Appendix F. Radiation

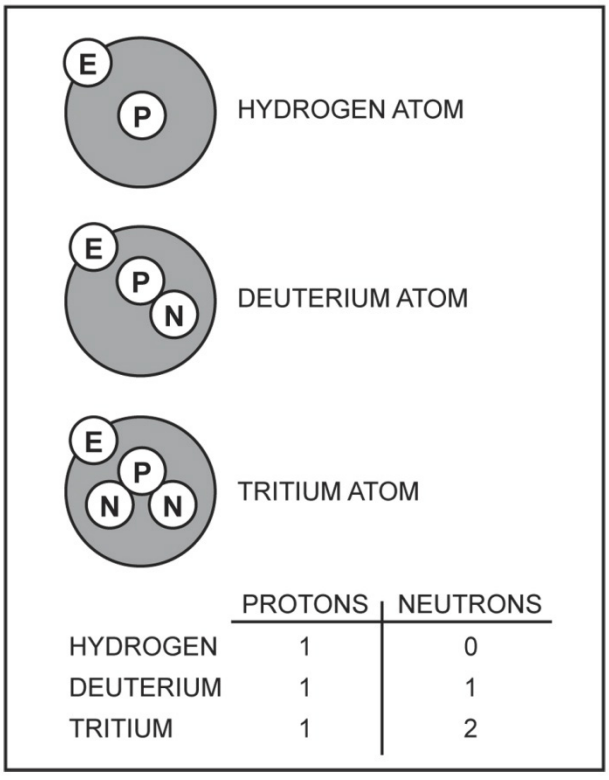
Appendix F. Radiation

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.

F.1 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" (Alter 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. F.1).



	PROTONS	NEUTRONS
HYDROGEN	1	0
DEUTERIUM	1	1
TRITIUM	1	2

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

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 (millions of years), depending on the isotope (Table F.1).

Table F.1. Selected radionuclide half-lives

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*	^{234m}Pa	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
Cesium-138	^{138}Cs	32.2 min	Technetium-99	^{99}Tc	2.13E+5 years
Cobalt-58	^{58}Co	70.80 days	Thorium-228	^{228}Th	1.9132 years
Cobalt-60	^{60}Co	5.271 years	Thorium-230	^{230}Th	7.54E+4 years
Curium-242	^{242}Cm	163.2 days	Thorium-232	^{232}Th	1.405E+10 years
Curium-244	^{244}Cm	18.11 years	Thorium-234	^{234}Th	2.41E+1 day
Iodine-129	^{129}I	157E+7 years	Tritium	^{3}H	12.28 years
Iodine-131	^{131}I	8.04 days	Uranium-234	^{234}U	2.445E+5 years
Krypton-85	^{85}Kr	10.72 years	Uranium-235	^{235}U	7.038E+8 years
Krypton-88	^{88}Kr	2.84 hours	Uranium-236	^{236}U	2.3415E+7 years
Manganese-54	^{54}Mn	312.7 days	Uranium-238	^{238}U	4.468E+9 years
Neptunium-237	^{237}Np	2.14E+6 days	Xenon-133	^{133}Xe	5.245E+9 years
Niobium-95	^{95}Nb	35.06 days	Xenon-135	^{135}Xe	9.11 hours
Osmium-185	^{185}Os	93.6 days	Yttrium-90	^{90}Y	64.1 hours
Phosphorus-32	^{32}P	14.29 days	Zirconium-95	^{95}Zr	64.02 days
Polonium-210	^{210}Po	138.378 days			

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

F.2 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 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 non-ionizing because of the way in which it interacts with matter.

F.2.1 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.

