and Environmental Protection Agency (EPA)[e][f]

The Three Mile Island Unit 2 reactor, near Middletown, Pennsylvania, partially melted down on March 28, 1979. This was the most serious accident in U.S. commercial nuclear power plant operating history, although its small radioactive release had no detectable health effects on plant workers or the public. An interagency analysis concluded that the accident did not raise radioactivity far enough above background levels to cause any cancer deaths among the people in the area. The analysis found no contamination in water, soil, sediment, or plant samples.

Its aftermath brought about sweeping changes involving emergency response planning, reactor operator training, human factors engineering, radiation protection, and many other areas of nuclear power plant operations. It also caused the NRC to tighten and heighten its regulatory oversight. All of these changes significantly enhanced reactor safety in the United States.

[d] https://www.nrc.gov/about-nrc/radiation/related-info/faq.html

[e] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

[f] https://web.archive.org/web/20110318094452/http://www.epa.gov/history/topics/tmi/02.htm

5.2 The Chernobyl Disaster

From the NRC and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[g][h][i]

The Chernobyl disaster was caused by an explosion that took place on April 26, 1986, at Unit 4 of the Chernobyl nuclear power plant in Ukraine, which was part of the Soviet Union at the time. It is considered the worst man-made civilian nuclear accident in history that resulted from flaws in the reactor design as well as a severe breach of safety protocols during testing. The accident and the fire that followed released massive amounts of radioactive material into the environment. The Chernobyl disaster is one of only two accidents that has received the maximum rating of a seven on the International Atomic Energy Agency's (IAEA) International Nuclear Event Scale (INES).

To date, the disaster has claimed fewer than 100 lives from the immediate explosion, acute radiation exposure, and induced-cancers caused by the initial radiological contamination release. These attributable deaths have taken place within the groups of plant workers and emergency responders present at the accident. Long-term health impacts are estimated to claim 4,000 lives among cleanup workers and Chernobyl residents as a result of various illnesses stemming from radiation exposure.

5.3 The Fukushima Disaster

From the NRC UNSCEAR.[j][k]

On March 11, 2011, a 9.0-magnitude earthquake struck Japan about 231 miles (372 kilometers) northeast of Tokyo off the Honshu Island coast. Eleven reactors at four sites (Fukushima Dai-ichi, Fukushima Dai-ni, Onagawa, and Tokai) along the northeast coast automatically shut down after the quake. Fukushima Dai-ichi lost all power from the electric grid, with diesel generators providing power for about 40 minutes. At that point, an estimated 45-foot-high (14 meter) tsunami hit the site, damaging many of the generators. Four of six Fukushima Dai-ichi reactors lost all power from the generators. The tsunami also damaged some of the site's battery backup systems. The Fukushima Dai-ichi nuclear disaster is the only other event since Chernobyl to receive a seven rating on the INES.

While the severity of the Chernobyl and Fukushima disasters is comparable, the public health impact of the latter has been significantly smaller. The 2013 UNSCEAR Report "Levels and Effects of Radiation Exposure Due to the Nuclear Accident After the 2011 Great East-Japan Earthquake and Tsunami" concluded[l] that in the region affected, cancer will remain stable, no impact will be registered on birth defects/hereditary effects, and no discernible increase in cancer rates for workers is expected. However, a temporary impact on wildlife was recorded, and researchers acknowledge a theoretical increased risk of thyroid cancer among most exposed children.

[g] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/chernobyl-bg.html

[h] https://www.unscear.org/unscear/en/chernobyl.html

[i] https://www.un.org/press/en/2005/dev2539.doc.htm

[j] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/japan-events.html

[k] https://www.unscear.org/unscear/en/fukushima.html

[l] https://www.unscear.org/docs/publications/2016/factsheet_en_2016_web.pdf

6. LESSONS LEARNED: FROM THE NRC[m] [n] [o]

6.1 Three Mile Island

A combination of personnel error, design deficiencies, and component failures caused the Three Mile Island accident which permanently changed both the nuclear industry and the NRC. Public fear and distrust increased, the NRC's regulations and oversight became broader and more robust, and management of the plants was scrutinized more carefully. Careful analysis of the accident's events identified problems and led to permanent and sweeping changes in how the NRC regulates its licensees…which, in turn, has reduced the risk to public health and safety.

