APPENDIX B
Understanding Radiation

This section introduces the general reader to some basic concepts of radioactivity and an understanding of the radiation emitted as radioactive materials decay to a stable state. To better comprehend the radiological information in the Site Environmental Report (SER), it is important to remember that not all types of radiation are the same and that different kinds of radiation affect living beings differently.

This appendix includes discussions on the common sources of radioactivity in the environment, types of radiation, the analyses used to quantify radioactive material, definitions and background information, scientific notation and numerical prefixes used when measuring dose and radioactivity, and finally, a discussion of radionuclides that are of environmental interest at Brookhaven National Laboratory (BNL). The definitions of commonly used radiological terms are found in the Technical Topics section of the glossary, Appendix A.

Radioactivity and Radiation

All substances are composed of atoms that are made of subatomic particles: protons, neutrons, and electrons. The protons and neutrons are tightly bound together in the positively charged nucleus (plural: nuclei) at the center of the atom. The nucleus is surrounded by a cloud of negatively charged electrons. Most nuclei are stable because the forces holding the protons and neutrons together are strong enough to overcome the electrical repulsive force that tries to push them apart. Radioactivity occurs when the ratio between protons and neutrons in the nucleus becomes too unbalanced (too many or too few neutrons). If this ratio is unbalanced, the nucleus becomes unstable and will spontaneously "decay," emitting excess energy in the form of charged particles or electromagnetic waves. Unstable atoms are called radionuclides, and their emissions are known as radiation. When a radionuclide decays, it transforms into a different atom, which may be stable or continue decaying until stability is reached. This is one reason radioactivity decreases over time. Not all atoms decay at the same rate — some decay faster than others. The time it takes for half of a sample of radioactive atoms to decay is called the half-life. After one half-life, half the original substance remains; after two, one quarter; then one-eighth, and so on. Different radionuclides have different half-lives.

Radiation that has enough energy to remove orbital electrons (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 types of radiation, whether ionizing or not, may pose health risks in sufficient quantities. In the SER, radiation refers to ionizing radiation.

Radioactive elements (or radionuclides) are referred to by name followed by a number, such as cesium-137. The number indicates the mass of that element, and the total number of neutrons and protons 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 Periodic Table of the Elements. This type of abbreviation is used throughout the SER.

Scientific Notation and Numerical Prefixes

Some numbers used for measurement and quantification in the SER are either very large or very small therefore, scientific notation is used to effectively communicate the information. For example, the number two million five hundred thousand (2,500,000) is written in scientific notation as 2.5×10^{6} or 2.5E+06. A small number like 0.0000025 is written in scientific notation as 2.5×10^{-6} or 2.5E-06.

Another method of representing very large or small numbers is to use prefixes. For example, the prefix milli (m) means that the value being represented is one-thousandth of a whole unit; 3 mg (milligrams) is 3 thousandths of a gram or E-03. See Appendix C for additional common prefixes, including pico (p), which means trillionth or E-12, giga (G), which means billion or E+09, and tera (T), which means trillion, E+12.

Sources of Ionizing Radiation

Radiation surrounds us from both natural and human-made sources. Referred to as "Background Radiation," it consists of cosmic radiation from outer space, radiation from radioactive elements in soil and rocks, and radiation from radon and its decay products. In the SER, the term natural background is used to refer to radiation from cosmic and terrestrial radiation.

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. 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 approximately 33 mrem per year (For an explanation of dose, see effective dose equivalent in Appendix A).

Radon Gas – Is produced from the radioactive decay of uranium which is naturally present in soil. Radon gas migrates through the soil and into the air. Long Island has minimum uranium in its soil; therefore, the background dose from radon gas is much lower than the national average.

Terrestrial – Terrestrial radiation is released by radioactive elements that have been present in the soil since the formation of the earth. 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 approximately 21 mrem per year but may vary considerably depending on the local geology.

Internal – Potassium-40 (K-40) is the most common naturally occurring radionuclide in the body and in animals. Potassium-40 is found in the food, soil, and water we ingest. The average dose received from food in the United States is about 29 mrem per year.

Human-Made Sources of Radioactivity

Medical – Procedures such as chest and dental x-rays, Computed Tomography (CT), mammography, heart stress tests, and tumor irradiation therapies utilize ionizing radiation. The average dose received from medical procedures are: CT at 147 mrem, nuclear medicine at 77 mrem, and radiography/fluoroscopy at 43 mrem.

Anthropogenic – Sources of anthropogenic (human-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 from uranium and thorium decay series), and tobacco products (containing polonium-210 and lead-210). The average dose from consumer products is 13 mrem per year (excluding tobacco contribution).

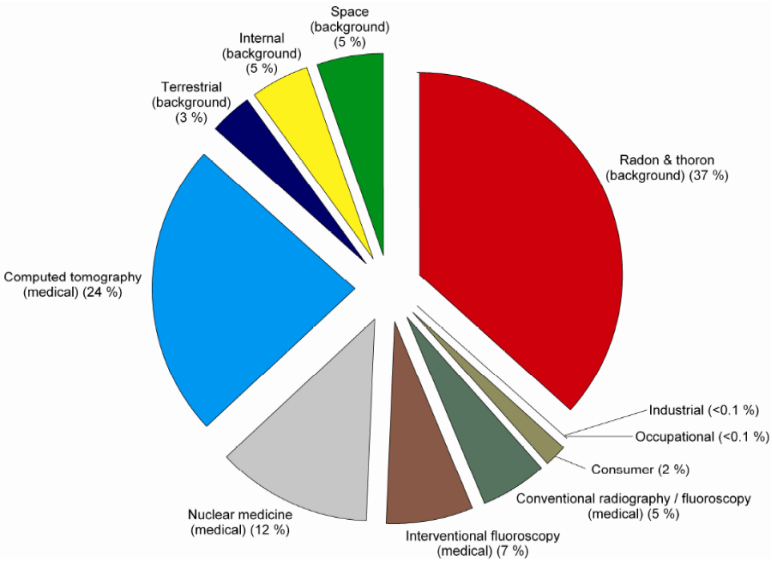

Figure B-1. Typical Annual Radiation Doses from Natural and Man-Made Sources (mrem). Source: NCRP Report No. 160 (NCRP 2009).

