7. Dose

Activities on Oak Ridge Reservation (ORR) have the potential to release small quantities of radionuclides and hazardous chemicals to the environment. These releases could expose members of the public to low concentrations of radionuclides or chemicals. Monitoring of materials released from the reservation and environmental monitoring and surveillance on and around the reservation provide data used to show that doses from released radionuclides and chemicals are in compliance with the law.

In 2016, a hypothetical maximally exposed individual could have received an effective dose (ED) of about 0.2 mrem from radionuclides emitted to the atmosphere from all ORR sources; this is well below the National Emission Standards for Hazardous Air Pollutants for Radionuclides standard of 10 mrem/year for protection of the public.

A worst-case analysis of exposures to waterborne radionuclides for all pathways combined gives a maximum possible individual ED of about 1 mrem. This dose is based on a person eating 27 kg/year (60 lb/year) of the most contaminated fish accessible, drinking 680 L/year (180 gal/year) of the most contaminated drinking water, and using the shoreline near the most contaminated stretch of water for 60 h/year.

In addition, if a hypothetical person consumed one deer, one turkey, and two geese (containing the maximum ^{137}Cs concentration and maximum weights), that person could have received an ED of about 1 mrem. This calculation is conducted to provide an estimated upper-bound ED from consuming wildlife harvested from the ORR.

Therefore, the annual dose to a maximally exposed individual from all these potential exposure pathways combined was estimated to be about 3 mrem. There are no known significant doses from discharges of radioactive constituents from the ORR other than those reported. U.S. Department of Energy (DOE) Order 458.1, *Radiation Protection of the Public and the Environment* (DOE 2011), limits the ED that an individual may receive from all exposure pathways from all radionuclides released from the ORR during 1 year to no more than 100 mrem. The 2016 maximum ED was about 3% of the limit given in DOE O 458.1.

The potential doses to aquatic and terrestrial biota from contaminated soil and water were evaluated using a graded approach. Results of the screening calculations indicate that contaminants released from ORR site activities do not have an adverse impact on plants or animal populations.

Because of differing permit-reporting requirements and instrument capabilities, various units of measurement are used in this report. The information found in "Units of Measure and Conversion Factors" is intended to help readers convert numeric values presented here as needed for specific calculations and comparisons.

7.1 Radiation Dose

Small quantities of radionuclides were released to the environment from operations at Oak Ridge Reservation (ORR) facilities during 2016. Those releases were described, characterized, and quantified in previous chapters of this report. This chapter presents estimates of potential radiation doses to the public from the releases. The dose estimates were obtained using monitored and estimated release data, environmental monitoring and surveillance data, estimated exposure conditions that tend to maximize

calculated doses, and environmental transport and dosimetry codes that may also tend to overestimate the calculated doses. Thus the presented doses are likely overestimates of the doses received by actual people in the ORR vicinity.

7.1.1 Terminology

Exposures to radiation from nuclides located outside the body are called "external exposures"; exposures to radiation from nuclides deposited inside the body are called "internal exposures." This distinction is important because external exposures occur only when a person is near or in a radionuclide-containing medium, whereas internal exposures continue as long as the radionuclides remain inside a person. Also, external exposures may result in uniform irradiation of the entire body, including all organs, while internal exposures usually result in nonuniform irradiation of the body and organs. When taken into the body, most radionuclides deposit preferentially in specific organs or tissues and thus do not irradiate the body uniformly.

A number of the specialized terms and units used to characterize exposures to ionizing radiation are defined in Appendix E. "Effective dose" (ED) is a risk-based equivalent dose that is used to estimate health effects or risks to exposed persons. It is a weighted sum of dose equivalents to specified organs and is expressed in rem or sieverts (1 rem = 0.01 Sv).

One rem of ED, regardless of radiation type or method of delivery, has the same total radiological (in this case, also biological) risk effect. Because the doses discussed here are very small, EDs are expressed in millirem (mrem), which is one one-thousandth of a rem. (See Appendix E for a comparison and description of various dose levels.)

