Appendix A: Radiation

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This appendix presents basic facts about radiation. The information is intended to be a basis for understanding the potential doses associated with releases of radionuclides from the Oak Ridge Reservation (ORR), not as a comprehensive discussion of radiation and its effects on the environment and biological systems.

Radiation comes from natural and human-made sources. People are exposed to naturally occurring radiation constantly. For example, cosmic radiation; radon in air; potassium in food and water; and uranium, thorium, and radium in the earth's crust are all sources of radiation. The following discussion describes important aspects of radiation, including atoms and isotopes; types, sources, and pathways of radiation; radiation measurement; and dose information.

ATOMS AND ISOTOPES

All matter is made up of atoms. An atom is "a unit of matter consisting of a single nucleus surrounded by a number of electrons equal to the number of protons in the nucleus" (ANS 1986). The number of protons in the nucleus determines an element's atomic number or chemical identity. With the exception of hydrogen, the nucleus of each type of atom also contains at least one neutron. Unlike protons, the neutrons may vary in number among atoms of the same element. The number of neutrons and protons determines the atomic weight. Atoms of the same element that have different numbers of neutrons are called isotopes. In other words, isotopes have the same chemical properties but different atomic weights (Fig. A.1).

For example, the element uranium has 92 protons. All isotopes of uranium, therefore, have 92 protons. However, each uranium isotope has a different number of neutrons. Uranium-238 has 92 protons and 146 neutrons; uranium-235 has 92 protons and 143 neutrons; and uranium-234 has 92 protons and 142 neutrons.

Some isotopes are stable, or nonradioactive; some are radioactive. Radioactive isotopes are called radionuclides, or radioisotopes. In an attempt to become stable, radionuclides "throw away," or emit, rays or particles. This emission of rays and particles is known as radioactive decay. Each radioisotope has a "radioactive half-life," which is the average time that it takes for half of a specified number of atoms to decay. Half-lives can be very short (fractions of a second) or very long (thousands of years), depending on the isotope (Table A.1).

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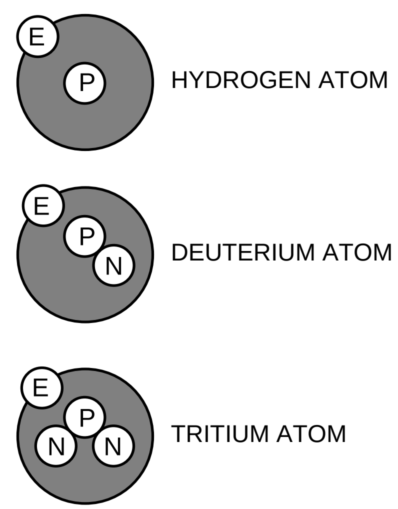

	PROTONS	NEUTRONS
HYDROGEN	1	0
DEUTERIUM	1	1
TRITIUM	1	2

Fig. A.1. The hydrogen atom and its isotopes.

