Chapter 4

RADIOACTIVITY

To define radiation, it is necessary to discuss the atom. The atom, the basic constituent of all matter, is one of the smallest units into which matter can be divided. It is composed of a tiny central core of particles, or *nucleus*, surrounded by a cloud of negatively charged particles called *electrons*. Most atoms in the physical world are stable, meaning that they are nonradioactive. However, some atoms possess an excess of energy which causes them to be physically unstable. In order to become stable, an atom rids itself of this extra energy by casting it off in the form of radiation. Radiation is the emission of a charged particle or electromagnetic wave from the atom. The three most important types of radiation are described in the following section.

4.1 Types of Radiation

Alpha An alpha particle is identical in make-up to the nucleus of a helium atom. 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 radon emit alpha radiation.

Beta Beta radiation is composed of particles which are identical to electrons. As a result, beta particles have a negative charge. Beta radiation is slightly more penetrating than alpha, but may be stopped by materials such as aluminum foil. They have a range in air of a few inches. 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 smaller wavelength. It is more penetrating than alpha or beta radiation, and is capable of passing through dense materials such as concrete. X-rays are essentially a form of gamma radiation.

4.2 Nomenclature

Throughout this report, radioactive elements (also called radionuclides) are referred to by a name followed by a number, e.g., potassium-40. The number following the name of the element is called the mass of the element and is equal to the total number of particles contained in the nucleus of the atom. Another way to specify the identity of potassium-40 is by writing it as K-40, where ‘K’ is the chemical symbol for potassium as it appears in the standard Periodic Table of the Elements. This type of abbreviation is used throughout many of the data tables in this report.

4.3 Sources of Radiation

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

Cosmic Primarily consists of charged particles which originate in space, beyond the earth's atmosphere. This includes 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.

Terrestrial Released by radioactive elements present in the soil since the formation of the earth about five billion years ago. Common radioactive elements contributing to terrestrial exposure include isotopes of potassium, thorium, actinium, and uranium.

Internal Internal exposure occurs when radionuclides are ingested absorbed or inhaled. Radioactivity in food occurs through the uptake of terrestrial radionuclides by plant roots. Human ingestion of natural radionuclides occurs when plant matter or animals that consume plant matter are eaten.

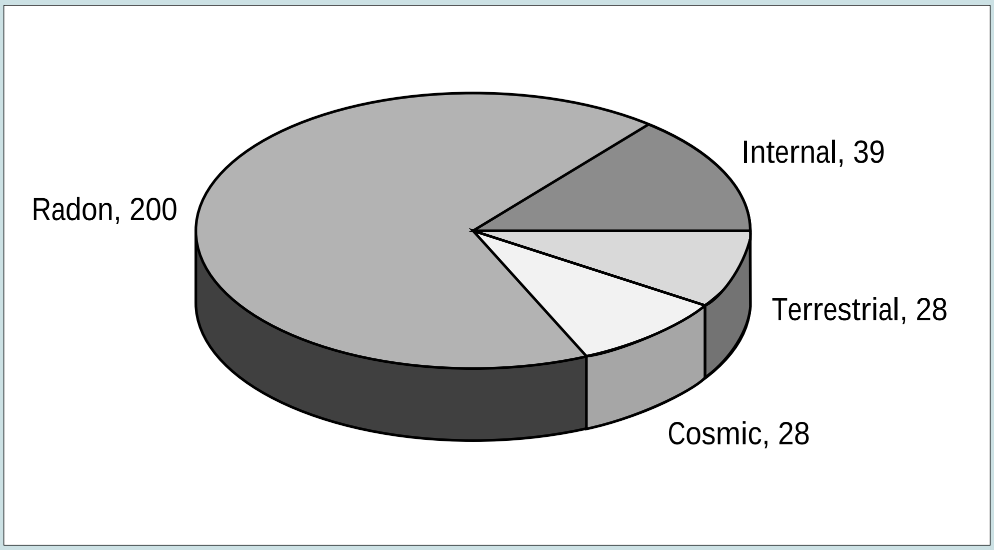
Radon Radon is a naturally-occurring radionuclide that is generated by the decay of uranium ores in the soil. It is by far the greatest contributor to an individual's radiation dose. Exposure occurs through the inhalation of radon decay products in the atmosphere. The level of exposure varies greatly from person to person depending on the quality of home insulation (which determines the degree to which the radon concentration will build up), the presence of a basement, ventilation rate, and geographic location.

