APPENDIX B

INTRODUCTION TO RADIATION

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This section presents basic facts concerning radiation. The information is intended as a basis for understanding the dose associated with releases from the Portsmouth Gaseous Diffusion Plant (PORTS), not as a comprehensive discussion of radiation and its effects on the environment and biological systems. *The McGraw-Hill Dictionary of Scientific and Technical Terms* (McGraw-Hill 1989) defines radiation and radioactivity as follows:

> *radiation*—1) The emission and propagation of waves transmitting energy through space or through some medium; for example, the emission and propagation of electromagnetic, sound, or elastic waves. 2) The energy transmitted through space or some medium; when unqualified, usually refers to electromagnetic radiation. Also known as radiant energy. 3) A stream of particles, such as electrons, neutrons, protons, alpha particles, or high-energy photons, or a mixture of these (McGraw-Hill 1989).
>
> *radioactivity*—A particular type of radiation emitted by a radioactive substance, such as alpha radioactivity (McGraw-Hill 1989).

Radiation occurs naturally; it was not invented but discovered. People are constantly exposed to radiation. For example, 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 of radiation; radiation measurement; sources of radiation; and dose information.

ATOMS AND ISOTOPES

All matter is made up of atoms. An atom is "a unit of measure consisting of a single nucleus surrounded by a number of electrons equal to the number of protons in the nucleus" (American Nuclear Society 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 number of neutrons may vary among atoms of the same element. The number of neutrons and protons determines the atomic weight. Atoms of the same element with a different number of neutrons are called isotopes. In other words, isotopes have the same chemical properties but different atomic weights. Figure B.1 depicts isotopes of the element hydrogen.

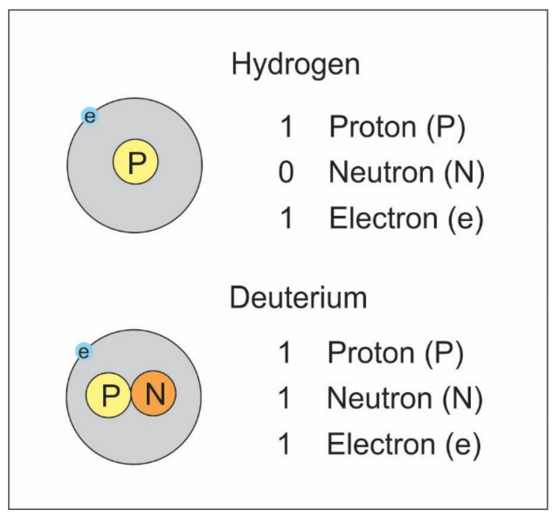

Figure B.1. Isotopes of the element hydrogen.

Another example is the element uranium, which has 92 protons; all isotopes of uranium, therefore, have 92 protons. However, each uranium isotope has a different number of neutrons. Uranium-238 (also denoted ^{238}U) has 92 protons and 146 neutrons; uranium-235 has 92 protons and 143 neutrons; uranium-234 has 92 protons and 142 neutrons.

Some isotopes are stable, or nonradioactive; some are radioactive. A radioactive isotope, or radionuclide, gives off radioactivity because the nucleus has too many particles, too much energy, or too much mass to be stable. The nucleus of the atom disintegrates in an attempt to reach a stable or nonradioactive state. As the nucleus disintegrates, energy is released in the form of radiation. Each radionuclide 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 (less than a second) or very long (millions of years), depending on the radionuclide. Appendix C presents the half-lives of radionuclides of interest at PORTS.

RADIATION

Although there are different types of radiation, radiation given off by radionuclides such as uranium-235 is called ionizing radiation. In this report, the term radiation is used to describe ionizing radiation.

Ionizing radiation is capable of changing the chemical state of matter and subsequently causing biological damage, and thus is potentially harmful to human health. Ionizing radiation can include alpha particles, beta particles, and gamma rays. Figure B.2 shows the penetrating potential of different types of ionizing radiation.

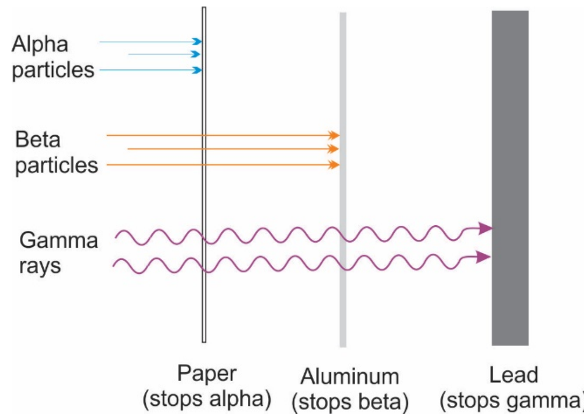

Figure B.2. Penetrating power of radiation.

MEASURING RADIATION

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

Activity

When measuring 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 radionuclides. For that reason, 1 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, 1 curie = 3.7E+10 (37,000,000,000) atom disintegrations per second (dps). A curie is a relatively large measure of radiation; therefore, radioactivity is often measured in this report in picocuries (pCi). A picocurie is one trillionth of a curie or 2.2 disintegrations per minute.