Table A.1. Radionuclide nomenclature

Radionuclide	Symbol	Half-life	Radionuclide	Symbol	Half-life
Americium-241	^{241}Am	432.2 years	Plutonium-238	^{238}Pu	87.75 years
Americium-243	^{243}Am	7.38E+3 years	Plutonium-239	^{239}Pu	2.41E+4 years
Antimony-125	^{125}Sb	2.77 years	Plutonium-240	^{240}Pu	6.569E+3 years
Argon-41	^{41}Ar	1.827 hours	Potassium-40	^{40}K	1.2777E+9 years
Beryllium-7	^{7}Be	53.44 days	Promethium-147	^{147}Pm	2.6234 years
Californium-252	^{252}Cf	2.639 years	Protactinium-234*m*	^{234}mPa	1.17 minutes
Carbon-14	^{14}C	5.730E+3 years	Radium-226	^{226}Ra	1.6E+3 years
Cerium-141	^{141}Ce	32.50 days	Radium-228	^{228}Ra	5.75 years
Cerium-143	^{143}Ce	1.38 days	Ruthenium-103	^{103}Ru	39.35 days
Cerium-144	^{144}Ce	284.3 days	Ruthenium-106	^{106}Ru	368.2 days
Cesium- 134	^{134}Cs	2.062 years	Strontium-89	^{89}Sr	50.55 days
Cesium-137	^{137}Cs	30.17 years	Strontium-90	^{90}Sr	28.6 years
Cobalt-58	^{58}Co	70.80 days	Technetium-99	^{99}Tc	2.13E+5 years
Cobalt-60	^{60}Co	5.271 years	Thorium-228	^{228}Th	1.9132 years
Curium-242	^{242}Cm	163.2 days	Thorium-230	^{230}Th	7.54E+4 years
Curium-244	^{244}Cm	18.11 years	Thorium-232	^{232}Th	1.405E+10 years
Iodine-129	^{129}I	157E+7 years	Thorium-234	^{234}Th	2.41E+1 day
Iodine-131	^{131}I	8.04 days	Tritium	^{3}H	12.28 years
Krypton-85	^{85}Kr	10.72 years	Uranium-234	^{234}U	2.445E+5 years
Krypton-88	^{88}Kr	2.84 hours	Uranium-235	^{235}U	7.038E+8 years
Manganese-54	^{54}Mn	312.7 days	Uranium-236	^{236}U	2.3415E+7 years
Neptunium-237	^{237}Np	2.14E+6 days	Uranium-238	^{238}U	4.468E+9 years
Niobium-95	^{95}Nb	35.06 days	Xenon-133	^{133}Xe	5.245E+9 years
Osmium-185	^{185}Os	93.6 days	Xenon-135	^{135}Xe	9.11 hours
Phosphorus-32	^{32}P	14.29 days	Yttrium-90	^{90}Y	64.1 hours
Polonium-210	^{210}Po	138.378 days	Zirconium-95	^{95}Zr	64.02 days

Source: DOE 1989. Radioactive Decay Data Tables: A Handbook of Decay Data for Application to Radioactive Dosimetry and Radiological Assessments, DOE/TIC-11026.

RADIATION

Radiation, or radiant energy, is energy in the form of waves or particles moving through space. Visible light, heat, radio waves, and alpha particles are examples of radiation. When people feel warmth from the sunlight, they are actually absorbing the radiant energy emitted by the sun.

Electromagnetic radiation is radiation in the form of electromagnetic waves. Examples include gamma rays, ultraviolet light, and radio waves. Particulate radiation is radiation in the form of particles. Examples include alpha and beta particles. Radiation also is characterized as ionizing or nonionizing because of the way in which it interacts with matter.

Ionizing Radiation

Normally, an atom has an equal number of protons and electrons; however, atoms can lose or gain electrons in a process known as ionization. Some forms of radiation (called ionizing radiation) can ionize atoms by "knocking" electrons off atoms. Examples of ionizing radiation include alpha, beta, and gamma radiation.

Ionizing radiation is capable of changing the chemical state of matter and subsequently causing biological damage. By this mechanism, it is potentially harmful to human health.

Nonionizing Radiation

Nonionizing radiation bounces off or passes through matter without displacing electrons. Examples include visible light and radio waves. At this time it is unclear whether or not nonionizing radiation is harmful to human health. In the discussion that follows, the term radiation is used to describe ionizing radiation.

SOURCES OF RADIATION

Radiation is everywhere. Most occurs naturally; a small percentage is human-made. Naturally occurring radiation is known as background radiation.

Background Radiation

Many materials are naturally radioactive. In fact, this naturally occurring radiation is the major source of radiation in the environment. Although people have little control over the amount of background radiation to which they are exposed, this exposure must be put into perspective. Background radiation remains relatively constant over time and is present in the environment today much as it was hundreds of years ago.

Sources of background radiation include uranium in the earth, radon in the air, and potassium in food. Background radiation is categorized as cosmic, terrestrial, or internal, depending on its origin.

Principal Radiation Types Emitted by Radionuclides

Alpha

A particle consisting of two protons and two neutrons emitted from the nucleus.