F.2.2 Non-ionizing Radiation

Non-ionizing radiation is described as a series of energy waves composed of oscillating electric and magnetic fields traveling at the speed of light. Non-ionizing radiation includes the spectrum of ultraviolet (UV), visible light, infrared (IR), microwave, radio frequency (RF), and extremely low frequency (ELF). Lasers commonly operate in the UV, visible, and IR frequencies. Microwave radiation is absorbed near the skin, while RF radiation may be absorbed throughout the body. At high enough intensities, both will damage tissue through heating. Excessive visible radiation can damage the eyes and skin (Department of Labor, OSHA Safety and Health Topics, www.OSHA.gov). However, in the discussion that follows, the term "radiation" is used to describe ionizing radiation.

F.3 Sources of Radiation

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

F.3.1 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.

F.3.1.1 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. For example, a person in Denver, Colorado, is exposed to more cosmic radiation than a person in New Orleans, Louisiana.

F.3.1.2 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 the radon isotope ^{222}Rn), potassium (^{40}K), isotopes of thorium (Th), and isotopes of uranium (U) are the elements responsible for most terrestrial radiation.

F.3.1.3 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 ^{87}Rb and ^{14}C (NCRP 1987).

F.3.2 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).

F.3.3 Consumer Products

Some consumer products are sources of radiation. The radiation in some of these products, such as smoke detectors, radioluminous products, and airport X-ray baggage inspection systems, is essential to the performance of the device. In other products, such as tobacco products and building materials, the radiation occurs incidentally to the product's function (NCRP 1987, NCRP 2009).

F.3.4 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.

F.3.5 Other Sources

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.

F.4 Pathways of Radionuclides

People can be exposed to radionuclides in the environment through a number of routes (Fig. F.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 could also inhale the 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.

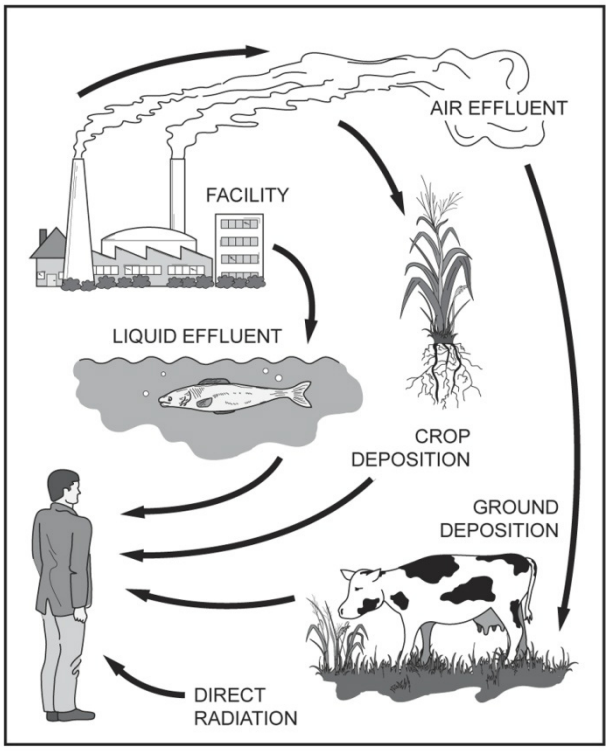


Fig. F.2. Examples of radiation pathways.

F.5 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.

F.5.1 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, 1 g 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 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).

F.5.2 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. 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).

F.5.3 Effective Dose

The measure of potential biological damage to the body caused by exposure to and subsequent absorption of radiation is expressed in a unit of measure known as a rem. For radiation protection purposes, 1 rem of any type of radiation has the same total damaging effect. Because a rem represents a fairly large equivalent dose, it is 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. The effective dose (ED) is the weighted sum of equivalent dose over specified tissues or organs. The ED is based on tissue-weighting factors for 12 specific tissues or organs plus a weight factor for the remainder organs and tissues. In addition, the ED is based on the latest lung model, gastrointestinal absorption fractions, and biokinetic models used for selected elements. Specific types of EDs are defined as follows:

- committed ED—the weighted sum of the committed ED in specified tissues in the human body during the 50-year period following intake; and
- collective ED—the product of the mean ED for a population and the number of persons in the population.