Absorbed Dose

The absorbed dose is the total amount of energy absorbed per unit mass (the amount of energy deposited in body tissue) as a result of exposure to radiation. Absorbed dose is expressed in a unit of measure known as a rad. In terms of human health, however, it is the effect of the absorbed energy that is important, not the actual amount. Therefore, this type of dose measurement is not used in this report.

Effective Dose

The effective dose is a measure of the potential biological damage that could be caused by exposure to and subsequent absorption of radiation to the body. Effective dose 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, dose is often expressed as a millirem (mrem) or 1/1000 of a rem.

Although there are several specific types of dose measurements, for simplicity, this report discusses dose in terms of the effective dose. The effective dose is the sum of the doses received by all organs or tissues of the body after each one has been multiplied by the appropriate radiation and tissue weighting factors. It includes the dose from radiation sources internal and/or external to the body. In this report, the term "effective dose" is often shortened to "dose".

Population Dose

The sum of the effective doses to all the people in a specified community is called the population dose, or sometimes, the collective dose. If 100 people in the community each received a dose of 1 mrem, the population dose would be 100 person-mrem, or 0.1 person-rem (changing the units from mrem to rem).

Table B.1 summarizes radiation and dose terminology, definitions, and units of measure used in this report.

Table B.1. Summary of radiation and dose terminology

Term	Definition	Unit of measure (Standard system)
Activity	The amount of radiation emitted by a radioactive material.	Ci or pCi
Absorbed dose	The total amount of energy deposited in body tissue as a result of exposure to radiation.	rad
Effective dose (shortened to dose in this report)	A measure of the potential biological damage that could be caused by exposure to and subsequent absorption of radiation to the body.	rem or mrem
Population dose	The sum of the effective doses to all persons in a specified community.	Person-rem

Table B.2 provides unit of radiation measure and applicable conversions to the international measurement system.

Table B.2. Units of radiation measure

Standard System	International System	Conversion
Ci (curie)	becquerel (Bq)	1 Ci = 3.7 x 10^{10} Bq
rad (radiation absorbed dose)	gray (Gy)	1 rad = 0.01 Gy
rem (roentgen equivalent man)	sievert (Sv)	1 rem = 0.01 Sv

SOURCES OF RADIATION

Radiation is everywhere. Most occurs naturally, but 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; background radiation present in the environment today is much the same 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. In the United States, the average person receives an annual dose from natural background radiation of 311 mrem/year. Table B.3 summarizes various doses from both naturally-occurring and human-made radiation sources.

Exposure to radiation from atmospheric testing of atomic weapons is considered part of background radiation. However, testing of atomic weapons has been suspended in the United States and most parts of the world. China conducted the last atmospheric atomic weapons test in 1980. Fallout from atmospheric weapons testing is not currently a significant contributor to background radiation (Health Physics Society 2010).

Cosmic/space 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 or space radiation. Because the atmosphere provides some shielding against cosmic radiation, the intensity of this radiation increases with altitude above sea level — the higher a person is in elevation, the less shielding is provided by the atmosphere.

The average annual dose received by residents of the United States from cosmic radiation is about 33 mrem/year (National Council on Radiation Protection [NCRP] 2009). The average annual dose to a person living in Honolulu, Hawaii (at sea level and near the equator) is about 20 mrem/year, while the average annual dose to a person living in Colorado Springs, Colorado (high altitude and latitude) is about 70 mrem/year (Health Physics Society 2010).

Terrestrial radiation. Terrestrial radiation refers to radiation emitted from radioactive materials in the earth's rocks, soils, and minerals. Radon, radon progeny, the relatively short-lived decay products of radium-226, potassium-40, thorium isotopes, and uranium isotopes are the elements responsible for most terrestrial radiation.

The average annual dose received from terrestrial gamma radiation is about 21 mrem/year in the United States (NCRP 2009). Similar to cosmic radiation, this dose varies geographically across the country with the lowest doses on the Atlantic and Gulf coastal plains and highest doses in the mountains in the western United States.

Internal radiation. Radioactive material in the environment can enter the body through different routes of exposure, for example, the air people breathe and the food they eat, or through an open wound. Natural radionuclides that can enter the body include isotopes of uranium, thorium, radium, radon, polonium, bismuth, and lead in the uranium-238 and thorium-232 decay series. In addition, the body contains isotopes of potassium (potassium-40), rubidium (rubidium-87), and carbon (carbon-14).

Inhalation of the short-lived decay products of radon are the major contributors to the annual dose equivalent for internal radionuclides, mostly radon-222). They contribute an average annual dose of about 228 mrem/year (NCRP 2009). The average annual dose from ingestion of radionuclides is about 29 mrem/year, which can be attributed to the naturally occurring potassium-40, thorium isotopes, uranium isotopes, and the uranium and thorium decay series (NCRP 2009).