Low penetration: the mean range of a 5-MeV alpha particle in air is about 3.5 cm; in tissue its range is about 44 µm.

For environmental dosimetry, particularly important as an internal emitter, especially in the respiratory passages, on bone surfaces, and in red marrow. Its energy is concentrated along short paths and can deliver high localized doses to sensitive surface regions.

Beta

An electron emitted from the nucleus.

The average range of a 1-MeV beta particle is about 3 m in air but only about 3 mm in tissue.

For environmental dosimetry, of primary concern as an internal emitter. Because of their relatively short range in tissue, beta particles principally irradiate the organs in which they originate.

Gamma and X rays

Electromagnetic radiation, emitted as energy packets called photons, similar to light and radio waves but from a different energy region of the electromagnetic spectrum. X rays originate in the orbital electron field surrounding the nucleus; gamma rays are emitted from the nucleus.

Gamma radiation: to absorb 95% of the gamma energy from a ^{60}Co source, 6 cm of lead, 10 cm of iron, or 33 cm of concrete would be needed.

For environmental dosimetry, gamma and X rays important both for internal and external exposure. Gamma emitters deposited in one organ of the body can significantly irradiate other organs.

Cosmic Radiation

Energetically charged particles from outer space continuously hit the earth's atmosphere. These particles and the secondary particles and photons they create are called cosmic radiation. Because the atmosphere provides some shielding against cosmic radiation, the intensity of this radiation increases with altitude above sea level. In other words, a person in Denver, Colorado, is exposed to more cosmic radiation than a person in New Orleans, Louisiana.

Terrestrial Radiation

Terrestrial radiation refers to radiation emitted from radioactive materials in the earth's rocks, soils, and minerals. Radon (Rn), radon progeny (the relatively short-lived decay products from the decay of radon ^{222}Rn), potassium (^{40}K), isotopes of thorium (Th), and isotopes of uranium (U) are the elements responsible for most terrestrial radiation.

Internal Radiation

Radionuclides in the environment enter the body with the air people breathe and the foods they eat. They also can enter through an open wound. Natural radionuclides that can be inhaled and ingested include isotopes of uranium and its progeny, especially radon (^{222}Rn) and its progeny, thoron (^{220}Rn) and its progeny, potassium (^{40}K), rubidium (^{87}Rb), and carbon (^{14}C). Radionuclides contained in the body are dominated by ^{40}K and ^{210}Po; others include rubidium (^{87}Rb) and carbon (^{14}C) (NCRP 1987).

Human-Made Radiation

In addition to background radiation, there are human-made sources of radiation to which most people are exposed. Examples include consumer products, medical sources, fallout from atmospheric atomic bomb tests, and industrial by-products. No atmospheric testing of atomic weapons has occurred since 1980 (NCRP 1987).

Consumer Products

Some consumer products are sources of radiation. The radiation in some of these products, such as smoke detectors and airport X-ray baggage inspection systems, is essential to the performance of the device. In other products, such as televisions and tobacco products, the radiation occurs incidentally to the product function.

Medical Sources

Radiation is an important tool of diagnostic medicine and treatment and is the main source of exposure to the public from human-made radiation. Exposure is deliberate and directly beneficial to the patients exposed. In general, medical exposures from diagnostic or therapeutic X rays result from beams directed to specific areas of the body. Thus, all body organs generally are not irradiated uniformly. Nuclear medicine examinations and treatments involve the internal administration of radioactive compounds, or radiopharmaceuticals, by injection, inhalation, consumption, or insertion. Even then, radionuclides are not distributed uniformly throughout the body. Radiation and radioactive materials also are used in the preparation of medical instruments, including the sterilization of heat-sensitive products such as plastic heart valves.

Other Sources

Radioactive fallout, the by-product of nuclear-weapon testing in the atmosphere, is a source of radiation. Other sources of radiation include emissions of radioactive materials from nuclear facilities such as uranium mines, fuel processing plants, and nuclear power plants; transportation of radioactive materials; and emissions from mineral-extraction facilities.