Medical Millions of people every year undergo medical procedures which utilize radiation. Such procedures include chest and dental x-rays, mammography, thallium heart stress tests, tumor irradiation therapies and many others.

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).

4.4 Dose Units

The amount of energy that radiation deposits in body tissue, when corrected for human risk factors, is referred to as dose equivalent or, more generally, as dose. Radiation doses are measured in units of *rem*. Since the rem is a fairly large unit, it is convenient to express most doses in terms of *millirem*. A millirem, abbreviated mrem, is equal to 0.001 rem. To give a feeling for the size and importance of a 1 mrem exposure, the following figure indicates the number of mrem received by an individual in one year from natural sources. These values represent typical values for residents of the United States, giving a total of 295 mrem.



Note that the alternate unit of dose measurement, commonly used internationally and increasingly in the United States is the Sievert, abbreviated Sv. One Sv is equivalent to 100 rem. Likewise, 1 millisievert (mSv) is equal to 100 mrem.

4.5 Types of Radiological Analyses

The following section deals with radiological parameters for which various effluents are evaluated. These parameters include gross alpha activity, gross beta activity, tritium and Strontium-90 content, and gamma-emitting radionuclides. The quality of environmental air, water and soil can be assessed in several ways when dealing with radioactive material. The analyses most commonly used to measure radioactivity in these media are described below.

Gross Alpha Many naturally-occurring radionuclides contained in environmental media emit alpha radiation. The alpha particles emitted by these radionuclides have many different energies, measured in electron volts, or eV. Frequently, analysis equipment is used which measures all alpha particle activity simultaneously, without regard to their particular energy. Hence, this is a gross alpha activity measurement. It is valuable as a screening tool to indicate the magnitude of radioactivity that may be present in a sample.

Gross Beta This is the same concept as described above, except that it applies to the measurement of beta particle activity.

Tritium Due to the nature of the radiation emitted from the tritium atom, a special analysis known as liquid scintillation counting is required to quantify it. See Section 4.9.2 for further details.

Gamma Spectroscopy This is an analysis technique which identifies specific radionuclides, unlike a gross analysis which measures overall activity without identifying the source. It measures the specific 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.

4.6 Statistics

4.6.1 Uncertainty

Because the emission of radiation from an atom is a random process, a sample counted several times will yield a slightly different result each time; a single measurement is, therefore, not definitive. To account for this phenomenon, the concept of *uncertainty* is applied to radiological data. Each individual analysis result is shown in this report in the format of x +/- y, where x is the result and y is the 95% confidence interval of the result. That is, there is a 95% probability that the true value of x lies between the range of $x + y$ and $x - y$. Conversely, there is a 5% probability that the true value of x lies outside of this range. The value of y is also referred to as the 2σ error of the result.

4.6.2 Average Values

Average (or *mean*) values are calculated throughout this report for sample locations for which multiple data points are available. The average indicates a central trend for multiple data points. Following each average value is a second number given as +/- x, where x is equal to two times the standard deviation of the data point population. This value is an indicator of the variability of the data, i.e., how widely values in the population are dispersed from the average. A large value indicates a high variability between data points in the population, while a small value indicates that the data points are in close agreement.

4.6.3 Negative values

It is possible for a radiological measurement to result in a negative number. Every sample which is analyzed for radioactive material is compared to an instrument background, which is the number of radiation events observed in a blank sample. Since naturally-occurring radiation cannot be completely isolated in a sample measurement, the instrument background must be subtracted from the sample analysis. When measuring very low levels of radiation (such as those encountered in environmental media), where only a few radiation events are counted, it is common for the sample result to be below the instrument background. When the background is subtracted, a negative net value results, signifying that the sample was found to contain no detectable radioactive material. Similarly, an average of several individual values in which some are positive and some are negative can result in a negative mean, indicating that the central trend of the data is a value which is not detectable.

