

Concepts of Radioactivity

This section introduces some of the basic concepts of radioactivity to provide the general reader with a basic understanding of the radiological information in the Site Environmental Report. The definitions of commonly used radiological terms are found in the Technical Topics section of the glossary, Appendix A, and are indicated in bold-face type the first time they are used only when the definition in the glossary provides additional detail.

Included here, in Appendix B, are discussions of the analyses used to quantify radioactive material, the common sources of radioactivity in the environment, and how radiation sources contribute to radiation dose. Some general statistical concepts are also presented, along with a discussion of radionuclides of environmental interest at BNL. The discussion begins with some definitions and background information on scientific notation, numerical prefixes, and units used when measuring dose and radioactivity.

RADIOACTIVITY AND OTHER TERMS

The atom is the basic constituent of all matter and is one of the smallest units into which matter can be divided. Each atom is composed of a tiny central core of particles (protons and neutrons) that comprise the nucleus, surrounded by a cloud of negatively charged particles called electrons. Some atoms possess excess energy, causing them to be physically unstable. Unstable atoms become stable when the excess energy is released in the form of charged particles or electromagnetic waves, known as *radiation*. The term *radioactivity* refers to the release of a charged particle or electromagnetic wave from an atom.

Radiation that has enough energy to remove electrons from atoms within material (a process called *ionization*) is classified as *ionizing radiation*. Radiation that does not have enough energy to remove electrons is called non-ionizing radiation. Examples of non-ionizing radiation include most visible light, infrared light, microwaves, and radio waves. All radiation, whether ionizing or not, may pose health risks. In the SER, *radiation* refers to ionizing radiation.

Radioactive elements (or *radionuclides*) are referred to by a name followed by a number, such as cesium-137. The number indicates the mass of that element and the total number of particles contained in the nucleus of the atom. Another way to specify cesium-137 is Cs-137, where *Cs* is the chemical symbol for cesium

in the standard Periodic Table of the Elements. This type of abbreviation is used in many of the SER data tables and text.

SCIENTIFIC NOTATION

Most numbers used for measurement and quantification in the SER are either very large or very small, and many zeroes would be required to express their value. To avoid this, scientific notation is used, with numbers represented as multiples of 10. For example, the number two million five hundred thousand (two and a half million, or 2,500,000) could be written in scientific notation as 2.5×10^6 , which represents “2.5 multiplied by (10 raised to the power of 6).” Since even “ 2.5×10^6 ” can be cumbersome, the capital letter E is substituted for the phrase “10 raised to the power of” Using this format, 2,500,000 is represented as 2.5E+06. The “+06” refers to the number of places the decimal point was moved to the left to create the shorter version. Scientific notation is also used to represent numbers smaller than zero, in which case a minus sign follows the E rather than a plus. For example, 0.00025 can be written as 2.5×10^{-4} or 2.5E-04. Here, “-04” indicates the number of places the decimal point was moved to the right.

NUMERICAL PREFIXES

Another method of representing very large or small numbers without using many zeroes is to use prefixes to represent multiples of ten.

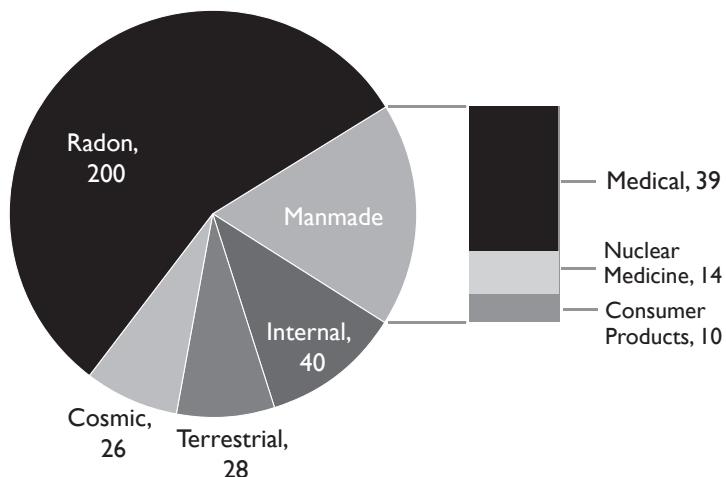


Figure B-1. Typical Annual Radiation Doses from Natural and Man-Made Sources (mrem). Source: NCRP Report No. 93 (NCRP 1987)

For example, the prefix *milli* (abbreviated *m*) means that the value being represented is one-thousandth of a whole unit; 3 mg (milligrams) is 3 thousandths of a gram. See the table on the inside back cover of the SER for additional common prefixes, including *pica* (*p*), which means trillionth, *giga* (*G*), which means billion or E+09, and *tera* (*T*), which means trillion, E+12.