F.5.4 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 ED, which is the ED that will be received during a specified time (50 years) from radionuclides taken into the body in the current year, and the ED due to exposure during the year to penetrating radiation from sources external to the body.

F.5.5 Dose Coefficient

A dose coefficient is defined as the ED received from exposure to a unit quantity of a radionuclide by way of a specific exposure pathway. There are two types of dose coefficients. One type gives the committed ED (rem) resulting from intake (by inhalation and ingestion) of a unit activity (1.0 μCi) of a radionuclide. The second gives the ED 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 dose coefficients used in this report, with Department of Energy concurrence, were approved by the Environmental Protection Agency (EPA 1999).

F.5.6 Comparison of Dose Levels

Figure F.3 gives the 2006 percent contributions of various sources of exposure to total collective dose for the U.S population. As shown the major sources are radon and thoron (37%), computed tomography

(24%) and nuclear medicine (12%) (NCRP 2009). Consumer, occupational, and industrial sources contribute about 2% to the total U.S. collective dose. This information is intended to help the reader become familiar with a range of doses that various individuals may receive.

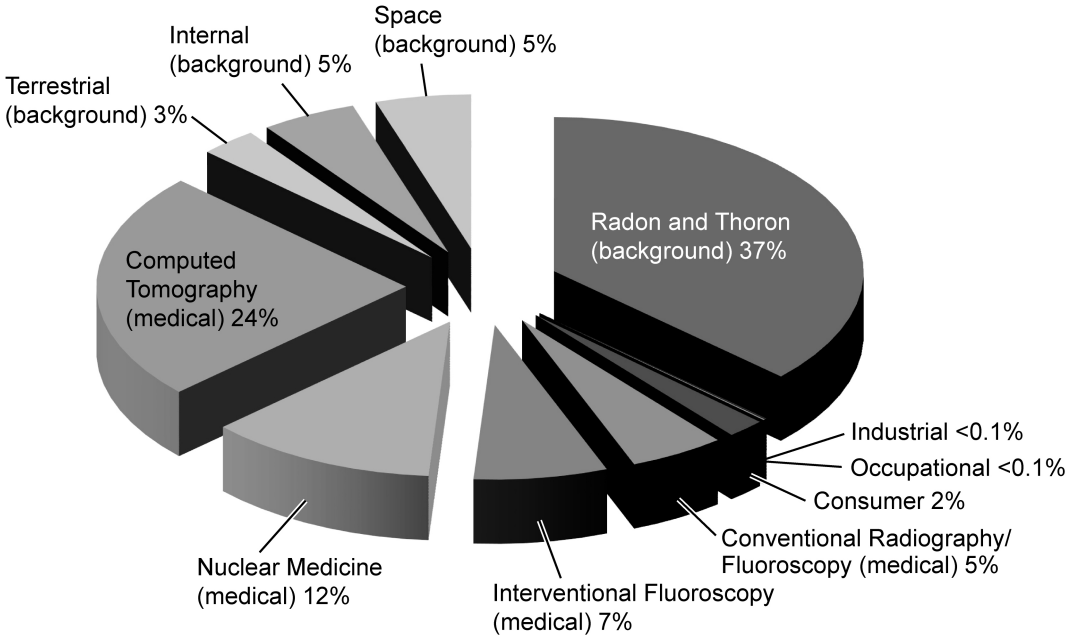


Fig. F.3. All exposure categories for collective effective dose (percent) for 2006.

F.5.7 Dose from Cosmic Radiation

The average annual dose equivalent to people in the United States from cosmic radiation is about 33 mrem (0.33 mSv) (NCRP 2009). 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.

F.5.8 Dose from Terrestrial Radiation

The average annual dose from terrestrial gamma radiation is about 21 mrem (0.21 mSv) in the United States but varies geographically across the country (NCRP 2009). 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.