4.7 Scientific Notation

Since many of the numbers used in measurement and quantification in this report are either very large or very small, many zeroes are required to express their value. Because this is inconvenient, scientific notation is used as a kind of numerical shorthand. Scientific notation is based on the principle of representing numbers in multiples of ten. For example, the number one million could be written as 1,000,000. Alternatively, this number could be written in scientific notation as 1×10^6. That is, “one times ten raised to the sixth power.” Since even this shorthand can be cumbersome, it can be reduced even further by using the capital letter E to stand for 10^x, or “ten raised to the power of some value x.” Using this notation, 1,000,000 would be represented as 1E6. Scientific notation is also used to represent very small numbers like 0.0001, which can be written as 1×10^{-4} or 1E-4. A minus sign on the power of ten represents a decimal value.

4.8 Prefixes

Another method of representing very large or very small numbers without the use of many zeroes is to use prefixes to represent multiples of ten. For example, the prefix milli- means that the value being represented is one thousandth of a whole unit, so that one milligram is equal to one thousandth of a gram. Other common prefixes used in this report are shown in Table 4-1.

Prefix	Multiplier		Prefix	Multiplier	
milli (m)	1×10^{-3}	1E-3	kilo (k)	1×10^{3}	1E3
micro (µ)	1×10^{-6}	1E-6	mega (M)	1×10^{6}	1E6
nano (n)	1×10^{-9}	1E-9	giga (G)	1×10^{9}	1E9
pico (p)	1×10^{-12}	1E-12	tera (T)	1×10^{12}	1E12

Table 4-1 Common Measurement Unit Prefixes

4.9 Radionuclides of Environmental Interest

4.9.1 Strontium-90

Strontium-90 is a beta-emitting radionuclide with a half-life of 28 years. It is found in the environment as a result of commercial power reactor operations, and, more importantly, nuclear weapons fallout. (*Fallout* refers to the deposition of radionuclides on soils and water bodies as a result of being dispersed high into the earth's atmosphere during nuclear explosions.) Because Strontium-90 released during weapons testing has such a lengthy half-life, it can still be detected in the environment today. Additionally, nations which were not signatories of the Nuclear Test Ban Treaty of 1963 have conducted tests which have contributed to the global Strontium-90 inventory. This radionuclide was also released as a result of the 1986 Chernobyl accident in the former Soviet Union.

Strontium-90 emits beta radiation only, which cannot be detected by gamma spectroscopy. It can only be detected by a specific chemical analysis (see Appendix C for description), followed by measurements of beta particle emissions. This is why it is reported as a separate parameter in the tables of this report. The level of sensitivity for detecting Strontium-90 using state-of-the-art analyses methods is less than 1 pCi/L, which makes it possible to detect Strontium-90 at levels which are indicative of the environmental sources described above.

No processes on the BNL site actively release Strontium-90 during their operation. When it is detected on the BNL site at levels above those associated with fallout and other background sources, it is due to historic landfill practices of the 1950s and 60s or the former operation of the Brookhaven Graphite Research Reactor, which ceased operation in 1969.

4.9.2 Tritium

Among the radioactive materials that are used or produced at Brookhaven National Laboratory, tritium has received some of the greatest public attention. Tritium, the common name for the isotope hydrogen-3, exists in nature and is formed when cosmic radiation from space interacts with the gaseous element nitrogen in the earth's upper atmosphere. Approximately 4 million Ci (1.5E5 TBq) per year are produced in the atmosphere in this way, with the total global quantity being about 70 million Ci (2.6E6 TBq) at any given time (NCRP, 1979). Human activities such as nuclear power reactor operations and nuclear weapons testing have also released tritium into the environment. Commercially, tritium is used in such products such as self-illuminating exit signs and wrist watches ('exit' signs may contain as much as 20 Ci [740 GBq] of tritium). It 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.

Tritium has a physical half-life of 12.3 years and a biological half-life of about 10 days, meaning that 50 percent of any tritium in the body is eliminated in approximately 10 days. When an atom of tritium decays, it releases a beta particle, transforming the tritium atom into stable (nonradioactive) helium. This beta radiation is of a very low energy when compared to the emissions of other radioactive elements and it is easily stopped by the body's outer layer of dead skin cells; only when taken into the body can tritium cause any significant exposure. Because of its low energy radiation and short residence time in the body, the health threat posed by tritium is very small for most credible 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 short hand notation *HTO*. All tritium released from BNL sources is in the form of HTO. Since tritium is incorporated directly into the water molecule, absorbed or ingested HTO passes through the body as water does, minimizing the accumulation in the body over time from one-time exposures.