UNITS FOR DOSE AND RADIOACTIVITY

Rem – The amount of radiation absorbed by body tissues or organs is referred to as the *dose equivalent* or, more generally, as the *dose*. Radiation doses are measured in units of *rem*. Since the rem is a fairly large unit, most doses are expressed in terms of thousandths of a rem, *millirem* or *mrem* (1,000 mrem = 1 rem). To give a sense of the size and importance of a 1-mrem dose, Figure B-1 indicates the number of mrem typically received each year by a person (living in the United States) from natural and non-occupational sources of radiation. Dose varies with location, as the section Sources of Radiation explains.

Sievert – Instead of rem, the International System of Units (SI) measures dose using the *sievert*, abbreviated *Sv*. One sievert is equivalent to 100 rem. Likewise, 1 one-thousandth of a sievert (1 millisievert, or 1 mSv) is equivalent to 100 one-thousandths of a rem (100 mrem).

Curie – The unit used to express the quantity of radioactive material in a sample is the *curie*

(Ci). This is a measure of the rate at which radioactive atoms are transformed to stable atoms. Since 1 curie represents a relatively large number of decays per second (3.7E+10, or 37 billion), the *picocurie* (pCi) is often used. This unit is equal to one trillionth of a Ci, or 0.037 (3.7E-02) decays per second.

Becquerel – Another unit for quantifying radioactivity is the SI unit *becquerel*, abbreviated *Bq*. One becquerel is equal to one decay per second. In the SER, radioactivity is expressed in curies.

SOURCES OF IONIZING RADIATION

Radioactivity and radiation are part of the earth's natural environment. Humans are exposed to ionizing radiation from a variety of common sources, the most significant of which are discussed below.

Cosmic – Cosmic radiation primarily consists of charged particles that originate in space, beyond the Earth's atmosphere. This includes ionizing radiation from the sun, and secondary radiation generated by the entry of charged particles into the Earth's atmosphere at high speeds and energies. Radioactive elements such as hydrogen-3 (tritium), beryllium-7, carbon-14, and sodium-22 are produced in the atmosphere by cosmic radiation. Exposure to cosmic radiation increases with altitude, because at higher elevations the atmosphere and the Earth's magnetic field provide less shielding. Therefore, people who live in the mountains are exposed to more cosmic radiation than people who live at sea level. The average dose from cosmic radiation to a person living in the United States is about 26 mrem per year.

Terrestrial – Terrestrial radiation is released by radioactive elements that have been present in the soil since the formation of the Earth about five billion years ago. Common radioactive elements that contribute to terrestrial exposure include isotopes of potassium, thorium, actinium, and uranium. The average dose from terrestrial radiation to a person living in the United States is about 28 mrem per year, but may vary considerably depending on the local geology.

Internal – Internal exposure occurs when radionuclides are ingested, inhaled, or absorbed through the skin. Radioactive material may be

incorporated into food through the uptake of terrestrial radionuclides by plant roots. People can ingest radionuclides when they eat contaminated plant matter or meat from animals that consumed contaminated plants. The average dose from food for a person living in the United States is about 40 mrem per year. A larger exposure, for most people, comes from breathing the decay products of naturally occurring radon gas. The average dose from breathing air with radon byproducts is about 200 mrem per year, but that amount varies depending on geographical location.

Medical – Every year, millions of people undergo medical procedures that use ionizing radiation. Such procedures include chest and dental x-rays, mammography, thallium heart stress tests, and tumor irradiation therapies. The average doses from nuclear medicine and x-ray examination procedures in the United States are about 14 and 39 mrem per year, respectively.

Anthropogenic – Sources of anthropogenic (man-made) radiation include consumer products such as static eliminators (containing polonium-210), smoke detectors (containing americium-241), cardiac pacemakers (containing plutonium-238), fertilizers (containing isotopes of the uranium and thorium decay series), and tobacco products (containing polonium-210 and lead-210). The average dose from consumer products to a person living in the United States is 10 mrem per year (excluding tobacco contributions).

Background – Some people use the term *background* when referring to all non-occupational sources commonly present. Other people use *natural* to refer only to cosmic and terrestrial sources, and *background* to refer to common man-made sources such as medical procedures, consumer products, and radioactivity present in the atmosphere from former nuclear testing.

COMMON TYPES OF IONIZING RADIATION

The three most common types of ionizing radiation are described below.

Alpha – An alpha particle is identical in makeup to the nucleus of a helium atom, consisting of two neutrons and two protons. Alpha particles have a positive charge and have little or no

penetrating power in matter. They are easily stopped by materials such as paper and have a range in air of only an inch or so. Naturally occurring radioactive elements such as uranium emit alpha radiation.