F.5.9 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 228 mrem (2.28 mSv) per year. This dose estimate is based on an average radon concentration of about 1 pCi/L (0.037 Bq/L) (NCRP 2009).

The average dose from other internal radionuclides is about 29 mrem (0.29 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 2009).

F.5.10 Dose from Consumer Products and Activities

The U.S. average annual dose to an individual from consumer products and activities is about 13 mrem (0.13 mSv), ranging between 0.1 and 40 mrem (0.001 and 0.4 mSv). Cigarette smoking accounts for about 35% of this dose. Other important sources are building materials (27%), commercial air travel (26%), mining and agriculture (6%), miscellaneous consumer-oriented products (3%), combustion of fossil fuels (2%), highway and road construction materials (0.6%), and glass and ceramics (<0.003%). Television and video, sewage sludge and ash, and self-illuminating signs all contribute negligible doses (NCRP 2009).

F.5.11 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 ED, 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 ED from medical examinations is 300 mrem (3 mSv), including 147 mrem (1.47 mSv) from computed tomography scans, 77 mrem (0.77 mSv) from nuclear medicine procedures, 43 mrem (0.43 mSv) from interventional fluoroscopy, and 33 mrem (0.33 mSv) from conventional radiography and fluoroscopy (NCRP 2009). Not everyone receives such exams each year.

F.5.12 Doses 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).

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 an individual's average dose (NCRP 1987).

F.6 Water Pathway Dose Methodology

People can be exposed to radionuclides in the environment through a number of routes (Fig. F.2). Potential routes for internal and/or external exposure are referred to as exposure pathways. Several such pathways exist for exposures of humans to radionuclides in water. People may directly ingest (drink) the water. They may eat fish that were caught from the water that contain radionuclides taken in from the water. Also, people may swim in or boat on the water or use shoreline that has absorbed radionuclides from the water. The following sections discuss the methodologies used to calculate potential radiological impacts to persons who drink water; eat fish; and swim, boat, and use the shoreline at various locations along the Clinch and Tennessee Rivers. The results of these calculations are summarized in Sect. 7.1.2.2.

Radionuclides discharged to surface waters from the ORR enter the Tennessee River system by way of the Clinch River and various feeder streams (see Sect. 1.3.4 for the surface water setting of the ORR). Discharges from the Y-12 Complex enter the Clinch River via Bear Creek and East Fork Poplar Creek, both of which enter Poplar Creek before it enters the Clinch River, and by discharges from Rogers Quarry into McCoy Branch and then into Melton Hill Lake. Discharges from ORNL enter the Clinch River via White Oak Creek and Melton Hill Lake via some small drainage creeks. Discharges from the ETTP enter the Clinch River either directly or via Poplar Creek. For convenience, and to correspond to water sampling locations, surface waters around and below the ORR are divided into seven segments (called water bodies in this appendix):

- Melton Hill Lake above all possible ORR inputs,
- Melton Hill Lake,
- Upper Clinch River from Melton Hill Dam to confluence with Poplar Creek,
- Lower Clinch River (from confluence with Poplar Creek to confluence with the Tennessee River),
- Upper Watts Bar Lake (from around the confluence with the Clinch River to below Kingston),
- Lower System (remainder of Watts Bar Lake and Chicamauga Lake), and
- Poplar Creek, including the confluence of East Fork Poplar Creek.

Since East Fork Poplar Creek is posted against water use, dose estimates for such uses are not reported.

The LADTAP XL methodology (Hamby 1991) is used to calculate individual and population doses via waterborne exposure pathways. All dose calculations require definition of radionuclide concentrations in the medium of interest (water, fish, and shoreline) in the water body of interest.

Two methods, determined by the type of data used, are used to estimate potential radiation doses to the public. The first method uses radionuclide concentrations in the medium of interest (i.e., in water and fish) that were determined by laboratory analyses of actual water and fish samples (see Sects. 6.4 and 6.6). The second method estimates radionuclide concentrations in water and fish that were calculated from measured radionuclide discharges and known or estimated stream flows.