Common Types of Ionizing Radiation

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

Alpha Radiation – 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 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. However, if ingested, alpha particles can pose a health risk inside the body.

Beta Radiation – Beta radiation is composed of either electrons or positrons. Beta radiation is slightly more penetrating than alpha radiation, but most beta radiation can be stopped by materials such as aluminum foil and plexiglass panels. Beta radiation has a range in air of several feet. Beta particles present a hazard to the skin and eyes.

Gamma Radiation – Gamma radiation is a high-energy form of electromagnetic radiation (light). Gamma rays are emitted from a radioactive nucleus along with alpha or beta particles. Gamma radiation is capable of passing through dense material such as concrete. Because gamma rays are so penetrating, only a fraction of the total gamma rays a person is exposed to will interact with the human body — most will pass straight through.

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 – 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, later in this appendix.

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

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 ± y format, where "x" is the analysis result and "± y" is the 95% "confidence interval" of that result. That means there is a 95% probability that the true value of x lies between (x + y) and (x - y).

Negative values – There is always a small amount of natural 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. Negative results are reported, even though doing so may seem illogical, but they are essential when conducting statistical evaluations of data.

Subtraction of background activity from the measured sample activity may result in values that vary slightly from one analysis to the next. Therefore, the concept of a minimum detection limit (MDL) was established to determine the statistical likelihood that a sample's activity is greater than the background reading recorded by the instrument. For any value that is greater than or equal to the MDL, there is 95% confidence that it represents the true activity of the sample.

When the annual data for the SER are compiled, results may be averaged; therefore, all negative values are retained for reporting as well. This data handling practice is consistent with the guidance provided in the *Handbook of Radioactivity Measurements Procedures (NCRP 1985)* and the *Environmental Regulatory Guide for Radiological Effluent Monitoring and Environmental Surveillance (DOE 2015)*.

Average values are calculated using actual analytical results, regardless of whether they are above or below the MDL, or even equal to zero. The uncertainty of the mean, or the 95% confidence interval, is determined by multiplying the sample standard deviation of the mean by the t-statistic (0.05).

Radionuclides of Environmental Interest

Several radionuclides are found in the environment at BNL.

Cesium-137 – Cs-137 is a fission produced radionuclide with a half-life of 30 years. It is found worldwide as a result of past above ground nuclear weapons testing and can be observed in surface soils at very low concentrations, usually less than 1 pCi/g (0.004 Bq/g). Cs-137 is found in the environment at BNL mainly as a soil contaminant, from worldwide deposition from nuclear accidents, fallout from weapons testing programs, and from spills or releases from BNL operations. In the past, wastewater containing small amounts of Cs-137 generated from some research operations was routinely discharged to the Sewage Treatment Plant (STP), resulting in low-level contamination of the STP and the Peconic River. In 2002 and 2003, under the Environmental Restoration Program, sand and its debris containing low levels of Cs-137, Sr-90, and heavy metals were removed, assuring that future discharges from the STP are free of these contaminants. Soil contaminated with Cs-137 was associated with the following areas that have been addressed as part of the Environmental Remediation Program: former Hazardous Waste Management Facility, Waste Concentration Facility, Building 650 Reclamation Facility and Sump Outfall Area, and the Brookhaven Graphite Research Reactor (BGRR).

Strontium-90 – Sr-90 is a beta-emitting radionuclide with a half-life of 28 years. Sr-90 is found in the environment principally from fall-out from above-ground 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 contributed to the global inventory of fission products (Sr-90 and Cs-137). Sr-90 was also released from the 1986 Chernobyl accident in the former Soviet Union.

Sr-90 is present at BNL in the soil and groundwater from worldwide nuclear testing and reactor operations. The following areas with Sr-90 contamination have been or are being addressed as part of the Environmental Remediation Program: former Hazardous Waste Management Facility, Waste Concentration Facility, Building 650 Reclamation Facility and Sump Outfall Area, the BGRR, Former and Interim Landfills, Chemical and Glass Holes Area, and the STP.

Tritium – Among the radioactive materials that are used or produced at BNL, tritium has received the most public attention. Tritium has a half-life of 12.3 years and approximately four to five million Ci (1.5E+5 TBq) per year is produced in the atmosphere naturally (NCRP 1979).

Above-ground weapons testing was a major contributor to the increase of tritium in the global atmosphere. Other 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 wristwatches and exit signs. 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 other National Laboratories.

Of the sources mentioned above, the most significant contributor to tritium in the environment has been above-ground 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.

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 H2O water molecule has been replaced by a tritium atom (hence, its shorthand notation, HTO). Most of the tritium released from BNL sources is in the form of HTO, none as elemental tritium. Sources of tritium at BNL include the reactor facilities (all now non-operational), where residual water (either heavy or light) is converted to tritium via neutron bombardment; the accelerator

facilities, where tritium is produced by secondary radiation interactions with soil and water; and facilities like the Brookhaven Linac Isotope Producer (BLIP), where tritium is formed from secondary radiation interaction with cooling water. 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 as discussed in Chapters 4 and 5.

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