Beta – Beta radiation is composed of particles that are identical to electrons. Therefore, beta particles have a negative charge. Beta radiation is slightly more penetrating than alpha radiation, but most beta radiation can be stopped by materials such as aluminum foil and Lucite™ (plexiglass) panels. Beta radiation has a range in air of several feet. Naturally occurring radioactive elements such as potassium- 40 emit beta radiation.

Gamma – Gamma radiation is a form of electromagnetic radiation, like radio waves or visible light, but with a much shorter wavelength. The Radiochemistry Society Online defines gamma radiation as “electromagnetic radiation emitted in the process of nuclear transformation or particle annihilation” Gamma radiation is more penetrating than alpha or beta radiation, capable of passing through dense materials such as concrete. Gamma radiation is identical to x-rays except for the source.

TYPES OF RADIOLOGICAL ANALYSES

The amount of radioactive material in a sample of air, water, soil, or other material can be assessed using several analyses, the most common of which are described below.

Gross alpha – Alpha particles are emitted from radioactive material in a range of different energies. An analysis that measures all alpha particles simultaneously, without regard to their particular energy, is known as a *gross alpha activity* measurement. This type of measurement is valuable as a screening tool to indicate the total amount but not the type of alpha-emitting radionuclides that may be present in a sample.

Gross beta – This is the same concept as that for gross alpha analysis, except that it applies to the measurement of gross beta particle activity.

Tritium – Tritium radiation consists of low-energy beta particles. It is detected and quantified by liquid scintillation counting. More information on tritium is presented in the section Radionuclides of Environmental Interest.

Strontium-90 – Due to the properties of the radiation emitted by strontium-90 (Sr-90), a special analysis is required. Samples are chemically processed to separate and collect any strontium atoms that may be present. The collected atoms are then analyzed separately. More information on Sr-90 is presented in the section Radionuclides of Environmental Interest.

Gamma – This analysis technique identifies specific radionuclides. It measures the particular energy of a radionuclide's gamma radiation emissions. The energy of these emissions is unique for each nuclide, acting as a "fingerprint" to identify a specific nuclide.

STATISTICS

Two important statistical aspects of measuring radioactivity are uncertainty in results, and negative values.

Uncertainty – Because the emission of radiation from an atom is a random process, a sample counted several times usually yields a slightly different result each time; therefore, a single measurement is not definitive. To account for this variability, the concept of *uncertainty* is applied to radiological data. In the SER, analysis results are presented in an $x \pm y$ format, where "x" is the analysis result and " $\pm y$ " is the 95 percent "confidence interval" of that result. That means there is a 95 percent probability that the true value of x lies between $(x + y)$ and $(x - y)$.

Negative values – There is always a small amount of background radiation. The laboratory instruments used to measure radioactivity in samples are sensitive enough to measure the background radiation along with any contaminant radiation in the sample. To obtain a true measure of the contaminant level in a sample, the background radiation level must be subtracted from the total amount of radioactivity measured. Due to the randomness of radioactive emissions and the very low concentrations of some contaminants, it is possible to obtain a background measurement that is larger than the actual contaminant measurement. When the larger background measurement is subtracted from the smaller contaminant measurement, a negative result is generated. The negative results are reported, even though doing so may

seem illogical, because they are essential when conducting statistical evaluations of data.

RADIONUCLIDES OF ENVIRONMENTAL INTEREST

Several types of radionuclides are found in the environment at BNL due to historical operations.

Cesium-137 – Cesium-137 (Cs-137) is a man-made, fission-produced radionuclide with a half-life of 30 years (after 30 years only one half of the original activity level remains). It is found in the environment as a result of past aboveground nuclear weapons testing and can be observed in near-surface soils at very low concentrations, usually less than 1 pCi/g (0.004 Bq/g). Cesium-137 is a beta-emitting radionuclide, but it can be detected by gamma spectroscopy because its decay product, barium-137m, emits gamma radiation.

Cesium-137 is found in the environment at BNL mainly as a soil contaminant, from two main sources. The first source is the worldwide deposition from nuclear accidents and fallout from weapons testing programs. The second source is deposition from spills or releases from BNL operations. Nuclear reactor operations produce Cs-137 as a byproduct. For many years in the past, wastewater containing small amounts of Cs-137 generated at the reactor facilities was routinely discharged to the Sewage Treatment Plant (STP), resulting in low-level contamination of the STP and the Peconic River. Soil contaminated with Cs-137 is associated with the following areas that have been, or are being, addressed as part of the Environmental Remediation Program: Former Waste Management Facility, Waste Concentration Facility, Bldg. 650 Reclamation Facility and Sump Outfall Area, and the Brookhaven Graphite Research Reactor.

