USEFUL INFORMATION

Radiation and Radioactivity

Radioactivity is a characteristic of some elements that have unstable atomic nuclei, which spontaneously disintegrate or "decay" into atomic nuclei of another isotope or element. The nuclei decay until only a stable, nonradioactive isotope remains. Depending on the isotope, this process can take anywhere from less than a second to billions of years.

Atoms that emit radiation are called radionuclides. Radionuclides are unstable isotopes of an element that have the same number of protons but different numbers of neutrons, resulting in different atomic masses. For example, the element hydrogen has two stable isotopes, hydrogen-1 (^{1}H) and hydrogen-2 (^{2}H) (deuterium), and one radioactive isotope, hydrogen-3 (^{3}H) (tritium). The superscript preceding the element's symbol identifies the atomic mass, which is the number of protons plus neutrons in the nucleus. Thus, ^{1}H has one proton and no neutrons, ^{2}H has one proton and one neutron, and ^{3}H has one proton and two neutrons.

When radioactive atoms decay by emitting radiation, the daughter products that result may be either radioactive or stable. Generally, radionuclides with high atomic numbers, such as uranium-238 and plutonium-239, have many generations of radioactive progeny. For example, the radioactive decay of plutonium-239 creates uranium-235, thorium-231, protactinium-231, and so on, through 11 progeny until only the stable isotope lead-207 remains.

Radionuclides with lower atomic numbers often have no more than one daughter. For example, strontium-90 has one radioactive daughter, yttrium-90, which finally decays into stable zirconium; cobalt-60 decays directly to stable nickel with no intermediate nuclide.

The time required for half of the radioactivity of a radionuclide to decay is referred to as the radionuclide's half-life. Each radionuclide has a unique half-life; both strontium-90 and cesium-137 have half-lives of approximately 30 years while plutonium-239 has a half-life of 24,110 years. Knowledge of radionuclide half-lives is often used to estimate past and future inventories of radioactive material. For example, a 1.0-millicurie source of cesium-137 in 2005 would have measured 2.0 millicuries in 1975 and will be 0.5 millicuries in 2035. For a list of half-lives of radionuclides applicable to the West Valley Demonstration Project (WVDP), see Table K-1 in Appendix K.

Radiation emitted by radionuclides may consist of charged particles, such as alpha and beta particles, or electromagnetic rays, such as x-rays and gamma rays. A radionuclide may emit one or more of these radiations at characteristic energies that can be used to identify them.

Alpha Particles. An alpha particle is a fragment of a much larger nucleus. It consists of two protons and two neutrons (similar to the nucleus of a helium atom) and is positively charged. Compared to beta particles, alpha particles are relatively large and heavy and do not travel very far when ejected by a decaying nucleus. Therefore, alpha radiation is easily stopped by a thin layer of material, such as paper or skin. However, if radioactive material is ingested or inhaled, the alpha particles released inside the body can damage soft internal tissues because their energy can be absorbed by tissue cells in the immediate vicinity of the decay. An example of an alpha-emitting radionuclide is the uranium isotope with an atomic weight of 232 (uranium-232). Uranium-232 was in the high-level waste (HLW) mixture at the WVDP as a result of a thorium-based nuclear fuel reprocessing campaign conducted by Nuclear Fuel Services, Inc. Uranium-232 has been detected in liquid waste streams.

Beta Particles. A beta particle is an electron emitted during the breakdown of a neutron in a radioactive nucleus. Compared to alpha particles, beta particles are smaller, have less of a charge, travel at a higher speed (close to the speed of light), and can be stopped by wood or less than an inch of aluminum. If released inside the body, beta particles do much less damage than an equal number of alpha particles because beta particles deposit energy in tissue cells over a larger volume than alpha particles. Strontium-90, a fission product found in the stabilized supernatant, is an example of a beta-emitting radionuclide.

Gamma Rays. Gamma rays are high-energy "packets" of electromagnetic radiation, called photons, that are emitted from the nucleus. Gamma rays are similar to x-rays, but are generally more energetic. If an alpha or beta particle released by a decaying nucleus does not carry off all the energy generated by the nuclear disintegration, the excess energy may be emitted as gamma rays. If the released energy is high, a very penetrating gamma ray is produced that can be effectively reduced only by shielding consisting of several inches of a dense material, such as lead, or of water or concrete several feet thick. Although large amounts of gamma radiation are dangerous, gamma rays are also used in lifesaving medical procedures. An example of a gamma-emitting radionuclide is barium-137m, a short-lived daughter product of cesium-137. Both barium-137m and its precursor, cesium-137, are major constituents of the WVDP HLW.