PATHWAYS OF RADIONUCLIDES

People can be exposed to radionuclides in the environment through a number of routes (Fig. A.2). Potential routes for internal and/or external exposure are referred to as pathways. For example, radionuclides in the air could fall on a pasture. The grass then could be eaten by cows, and the radionuclides deposited on the grass would show up in milk. People drinking the milk would be exposed to this radiation. People also could simply inhale airborne radionuclides. Similarly, radionuclides in water could be ingested by fish, and people eating the fish would also ingest the radionuclides in the fish tissue. People swimming in the water would be exposed also.

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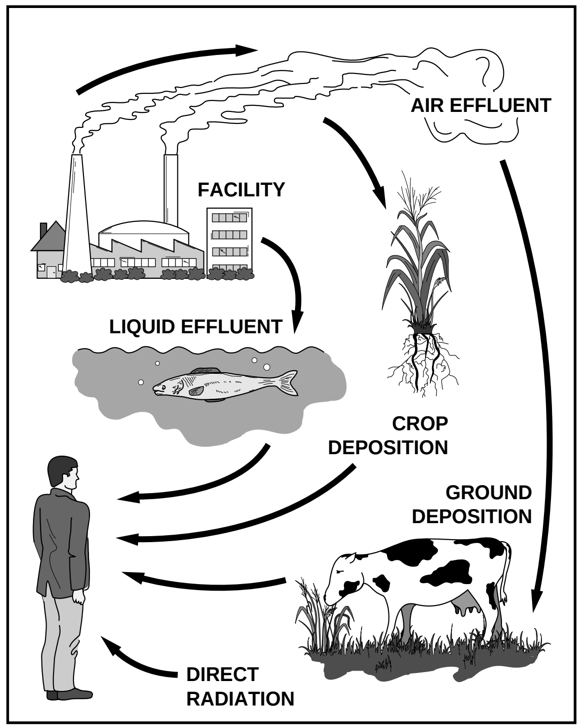

Fig. A.2. Examples of radiation pathways.

MEASURING RADIATION

To determine the possible effects of radiation on the health of the environment and people, the radiation must be measured. More precisely, its potential to cause damage must be ascertained.

Activity

When we measure the amount of radiation in the environment, what is actually being measured is the rate of radioactive decay, or activity. The rate of decay varies widely among the various radioisotopes. For that reason, one gram of a radioactive substance may contain the same amount of activity as several tons of another material. This activity is expressed in a unit of measure known as a curie (Ci). More specifically, one curie equals 3.7×10^{10} (37,000,000,000) atomic disintegrations per second (dps). In the international system of units, 1 dps equals 1 becquerel (Bq).

Absorbed Dose

The total amount of energy absorbed per unit mass of the exposed material as a result of exposure to radiation is expressed in a unit of measure known as a rad. In this case, it is the effect of the absorbed energy (the biological damage that it causes) that is important, not the actual amount. In the international system of units, 100 rad equals 1 gray (Gy).

Dose Equivalent

The measure of potential biological damage to specific body organs or tissues caused by exposure to and subsequent absorption of radiation is expressed in a unit of measure known as a rem. One rem of any type of radiation has the same total damaging effect. Because a rem represents a fairly large dose equivalent, dose equivalents are usually expressed as millirem (mrem), which is 1/1000 of a rem. In the international system of units, 1 sievert (Sv) equals 100 rem; 1 millisievert (mSv) equals 100 mrem. Specific types of dose equivalents are defined as follows:

- committed dose equivalent—the total dose equivalent to an organ during the 50-year period following intake.
- effective dose equivalent (EDE)—the weighted sum of dose equivalents to a specified list of organs. The organs and weighting factors are selected on the basis of risk to the entire body. "EDE" is the unit used in the *Annual Site Environmental Report*.
  - — committed effective dose equivalent: the total effective dose to specified organs in the human body during the 50-year period following intake.
  - — collective effective dose equivalent: the sum of effective dose equivalents of all members of a given population.

Units of Radiation Measure

To comply with DOE orders, this report will present results using the current system followed by Système International (SI) units in parentheses. For example, the dose from a typical chest X ray is 10 mrem (0.10 mSv).