The advantage of the first method is the use of radionuclide concentrations actually measured in water and fish; disadvantages are the inclusion of naturally occurring radionuclides, especially in gross alpha- and beta-activity measurements, the possibility that some radionuclides of ORR origin might be present in quantities too low to be measured, and the possibility that the presence of some radionuclides might be misstated (e.g., present in a quantity below the detection limit). The advantages of the second method are that most radionuclides discharged from the ORR will be quantified and that naturally occurring radionuclides will not be considered or will be accounted for separately; the disadvantage is the lack of complete river, discharge, and stream flow data. Both methods use models to estimate the concentrations of the radionuclides in water and fish, except at locations (water bodies) where actual measurements are made. Using the two methods should allow the potential radiation doses to be bounded.

For some water bodies, radionuclide concentrations are measured directly. These concentrations are used to calculate concentrations in fish and shoreline, as described below. Concentrations in the water body downstream of the measured water body are obtained by multiplying the measured water body concentrations by the ratio of the measured water body flow (liters per year) to the downstream water body flow (liters per year); in essence, the concentrations in the upstream water body are diluted by any additional water input to the downstream water body. This dilution calculation continues for all other downstream water bodies.

For other water bodies, data are available on the activities of radionuclides discharged to a water body. These data may be in the form of (1) total activities discharged per year (curies per year) or (2) activities per unit volume of water (curies per liter) plus the total volume of water discharged per year (liters per year). Radionuclide concentrations in the receiving water body are calculated simply by dividing the measured discharge activities (curies per year) by the total annual flow of the receiving water body (liters per year). The process for calculating concentrations in downstream water bodies is the same as that described in the previous paragraph. The discharge flow rate is usually negligible with respect to the receiving water body flow rate.

Equations used to estimate water pathway doses from radionuclide concentrations in water are given in the following sections.

F.6.1 Drinking Water

Several water treatment plants along the Clinch and Tennessee River systems could be affected by discharges from the ORR. Since plant radionuclide concentration data are not available for these plants, the dose estimates given below likely are high because they are based on concentrations of radionuclides in water before it enters the water treatment plant. Most water treatment plants use flocculation/sedimentation processes. The flocculant process produces a precipitate that helps to remove

solids and also adsorbs dissolved metals. Many radionuclides would be adsorbed by the solids. However, the fraction removed depends on the radionuclide and initial concentration. For purposes of assessment, it was assumed that maximally exposed individuals drink 730 L/year of water and that the average person drinks 370 L/year.

Table F.2 is a summary of potential EDs from identified waterborne radionuclides around the ORR and shows the variation in dose based on method used to estimate dose. The ED from ingestion of water is given by

$$D_{E,i,drink} = U_{drink} * C_{w,i} * DC_{i,ing} * EXP(-\lambda_{r,i} * t_{drink}) ,$$

where

$D_{E,i,drink}$ = ED due to drinking water containing nuclide *i* (mrem/year),

U_{drink} = water consumption rate (L/year),

$C_{w,i}$ = concentration of nuclide *i* in water (μCi/L),

$DC_{i,ing}$ = dose coefficient for ingestion of nuclide *i* (mrem/μCi),

$\lambda_{r,i}$ = radioactive decay constant for nuclide *i* (I/d), and

t_{drink} = time between entry of nuclide into plant and consumption (assumed 1 day).