Table B.3. Comparison and description of various dose levels[a]

Dose level	Description
0.85 mrem	Approximate daily dose for a person in the United States from natural background radiation, including radon
1.92 mrem	Cosmic dose to a person on a one-way airplane flight from Washington D.C. to Seattle
10 mrem	Annual exposure limit, set by the U.S. Environmental Protection Agency (U.S. EPA), for exposures from airborne emissions from operations of nuclear fuel cycle facilities, including power plants and uranium mines and mills
36 mrem	Average annual dose to a person who smokes one pack of cigarettes per day
36 mrem	Mammogram (two views)
46 mrem	Estimate of the largest dose any off-site person could have received from the March 28, 1979, Three Mile Island nuclear power plant accident
60 mrem	X-ray (single exposure) of abdomen or hip
100 mrem	Annual dose limit to a member of the public from radiological activities, including remediation, at a DOE facility
244 mrem	Average dose from an upper gastrointestinal diagnostic X-ray series
300 mrem	Average annual dose to a person in the United States from all sources of medical radiation
311 mrem	Average annual dose to a person in the United States from all sources of natural background radiation, including radon
620 mrem	Average annual dose to a person in the United States from all sources of natural and human-made radiation (based on rounded values for individual categories)
700 mrem	Computed tomography (CT scan) – chest
1000-5000 mrem	U.S. EPA protective action guideline calling for public officials to take emergency action when the dose to a member of the public from a nuclear accident will likely reach this range
5000 mrem	Annual dose limit for occupational exposure of radiation workers set by the Nuclear Regulatory Commission and DOE
10,000 mrem	The Biological Effects of Ionizing Radiation V report estimated that an acute dose at this level would result in a lifetime excess risk of death from cancer of 0.8%, which means that of 1000 persons exposed at 10,000 mrem, eight persons would die from cancer caused by the radiation exposure (Biological Effects of Ionizing Radiation 1990)
25,000 mrem	U.S. EPA guideline maximum dose to emergency workers volunteering for non-lifesaving work

Table B.3. Comparison and description of various dose levels[a] (continued)

Dose level	Description
75,000 mrem	U.S. EPA guideline for maximum dose to emergency workers volunteering for lifesaving work
50,000-600,000 mrem	Doses in this range received over a short period of time will 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 would die within 60 days.

[a]Adapted from Savannah River Site Environmental Report for 1993, Summary Pamphlet, WSRC-TR-94-076, (Westinghouse Savannah River Company 1994) and NCRP Report No. 160, *Ionizing Radiation Exposure of the Population of the United States* (NCRP 2009).

Human-made Radiation

Most people are exposed to human-made sources of radiation. Examples include consumer products, medical sources, and industrial or occupational sources. About one-half of 1% of the U.S. population performs work in which radiation in some form is present. In the United States, the average person receives an annual dose from human-made radiation of approximately 313 mrem/year, primarily from medical procedures.

Consumer products and activities. Some consumer products are sources of radiation. In some consumer products, such as smoke detectors, watches, or clocks, radiation is essential to the performance of the device. In other products or activities, such as smoking tobacco products or building materials, the radiation occurs incidentally to the product function. Commercial air travel is another consumer activity that results in exposure to radiation (from cosmic radiation).

The U.S. average annual dose received by an individual from consumer products is about 13 mrem/year (NCRP 2009). Almost 90 percent of this annual dose results from smoking cigarettes, commercial air travel, and building materials (radionuclides present in brick, masonry, cement, concrete, and other materials).

Medical sources. Radiation is an important tool of diagnostic medicine and treatment, and, in this use, is the main source of exposure to human-made radiation. Exposure is deliberate and directly beneficial to the patients exposed. Generally, medical exposures result from beams directed to specific areas of the body. Thus, all body organs generally are not irradiated uniformly. Radiation and radioactive materials are also used in a wide variety of pharmaceuticals and in the preparation of medical instruments, including the sterilization of heat-sensitive products such as plastic heart valves. Nuclear medicine examinations and treatment 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.

Medical exams and procedures account for the largest portion of the average annual dose received from human-made sources. These procedures include x-rays, computed tomography (CT) scans—a more sophisticated type of x-ray), fluoroscopy, and nuclear medicine. The increase in the use of medical imaging procedures, especially computed tomography, over the last 25 years has resulted in a marked increase in the average annual dose from medical sources received by a person in the United States: 53 mrem/year in the early 1980s to 300 mrem/year in 2006 (NCRP 2009). The actual annual doses received by individuals who complete such medical exams can be much higher than the average value because not everyone receives such exams each year.

Industrial and occupational sources. Other sources of radiation include emissions of radioactive materials from nuclear facilities such as uranium enrichment plants, uranium mines, and nuclear power plants; emissions from mineral extraction facilities; and the transportation of radioactive materials. Workers in certain occupations may also be exposed to radiation due to their jobs, in addition to the average background radiation exposure. These occupations include positions in medicine, aviation, research, education, and government. Pilots and other air crew members have the highest annual average exposure to radiation as part of their jobs: 307 mrem/year (NCRP 2009). This exposure is from cosmic radiation.

Small doses received by individuals occur as a result of 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/year to the average annual dose to an individual (NCRP 2009).