Current System	SI System	Conversion
Activity		
curie (Ci)	becquerel (Bq)	1 Ci = 3.7×10^{10} Bq
Absorbed dose		
rad (radiation absorbed dose)	gray (Gy)	1 rad = 0.01 Gy
Dose equivalent		
rem (roentgen equivalent man)	sievert (Sv)	1 rem = 0.01 Sv

Converting Dose Equivalent

Because a rem represents a fairly large dose of radiation, dose is best expressed as a millirem, or 1/1000 of a rem. The same is true of sieverts. Dose is expressed in millisieverts (mSv). Because 1 mrem equals 0.01 mSv, converting from millirem to millisieverts is simply a matter of moving the decimal point two places to the left. For example, 267 mrem equals 2.67 mSv.

Dose Determination

Determining dose is an involved process in which complex mathematical equations based on several factors, including the type of radiation, the rate of exposure, weather conditions, and typical diet, are used. Basically, radioactive decay, or activity, generates radiant energy. People absorb some of the energy to which they are exposed. The effect of this absorbed energy is responsible for an individual's dose. Whether radiation is natural or human-made, it has the same effect on people.

Many terms are used to report dose. The terms take several factors into account, including the amount of radiation absorbed, the organ absorbing the radiation, and the effect of the radiation over a 50-year period. The term "dose," in this report, means the committed EDE, which is the total effective dose equivalent that will be received during a specified time (50 years) from radionuclides taken into the body in the current year, and the EDE attributable to penetrating radiation from sources external to the body.

Dose Conversion Factor

A dose conversion factor (DCF) is defined as the dose equivalent received from exposure to a unit quantity of a radionuclide by way of a specific exposure pathway. Two types of DCFs exist. One type gives the committed dose equivalent (rem) resulting from intake (by inhalation and ingestion) of a unit activity (1.0 μCi) of a radionuclide. The second gives the dose equivalent rate (millirem per year) per unit activity (1.0 μCi) of a radionuclide in a unit (cubic or square centimeters) of an environmental compartment (air volume or ground surface). All DCFs used in this report were approved by DOE or by EPA (DOE 1988a; DOE 1988b; EPA 1993).

Comparison of Dose Levels

Table A.2 presents a scale of dose levels, with an example of the type of exposure that may cause such a dose, or the special significance of such a dose. This information is intended to help the reader become familiar with a range of doses that various individuals may receive.

The maximally exposed person living near the ORR area could receive an annual EDE of about 4.1 mrem (0.041 mSv) from radionuclides released from the ORR during 1997.

Dose from Cosmic Radiation

The average annual dose equivalent to people in the United States from cosmic radiation is about 27 mrem (0.27 mSv) (NCRP 1987). The average dose equivalent caused by cosmic radiation in Tennessee is about 45 mrem per year (0.45 mSv per year) (Tsakeres 1980). When shielding and the time spent indoors are considered, the dose for the surrounding population is reduced to 80%, or about 36 mrem (0.36 mSv) per year.

Dose from Terrestrial Radiation

The average annual dose from terrestrial gamma radiation is about 28 mrem (0.28 mSv) in the United States but varies geographically across the country (NCRP 1987). Typical reported values are about 16 mrem (0.16 mSv) on the Atlantic and Gulf coastal plains and about 63 mrem (0.63 mSv) on the eastern slopes of the Rocky Mountains. The average external gamma exposure rate in the vicinity of the ORR is about 7.8 μR/h, which results in an equivalent dose of about 51 mrem per year (0.51 mSv per year).

Dose from Internal Radiation

The major contributors to the annual dose equivalent for internal radionuclides are the short-lived decay products of radon, which contribute an average dose of about 200 mrem (2.00 mSv) per year. This dose estimate is based on an average radon concentration of about 1 pCi/L (0.037 Bq/L) (NCRP 1987).