Measurement of Radioactivity

The rate at which radiation is emitted from a disintegrating nucleus can be described by the number of decay events or nuclear transformations that occur in a radioactive material over a fixed period of time. This process of emitting energy, or radioactivity, is measured in curies (Ci) or becquerels (Bq).

The curie is based on the decay rate of the radionuclide radium-226. One gram of radium-226 decays at the rate of 37 billion nuclear disintegrations per second (3.7E+10 d/s), so one curie equals 37 billion nuclear disintegrations per second. One becquerel equals one decay, or disintegration, per second.

Very small amounts of radioactivity are sometimes measured in picocuries. A picocurie is one-trillionth (1E-12) of a curie, equal to 3.7E-02 d/s (3.7E-02 Bq), or 2.22 disintegrations per minute.

Background Radiation

Background radiation is always present, and everyone is constantly exposed to low levels of such radiation from both naturally occurring and man-made sources. In the United States the average total annual exposure to low-level background radiation is estimated to be about 360 millirem (mrem) or 3.6 millisieverts (mSv). Most of this radiation, approximately 295 mrem (2.95 mSv), comes from natural sources. The rest comes from medical procedures, consumer products, and other man-made sources (National Council on Radiation Protection and Measurements Report 93, 1987). (See Figure 2-1 in Chapter 2.)

Background radiation includes cosmic rays; the decay of natural elements, such as potassium, uranium, thorium, and radon; and radiation from sources such as chemical fertilizers, smoke detectors, and televisions. Actual doses vary depending on such factors as geographic location, building ventilation, and personal health and habits.

Measurement of Dose

The amount of energy absorbed by the receiving material is measured in rads (radiation absorbed dose). A rad is 100 ergs of radiation energy absorbed per gram of material. (An erg is the approximate amount of energy necessary to lift a mosquito one-sixteenth of an inch.) "Dose" is a means of expressing the amount of energy absorbed, taking into account the effects of different kinds of radiation.

Alpha, beta, and gamma radiation affect the body to different degrees. Each type of radiation is given a quality factor that indicates the extent of human cell damage it can cause compared with equal amounts of other ionizing radiation energy. Alpha particles cause 20 times as much damage to internal tissues as x-rays, so alpha radiation has a quality factor of 20, compared to gamma rays, x-rays, or beta particles, each of which have a quality factor of one.

The unit of dose measurement to humans is the rem (roentgen equivalent man). The number of rem are equal to the number of rads multiplied by the quality factor for each type of radiation. Dose can also be expressed in sieverts. One sievert (Sv) equals 100 rem.

For a more-detailed discussion of radiation dose and units of dose measurement, see the "Radiological Effluents and Dose" section of Chapter 2.

Derived Concentration Guides

A derived concentration guide (DCG) is defined in DOE Order 5400.5 as the concentration of a radionuclide in air or water that, under conditions of continuous exposure by one exposure mode (i.e., ingestion of water, immersion in air, or inhalation) for one year, would result in an effective dose equivalent of 100 mrem (1 mSv) to a "reference man." These concentrations – DCGs – are used as reference screening levels to enable WVDP personnel reviewing effluent and environmental data to decide if further investigation is needed. (See Appendix K for a list of DCGs.)

For liquid effluent screening purposes, the percentages of the DCGs for all radionuclides present are summed. If the total is less than 100%, then the effluent complies with the DOE guideline. DCGs are also compared with radionuclide concentrations from these sources to verify that Best Available Technology standards for treatment of water are being met.

The DOE provides DCGs for airborne radionuclides in locations where members of the public could, over an extended period of time, breathe air containing contaminants. DCGs are only applicable to radionuclides in air breathed by members of the public. DCGs may be used as a comparative basis for screening concentrations from air emission points.