Some of these changes include:

- Upgrading and strengthening plant design and equipment requirements. This includes fire protection, piping systems, auxiliary feedwater systems, containment building isolation, reliability of individual components (pressure relief valves and electrical circuit breakers), and the ability of plants to shut down automatically.
- Identifying the critical role of human performance in plant safety led to revamping operator training and staffing requirements, followed by improved instrumentation and controls for operating the plant, and establishing fitness-for-duty programs for plant workers to guard against alcohol or drug abuse.
- Enhancing emergency preparedness, including requirements for plants to immediately notify the NRC of significant events and an NRC Operations Center staffed 24 hours a day. Drills and response plans are now tested by licensees several times a year, and state and local agencies participate in drills with the Federal Emergency Management Agency and the NRC.
- Integrating NRC observations, findings, and conclusions about licensee performance and management effectiveness into a periodic, public report.
- Having senior NRC managers regularly analyze plant performance for those plants needing significant additional regulatory attention.
- Expanding the NRC's resident inspector program…first authorized in 1977…to have at least two inspectors live nearby and work exclusively at each plant in the United States to provide daily surveillance of licensee adherence to NRC regulations.
- Expanding performance-oriented, as well as safety-oriented, inspections and the use of risk assessment to identify vulnerabilities of any plant to severe accidents.
- Strengthening and reorganizing enforcement staff in a separate office within the NRC.
- Expanding the NRC's international activities to share enhanced knowledge of nuclear safety with other countries in several important technical areas.

6.2 Chernobyl

The NRC continues to conclude that many factors protect U.S. reactors against the combination of lapses that led to the accident at Chernobyl. Differences in plant design, broader safe shutdown capabilities, and strong structures to contain radioactive materials all help ensure U.S. reactors can keep the public safe. When the NRC reviews new information it considers possible

---

[m] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

[n] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/chernobyl-bg.html

[o] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/japan-events.html

major accidents; these reviews consider whether safety requirements should be enhanced to ensure ongoing protection of the public and the environment.

The NRC's post-Chernobyl assessment emphasized the importance of several concepts including:

- Designing reactor systems properly on the drawing board and implementing them correctly during construction and maintenance.
- Maintaining proper procedures and controls for normal operations and emergencies.
- Having competent and motivated plant management and operating staff.
- Ensuring the availability of backup safety systems to deal with potential accidents.

The post-Chernobyl assessment also examined whether changes to the NRC regulations or guidance on accidents were needed involving control of the chain reaction, accidents when the reactor is at low or zero power, operator training, and emergency planning.

The NRC's Chernobyl response included three major phases: (1) determining the facts of the accident; (2) assessing the accident's implications for regulating U.S. commercial nuclear power plants; and (3) conducting longer-term studies suggested by the assessment.

The NRC coordinated the fact-finding phase with other U.S. government agencies and some private groups. The NRC published the results of this work in January 1987 as NUREG-1250.

The NRC continues to examine Chernobyl's aftermath for lessons on decontaminating structures and land, as well as how people are returned to formerly contaminated areas. The NRC considers the Chernobyl experience a valuable piece of information for considering reactor safety issues in the future.

6.3 Fukushima

In March 2012, the NRC ordered U.S. nuclear power plants to meet specific deadlines for:

- Maintaining key safety functions even if installed electricity sources fail.
- Installing additional equipment to monitor spent fuel pool water levels.
- Installing/improving systems to safely vent pressure during an accident (for designs similar to Fukushima Dai-ichi). The NRC's March 2012 actions also asked all U.S. plants for information on comprehensive earthquake and flooding hazard analyses.

According to the NRC, as of September 2018, every U.S. commercial reactor has obtained the required additional on-site portable equipment and has satisfied the requirements of the emergency equipment order. The U.S. nuclear industry has also established and stocked two off-site response centers. Every operating U.S. reactor has met the requirements for the spent fuel pool order.

The NRC strengthened the venting order in 2013, requiring the vents to handle the pressures, temperatures, and radiation levels from a damaged reactor. The revised order also calls for plants to ensure their personnel could operate the vents under those conditions. Twenty-eight of 30 reactors covered by the order have met the requirements of the first phase, and 15 of 30 have met the requirements of the second phase.

7. ADVANCED NUCLEAR

While history's three largest civilian nuclear accidents have been destructive—and in the case of Chernobyl, deadly—each has provided a stern reminder of the safety imperative and provided an opportunity for nuclear technology to leap forward. As a similar example, the sinking of the RMS Titanic led to a range of safety improvements in terms of ship and lifeboat design, communications protocol, and maritime patrolling practices.

Advanced nuclear power plant designs build upon more than 60 years of experience in safety to ensure that accident probability is minimized and that any negative effects are hyper-localized to within plant boundaries in worst-case scenarios. Most importantly, the National Reactor Innovation Center team and the innovators we work with are committed to the safety of ourselves, our peers, and our communities. We are dedicated to protecting the natural environment today and for generations to come.