The average dose from other internal radionuclides is about 39 mrem (0.39 mSv) per year, which is predominantly attributed to the naturally occurring radioactive isotope of potassium, ^{40}K. The concentration of radioactive potassium in human tissues is similar in all parts of the world (NCRP 1987).

Dose from Consumer Products

The U.S. average annual dose to an individual from consumer products is about 10 mrem (0.10 mSv) (NCRP 1987); however, not all members of the U.S. population are exposed to all of these sources.

Table A.2. Comparison and description of various dose levels

Dose level	Description
1 mrem	Approximate daily dose from natural background radiation, including radon
2.5 mrem	Cosmic dose to a person on a one-way airplane flight from New York to Los Angeles
10 mrem	Annual exposure limit set by the U.S. Environmental Protection Agency (EPA) for exposures from airborne emissions from operations of nuclear fuel cycle facilities, including power plants, uranium mines, and mills
45 mrem	Average yearly dose from cosmic radiation received by people in the Paducah area
46 mrem	Estimate of the largest dose any off-site person could have received from the March 28, 1979, Three Mile Island nuclear accident
66 mrem	Average yearly dose to people in the United States from human-made sources
100 mrem	Annual limit of dose from all U.S. Department of Energy (DOE) facilities to a member of the public who is not a radiation worker
110 mrem	Average occupational dose received by U.S. commercial radiation workers in 1980
244 mrem	Average dose from an upper gastrointestinal diagnostic X-ray series
300 mrem	Average yearly dose to people in the United States from all sources of natural background radiation
1 to 5 rem	Level at which EPA Protective Action Guidelines state that public officials should take emergency action when this is a probable dose to a member of the public from a nuclear accident
5 rem	Annual limit for occupational exposure of radiation workers set by the U.S. Nuclear Regulatory Commission and DOE
10 rem	Estimated level at which an acute dose would result in a lifetime excess risk of death from cancer of 0.8%
25 rem	EPA guideline for voluntary maximum dose to emergency workers for non-lifesaving work during an emergency
75 rem	EPA guideline for maximum dose to emergency workers volunteering for lifesaving work
50 to 600 rem	Level at which doses received over a short period of time produce radiation sickness in varying degrees. At the lower end of this range, people are expected to recover completely, given proper medical attention. At the top of this range, most people will die within 60 days

Adapted from Westinghouse Savannah River Company 1994. *Savannah River Site Environmental Report for 1993, Summary Pamphlet*, WSRC-TR-94-076.

Dose from Medical Sources

Nuclear medicine examinations, which involve internal administration of radiopharmaceuticals, generally account for the largest portion of dose from human-made sources. However, the radionuclides used for specific tests are not distributed uniformly throughout the body. In these cases, the concept of EDE, which relates the significance of exposures of organs or body parts to the effect on the entire body, is useful in making comparisons. The average annual EDE from medical examinations is 53 mrem (0.53 mSv), including 39 mrem (0.39 mSv) for diagnostic X rays and 14 mrem (0.14 mSv) for nuclear medicine procedures (NCRP 1989). The actual doses to individuals who receive such medical exams are much higher than these values, but not everyone receives such exams each year (NCRP 1989).

Dose from Other Sources

A few additional sources of radiation contribute minor doses to individuals in the United States. The dose to the general public from nuclear fuel cycle facilities, such as uranium mines, mills, fuel-processing plants, nuclear power plants, and transportation routes, has been estimated at less than 1 mrem (0.01 mSv) per year (NCRP 1987).

A comprehensive U.S. Environmental Protection Agency report projected an average occupational dose to monitored radiation workers in medicine, industry, the nuclear fuel cycle, government, and miscellaneous industries to be 105 mrem (1.05 mSv) per year for 1985, down slightly from 110 mrem (1.10 mSv) per year in 1980 (Kumazawa et al. 1984).

Small doses to individuals occur as a result of radioactive fallout from atmospheric atomic bomb tests, emissions of radioactive materials from nuclear facilities, emissions from certain mineral extraction facilities, and transportation of radioactive materials. The combination of these sources contributes less than 1 mrem (0.01 mSv) per year to the average dose to an individual (NCRP 1987).