DOE Orders and federal regulations require that the hypothetical dose to the public from facility effluents be estimated using specific computer codes. (See "Dose Assessment Methodology" in Chapter 2.) Doses estimated for WVDP activities are calculated using actual site data and are not related directly to summed DCG values. Dose estimates for liquid effluents are based on the product of radionuclide quantities released and the site-specific dose equivalent effects for that radionuclide. Although airborne DCGs are used for comparison purposes, the more stringent EPA National Emission Standards for Hazardous Air Pollutants regulate Project airborne emissions at the point of release. For a consistent guide to relative concentrations, both air and water sampling results are compared with DCGs throughout this report.

Data Reporting

In the text of this report, traditional radiological units (e.g., rem, rad, curie, roentgen) are presented first, followed by Systeme Internationale (S.I.) units. Nonradiological measurements are presented in English units, followed by metric units in parentheses. A conversion chart for comparing traditional and S.I. radiological units and English and metric nonradiological units is presented under "Units of Measure," later in this section. Regulatory or guidance standards are presented as they appear in the source document.

The number of significant digits reported depends on the precision of the measurement technique. Integer counts will be reported without rounding. Calculated values are customarily reported to three significant figures. Dose estimates may be reported to two significant figures.

Radiological Data. Because the decay of radioactive atoms is a random process, an inherent uncertainty is associated with all measurements of environmental radioactivity. This can be demonstrated by repeatedly measuring the number of atoms that decay in a radioactive sample over some fixed period of time. The result of such an experiment would be a range of values for which the average value would provide the best indication of how many radioactive atoms were present in the sample.

In actual practice, an environmental sample is usually measured for radioactivity only once over a period of time. The inherent random uncertainty of the measurement, in an efficient process, is the major reason that the reported measurement is higher or lower than the "true" value.

The term "confidence interval" is used to describe the range of measurement values above and below the test result within which the "true" value is expected to lie. This interval is derived statistically. The width of the interval is based primarily on a predetermined confidence level, that is, the probability that the confidence interval actually encompasses the "true" value. The WVDP environmental monitoring program uses a 95% confidence level for all radioactivity measurements and calculates confidence intervals accordingly.

The confidence interval around a measured value is indicated by the plus-or-minus (±) value following the result (e.g., 5.30±3.6E-09 microcuries per milliliter [µCi/mL]), with the exponent of 10^{-9} expressed as "E-09." Expressed in decimal form, the result 5.30±3.6E-09 would be 0.00000000530±0.0000000036 µCi/mL. A sample measurement expressed this way is correctly interpreted to mean "there is a 95% probability that the concentration of radioactivity in this sample is between 1.7E-09 µCi/mL and 8.9E-09 µCi/mL." If the confidence interval for the measured value includes zero (e.g., 5.30±6.5E-09 µCi/mL), the value is considered to be below the detection limit. The values listed in tables of radioactivity measurements in the appendices include the confidence interval regardless of the detection limit value.

Chemical Data. In general, the detection limit is the minimum amount of constituent or material of interest detected by an instrument or method that can be distinguished from background and instrument noise. Thus, the detection limit is the lowest value at which a sample result shows a statistically positive difference from a sample in which no constituent is present.

Nonradiological data are conventionally presented without an associated uncertainty and are expressed by the detection limit prefaced by a "less than" symbol (<) if that analyte were not measurable.

Units of Measure

Radioactivity	Symbol	Name
	Ci	curie
	mCi	millicurie (1E-03 Ci)
	µCi	microcurie (1E-06 Ci)
	nCi	nanocurie (1E-09 Ci)
	pCi	picocurie (1E-12 Ci)
	Bq	becquerel (27 pCi)
	d/s	disintegrations per second

Dose	Symbol	Name
	Sv	sievert (100 rem)
	mSv	millisievert (1E-03 Sv)
	Gy	gray (100 rad)
	mrem	millirem (1E-03 rem)

Concentration	Symbol	Name
	µCi/mL	microcuries per milliliter
	mL/L	milliliters per liter
	µCi/g	microcuries per gram
	mg/L	milligrams per liter (ppm)
	mg/kg	milligrams per kilogram (ppm)
	µg/mL	micrograms per milliliter (ppm)
	pCi/L	picocuries per liter
	ng/L	nanograms per liter (ppt)
	µg/L	micrograms per liter (ppb)
	µg/g	micrograms per gram (ppm)
	Bq/L	becquerels per liter
	ppm	parts per million
	ppb	parts per billion
	ppt	parts per trillion
	NTU	nephlemetric turbidity units
	SU	standard units