Of the sources mentioned above, the most significant contributor to tritium in the environment has been above-ground nuclear weapons testing. In the early 60s, the average tritium concentration in surface streams in the United States reached a value of 4,000 pCi/L (148 kBq/L) (NCRP, 1979). Approximately the same concentration was measurable in precipitation. Today, the level of tritium in surface waters in New York State is below 200 pCi/L (7.4 kBq/L) (NYSDOH, 1993), less than the detection limit of most analytical laboratories.

4.9.3 Cesium-137

Cesium-137 is a man-made, fission-produced radionuclide with a half-life of 30 years. It is found in the general environment as a result of past above-ground nuclear weapons testing and can be observed in the upper levels of environmental soils at very low concentrations, of around 1 pCi/g (0.4 Bq/g) or less. It is a beta-emitting radionuclide, but can be detected by gamma spectroscopy by the gamma emissions of its decay product, barium-137m.

4.10 Definition of Radiological Terms

The following terms are used throughout this report where radiation and radioactive material are discussed:

Activation The process by which a non-radioactive material is made radioactive through exposure to neutrons or high energy particles.

Activation Product
An element which has become radioactive through the process of activation.

Activity Synonym for radioactivity.

Anthropogenic Radionuclides
Radionuclides produced as a result of human activity, i.e., man-made.

Background Radiation
Radiation present in the environment as a result of naturally-occurring radioactive materials, cosmic radiation, or fallout radionuclides deposited on the earth as a result of above-ground weapons testing.

Becquerel A quantitative measure of radioactivity, abbreviated *Bq*. This is an alternate measure of activity used internationally and with increasing frequency in the United States. One Bq of activity is equal to one nuclear decay per second. All references to quantities of radioactive material in this report are made in curies, followed in parentheses by the equivalent in Bq.

Derived Concentration Guide (DCG)
The concentration of a radionuclide in air or water that, under conditions of continuous exposure for one year by a single pathway (e.g. air inhalation/immersion, water ingestion), would result in an effective dose equivalent of 100 mrem (1 mSv). Established by DOE Order 5400.5, “Radiation Protection of the Public and Environment”.

Curie A quantitative measure of radioactivity, abbreviated *Ci*. One Ci of activity is equal to 3.7 X 10^{10} disintegrations per second, which is equal to 3.7 X 10^{10} Bq (see *radioactivity*).

Effective Dose Equivalent A normalized value which allows the inter-comparison of doses to various parts of the body. It is equal to the sum of the doses to different organs of the body multiplied by their respective weighting factors. Also referred to as the “whole body” dose, or simply “dose.”

Fallout Radioactive material made airborne as a result of above-ground nuclear weapons testing that has been deposited on the earth’s surface.

Half-Life The time required for the activity of a radioactive sample to be reduced by one half.

MDL Minimum Detection Limit. This is the lowest level to which an analytical parameter can be measured with certainty in the Laboratory. While results below the MDL are sometimes measurable, they represent values which have a reduced statistical confidence associated with them (less than 95% confidence).

Radioactivity The spontaneous transition of an atomic nucleus from a higher energy to a lower energy state. This transition is accompanied by the release of a charged particle or electromagnetic wave from the atom. Also known as *activity*.

Radionuclide A radioactive element.

Rem The unit by which human radiation exposure is measured. This is a risk-based value used to estimate the potential health effects to an exposed individual or population. Because the rem is a relatively large unit, doses are usually specified in millirems, abbreviated *mrem*. One mrem is equal to 0.001 rem. Typical exposure to natural sources of radiation in the environment results in a dose of 200 to 400 mrem per year. See also Section 5.

Sievert The alternate unit of measuring human radiation exposure used internationally and with increasing frequency in the United States, is the Sievert, abbreviated *Sv*. One sievert is equal to 100 rem.

Spallation The process by which a high energy particle striking a nucleus causes fragments to be ejected from the nucleus. The resulting atom is usually radioactive.

Stable Non-radioactive.

TLD Thermoluminescent Dosimeter. A device used to measure radiation exposure to occupational workers or radiation levels in the environment.