F.6.2 Eating Fish

Fishing is quite common on the Clinch and Tennessee River systems. For purposes of assessment, it was assumed that avid fish consumers eat 21 kg/year of fish and that the average person consumes 6.9 kg/year. EDs were calculated from measured radionuclide contents in fish (see Sect. 6.6), measured concentrations of radionuclides in water, and calculated concentrations in water. The ED from consumption of fish containing nuclide *i* is given by

$$D_{E,i,fish} = U_{fish} * C_{w,i} * DC_{i,ing} * B_{i,fish} * EXP(-\lambda_{r,i} * t_{fish}) ,$$

where

$D_{E,i,fish}$ = ED due to eating fish containing nuclide *i* (mrem/year),

U_{fish} = fish consumption rate (kg/year),

$C_{w,i}$ = concentration of nuclide *i* in water (μCi/L),

$DC_{i,ing}$ = dose coefficient for ingestion of nuclide *i* (mrem/μCi),

$B_{i,fish}$ = bioaccumulation factor (L/kg),

$\lambda_{r,i}$ = radioactive decay constant for nuclide *i* (I/d), and

t_{fish} = time between harvest and consumption (assumed 10 days).

Fish samples are collected from Melton Hill Lake above all ORR inputs (Clinch River kilometer [CRK] 70), from the upper part of the Clinch River (CRK 32), and from the Clinch River below all ORR inputs (CRK 16). Unidentified beta and alpha activities are often detected in many of the fish samples. Excess beta and alpha activities are estimated by subtracting activities of identified beta- and alpha-particle-emitting radionuclides from the corresponding unidentified activities. The excess unidentified beta and alpha activities are assumed to be from the naturally occurring radionuclides ^{234}Th and ^{226}Ra.

Table F.2. Summary of annual maximum individual effective dose equivalents from waterborne radionuclides (mrem)[a]

Type of sample	Drinking water	Eating fish	Other uses	Total of highest
Melton Hill Lake above ORR inputs, CRK 66, CRK 70				
Fish[b]		0.5		0.5
Water[c]	3E-09	0.0	0.0004	0.0004
Maximum	3E-09	0.5	0.0004	0.5
Melton Hill Lake, CRK 58				
Water[c]	4E-09	0.0	0.0004	0.0004
Discharge[d]	0.0005	0.0007	0.00004	0.001
Maximum	0.0005	0.0007	0.0004	0.002
Upper Clinch River, CRK 23, Gallaher Water Plant, CRK 32				
Fish[b]		0.03		0.03
Water[c]	0.2	1.2	0.2	1.6
Discharge[d]	0.02	0.06	0.008	0.09
Maximum	0.2	1.2	0.2	1.6
Lower Clinch River, CRK 16				
Fish[b]				
Water[c]	NA[e]	0.8	0.1	0.9
Discharge[d]	NA[e]	0.05	0.005	0.05
Maximum	NA[e]	0.8	0.1	0.9
Upper Watts Bar Lake, Kingston Municipal Water Plant				
Water[c]	0.03	0.2	0.05	0.3
Discharge[d]	0.008	0.01	0.002	0.02
Maximum	0.03	0.2	0.05	0.3
Lower System (Lower Watts Bar Lake and Chickamauga Lake)				
Water[c]	0.03	0.2	0.05	0.3
Discharge[d]	0.007	0.01	0.002	0.02
Maximum	0.03	0.2	0.05	0.3
Lower East Fork Poplar Creek and Poplar Creek				
Water[c]	NA[e]	0.06	0.007	0.07
Discharge[d]	NA[e]	1.2	0.03	1.2
Maximum	NA[e]	1.2	0.03	1.2

[a]1 mrem = 0.01 mSv.
[b]Doses based on measured radionuclide concentrations in fish tissue.
[c]Doses based on measured radionuclide concentrations in water.
[d]Doses based on measured discharges of radionuclides from on-site outfalls.
[e]Not at drinking water supply locations.

F.6.3 Other Uses

Other uses of the ORR area waterways include swimming or wading, boating, and use of the shoreline. A highly exposed "other user" was assumed to swim or wade for 30 h/year, boat for 63 h/year, and use the shoreline for 60 h/year. Measured and calculated concentrations of radionuclides in water and the LADTAP XL methodology were used to estimate potential EDs from these activities.