Mass	Symbol	Name
	g	gram
	kg	kilogram (1E+03 g)
	mg	milligram (1E-03 g)
	µg	microgram (1E-06 g)
	ng	nanogram (1E-09 g)
	t	metric ton (1E+06 g)

Volume	Symbol	Name
	cm^3	cubic centimeter
	L	liter
	mL	milliliter
	m^3	cubic meter
	gal	gallon
	ft^3	cubic feet

Area	Symbol	Name
	ha	hectare (10,000 m^2)

Length	Symbol	Name
	m	meter
	km	kilometer (1E+03 m)
	cm	centimeter (1E-02 m)
	mm	millimeter (1E-03 m)
	µm	micrometer (1E-06 m)

Exposure	Symbol	Name
	µR	microroentgen
	mR	milliroentgen

Flow Rate or Speed	Symbol	Name
	mgd	million gallons per day
	cfm	cubic feet per minute
	lpm	liters per minute
	gpd	gallons per day
	m/sec	meters per second

Unit Prefixes

centi	1/100 = 1 x 10^{-2} = 0.01 = E-02
milli	1/1,000 = 1 x 10^{-3} = 0.001 = E-03
micro	1/1,000,000 = 1 x 10^{-6} = 0.000001 = E-06
nano	1/1,000,000,000 = 1 x 10^{-9} = 0.000000001 = E-09
pico	1/1,000,000,000,000 = 1 x 10^{-12} = 0.000000000001 = E-12

Scientific Notation

Scientific notation may be used to express very large or very small numbers. A number smaller than 1 is expressed with a negative exponent (e.g., 1.3×10^{-6}). To convert this number to decimal form, the decimal point is moved left by the number of places equal to the exponent. Thus, 1.3×10^{-6} becomes 0.0000013.

A number larger than 10 is expressed with a positive exponent (e.g., 1.3×10^{6}). To convert this number to decimal form, the decimal point is moved right by the number of places equal to the exponent. Thus, 1.3×10^{6} becomes 1,300,000.

The power of 10 also is expressed as E. For example, 1.3×10^{-6} also can be written as 1.3E-06. The chart below shows equivalent exponential and decimal values.

1.0×10^{2}	=	1E+02	=	100		
1.0×10^{1}	=	1E+01	=	10		
1.0×10^{0}	=	1E+00	=	1		
1.0×10^{-1}	=	1E-01	=	0.1		
1.0×10^{-2}	=	1E-02	=	0.01		
1.0×10^{-3}	=	1E-03	=	0.001		
1.0×10^{-4}	=	1E-04	=	0.0001		
1.0×10^{-5}	=	1E-05	=	0.00001		
1.0×10^{-6}	=	1E-06	=	0.000001	One millionth	
1.0×10^{-7}	=	1E-07	=	0.0000001		
1.0×10^{-8}	=	1E-08	=	0.00000001		

Conversion Chart

Both traditional radiological units (curie, roentgen, rad, rem) and the Systeme Internationale (S.I.) units (becquerel, gray, sievert) are used in this report. Nonradiological measurements are presented in both English and metric units. Frequently-used radioactivity and dose conversions are bolded.

1 centimeter (cm)	=	0.3937 inches (in)
1 meter (m)	=	39.37 inches (in) = 3.28 feet (ft)
1 kilometer (km)	=	0.62 miles (mi)
1 milliliter (mL)	=	0.0338 ounces (oz)
	=	0.061 cubic inches (in^3)
	=	1 cubic centimeter (cm^3)
1 liter (L)	=	1.057 quarts (qt); 0.2641721 gallons (gal)
	=	61.02 cubic inches (in^3)
1 gram (g)	=	0.0353 ounces (oz)
	=	0.0022 pounds (lbs)
1 kilogram (kg)	=	2.2 pounds (lbs)
1 curie (Ci)	=	3.7E+10 disintegrations per second (d/s)
1 becquerel (Bq)	**=**	**1 disintegration per second (d/s)**
	=	**27 picocuries (pCi)**
1 roentgen (R)	=	2.58E-04 coulombs per kilogram of air (C/kg)
1 rad	**=**	**0.01 gray (Gy)**
1 rem	**=**	**0.01 sievert (Sv)**
1 millirem (mrem)	=	0.001 rem
1 sievert (Sv)	**=**	**100 rem**

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