Strontium-90 – Strontium-90 (Sr-90) is a beta-emitting radionuclide with a half-life of 28 years. Sr-90 is found in the environment principally as a result of fallout from aboveground nuclear weapons testing. Sr-90 released by weapons testing in the 1950s and early 1960s is still present in the environment today.

Additionally, nations that were not signatories of the Nuclear Test Ban Treaty of 1963 have conducted more recent tests that have contributed to the global Sr-90 inventory. This radionuclide was also released as a result of the 1986 Chernobyl accident in the former Soviet Union.

Sr-90 is present at BNL in the soil and ground-water. As in the case of Cs-137, some Sr-90 at BNL results from worldwide nuclear testing; the remaining contamination is a byproduct of reactor operations. The following areas with Sr-90 contamination have been or are being addressed as part of the Environmental Remediation Program: Former Waste Management Facility, Waste Concentration Facility, Bldg. 650 Reclamation Facility and Sump Outfall Area, the Brookhaven Graphite Research Reactor, the Former and Interim Landfills, the Chemical and Glass Holes Area, and the Sewage Treatment Plant.

The information in the SER tables is arranged by method of analysis. Because strontium-90 requires a unique method of analysis, it is reported as a separate entry. Methods for detecting strontium-90 using state-of-the-art equipment are quite sensitive (detecting concentrations less than 1 pCi/L), which makes it possible to detect background levels of strontium-90.

Tritium – Among the radioactive materials that are used or produced at BNL, tritium has received the most public attention. Tritium exists in nature and is formed when cosmic radiation from space interacts with the gaseous nitrogen in the Earth's upper atmosphere. Approximately 4 million Ci (1.5×10^5 TBq) per year are produced in the atmosphere in this way, with the total global quantity being about 70 million Ci (2.6×10^6 TBq) at any given time (NCRP 1979). As a result of the U.S. aboveground weapons testing in the 1950s and early 1960s, the global atmospheric tritium inventory was increased by a factor of about 200. Other human activities such as consumer product manufacturing and nuclear power reactor operations have also released tritium into the environment. Commercially, tritium is used in products such as self-illuminating wrist watches and Exit

signs (the signs may each contain as much as 25 Ci [925 GBq] of tritium). Tritium also has many uses in medical and biological research as a labeling agent in chemical compounds, and is frequently used in universities and other research settings such as BNL and the other national laboratories.

Of the sources mentioned above, the most significant contributor to tritium in the environment has been aboveground nuclear weapons testing. In the early 1960s, the average tritium concentration in surface streams in the United States reached a value of 4,000 pCi/L (148 Bq/L; NCRP 1979). Approximately the same concentration was measured in precipitation. Today, the level of tritium in surface waters in New York State is less than one-twentieth that amount, below 200 pCi/L (7.4 Bq/L; NYSDOH 1993). This is less than the detection limit of most analytical laboratories.

Tritium has a half-life of 12.3 years. When an atom of tritium decays, it releases a beta particle, causing transformation of the tritium atom into stable (nonradioactive) helium. The beta radiation that tritium releases has a very low energy, compared to the emissions of most other radioactive elements. In humans, the outer layer of dead skin cells easily stops tritium beta radiation; therefore, only when tritium is taken into the body can it cause an exposure. Tritium may be taken into the body by inhalation, ingestion, or absorption of tritiated water through the skin. Because of its low energy radiation and short residence time in the body, the health threat posed by tritium is very small for most exposures.

Environmental tritium is found in two forms: gaseous elemental tritium, and tritiated water or water vapor, in which at least one of the hydrogen atoms in the H_2O water molecule has been replaced by a tritium atom (hence, its shorthand notation, HTO). All tritium released from BNL sources is in the form of HTO. Sources of tritium at BNL include the reactor facilities, where water (either heavy or light) is converted to tritium via neutron bombardment; accelerator facilities, where tritium is produced by secondary radiation interactions with soil and water; and facilities like the Brookhaven

APPENDIX B: CONCEPTS OF RADIOACTIVITY

Linac Isotope Producer (BLIP), where tritium is formed from secondary radiation interaction with cooling water. Tritium has been found in the environment at BNL as a groundwater contaminant from operations in the following areas: Current Landfill, BLIP, Alternating Gradient Synchrotron, and the High Flux Beam Reactor. Although small quantities of tritium are still being released to the environment through BNL emissions and effluents, the concentrations and total quantity have been drastically reduced compared with historical operational releases.

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