The ED from swimming in water containing nuclide *i* (except tritium) is given by

$$D_{E,i,swim} = 0.142 * C_{w,i} * U_{swim} * DC_{i,WS},$$

where

$D_{E,i,swim}$ = ED from swimming in water containing nuclide *i* (mrem/year),

0.142 = unit conversion factor (1,000 L/m^3 divided by 8,760 h/year),

U_{swim} = time spent swimming (h/year),

$C_{w,i}$ = concentration of nuclide *i* in water (μCi/L), and

$DC_{i,WS}$ = dose conversion factor for submersion in water containing nuclide *i* (mrem-m^3/year-μCi).

Complete submersion is assumed while swimming. For tritium, the swimming dose equation is

$$D_{E,T,swim} = C_{W,T} * U_{swim} * I_T * DC_{T,ing},$$

where

$D_{E,T,swim}$ = ED from swimming in water containing tritium (mrem/year),

U_{swim} = time spent swimming (h/year),

$C_{W,T}$ = concentration of tritium in water (μCi/L),

I_T = absorption factor for tritium via whole body immersion in water (= 0.035 L/h), and

$DC_{T,ing}$ = dose coefficient for ingestion of tritium (mrem/μCi).

The ED from boating on water containing nuclide *i* (except tritium) is given by

$$D_{E,i,boat} = 0.5 * (0.142 * C_{w,i} * U_{boat} * DC_{i,WS}),$$

where

$D_{E,i,boat}$ = ED from boating on water containing nuclide *i* (mrem/year),

0.5 = correction factor,

0.142 = unit conversion factor (1,000 L/m^3 divided by 8,760 h/year),

U_{boat} = time spent boating (h/year),

$C_{w,i}$ = concentration of nuclide *i* in water (μCi/L), and

$DC_{i,WS}$ = dose coefficient for submersion in water containing nuclide *i* [mrem-m^3/year-μCi].

The 0.5 correction factor arises from the assumption used in LADTAP XL that doses per unit from boating equal one-half the doses from swimming. Any shielding by the boat's hull is ignored. The dose attributable to any tritium, which emits only very weak beta radiation, in the water is assumed to be 0.

The ED from using a shoreline containing nuclide *i* is given by

$$D_{E,i,shore} = C_{i,shore} * U_{shore} * (G_{shore} / 8760) * DC_{i,soil},$$

where

$D_{E,i,shore}$ = ED due to use of shoreline containing nuclide *i* (mrem/year),

$C_{i,shore}$ = annual average concentration of nuclide *i* in shoreline soil (μCi/m^2),

U_{shore} = duration of time spent on the shoreline (h/year),

G_{shore} = unitless shoreline width correction factor (0.2 for rivers),

8760 = number of hours in a year (h/year), and

$DC_{i,soil}$ = dose conversion factor for infinitely thick soil containing nuclide (mrem-m^2/μCi-year).

The annual average concentration of nuclide *i* in shoreline soil is obtained by

$$C_{i,shore} = C_{W,i} * F_{i,W-S} * T_{1/2,i} * (1 - EXP[-\lambda_{r,i} * 365 * t_{S-W}]) ,$$

where

$C_{W,i}$ = annual average concentration of nuclide *i* in water (μCi/L),

$F_{i,W-S}$ = water-to-sediment transfer coefficient nuclide *i* (= 100 L/m^2-day),

$T_{1/2,i}$ = radioactive half-life of nuclide *i* (d),

$\lambda_{r,i}$ = radioactive decay constant for nuclide *i* (1/d),

t_{S-W} = time over which shoreline soil is exposed to water containing nuclide *i* (= 50 years), and

365 = number of days in a year (d/year).

It is assumed that the buildup and decay of nuclides in shoreline soil have occurred at the current year's rates for the past 50 years.

When compared with EDs from drinking water and eating fish from the same waters, the EDs from these other uses are relatively small. Refer to Table F.2 for a summary of potential EDs from identified waterborne radionuclides around the ORR and the variation in dose based on the method used to estimate dose.

F.7 References

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