7.1.2 Methods of Evaluation

7.1.2.1 Airborne Radionuclides

The radiological consequences of radionuclides released to the atmosphere from ORR operations during 2016 were characterized by calculating EDs to maximally exposed on- and off-site members of the public and to the entire population residing within 80 km (50 miles) of the ORR center. The calculations were performed for each major facility and for the entire ORR. The dose calculations were made using the Clean Air Act Assessment Package—1988 (CAP-88 PC) Version 4 (EPA 2015), a software program developed under sponsorship of the US Environmental Protection Agency (EPA) to demonstrate compliance with 40 CFR 61, Subpart H, which governs the emissions of radionuclides other than radon from US Department of Energy (DOE) facilities. CAP-88 PC implements a steady-state Gaussian plume atmospheric dispersion model to calculate concentrations of radionuclides in the air and on the ground and uses food-chain models to calculate radionuclide concentrations in foodstuffs (vegetables, meat, and milk) and subsequent intakes by humans.

In this assessment, adult dose coefficients were used to estimate doses. These coefficients are weighted sums of equivalent doses to 12 specified tissues or organs plus a remainder term that accounts for the rest of the tissues and organs in the body.

A total of 35 emission points on the ORR were modeled during 2016. The total includes 3 (two combined) points at the Y-12 National Security Complex (Y-12), 28 points at Oak Ridge National Laboratory (ORNL), and 4 points at the East Tennessee Technology Park (ETTP). Table 7.1 lists the emission-point parameter values and receptor locations used in the dose calculations.

Meteorological data used in the calculations for 2016 were in the form of joint frequency distributions of wind direction, wind speed class, and atmospheric stability category. (See Table 7.2 for a summary of tower locations used to model the various sources.) During 2016, rainfall, as averaged over the six rain gauges located on the ORR, was 114.4 cm (45 in.). The average air temperature was 15.5°C (59.9°F) at the 10 to 15 m levels, and the average mixing-layer height for ETTP and ORNL was 919 m (3,016 ft) and for Y-12 was 899 m (2,956 ft). The mixing height is the depth of the atmosphere adjacent to the surface within which air is mixed.

Table 7.1. Emission point parameters and receptor locations used in the dose calculations

Source	Stack height (m)	Stack diameter (m)	Effective exit gas velocity (m/s) [a]	Distance (m) and direction to the maximally exposed individual			
				Plant maximum		Oak Ridge Reservation maximum	
Oak Ridge National Laboratory							
X-1000 Lab Hoods	15	0.5	0	4350	SW	4350	SW
X-2000 Lab Hoods	15	0.5	0	4770	SW	4770	SW
X-3000 Lab Hoods	15	0.5	0	5100	SW	5100	SW
X-4000 Lab Hoods	15	0.5	0	5270	SW	5270	SW
X-6000 Lab Hoods	15	0.5	0	5850	SW	5850	SW
X-7000 Lab Hoods	15	0.5	0	5290	WSW	5290	WSW
X-2026	22.9	1.05	7.42	4820	SW	4820	SW
X-2099	3.66	0.18	19.03	4810	SW	4810	SW
X-3018	61	1.75	0.95	5030	SW	5030	SW
X-3020	61	1.22	15.05	4970	SW	4970	SW
X-3039	76.2	2.44	6.39	5060	SW	5060	SW
X-3544	9.53	0.279	24.05	4810	SW	4810	SW
X-3608 Air Stripper	10.97	2.44	0.57	4930	SW	4930	SW
X-3608 Filter Press	8.99	0.36	9.27	4930	SW	4930	SW
X-5505M	11	0.305	2.54	5560	SW	5560	SW
X-5505NS	11	0.96	0	5560	SW	5560	SW
X-7503	30.5	0.91	12.85	5330	SW	5330	SW
X-7830 Group	4.6	0.25	7.67	3920	WSW	3920	WSW
X-7856-CIP	18.29	0.48	11.05	3970	WSW	3970	WSW
X-7877	13.9	0.41	13.56	3890	WSW	3890	WSW
X-7880	27.7	1.52	15.62	3860	WSW	3860	WSW
X-7911	76.2	1.52	14.38	5240	WSW	5240	WSW
X-7935 Building Stack	15.24	0.51	26.85	5250	SW	5250	SW
X-7935 Glove Box	9.14	0.25	0	5250	SW	5250	SW
X-7966	6.10	0.29	9.62	5330	SW	5330	SW
X-8915	104.0	1.22	6.68	8060	SW	8060	SW
X-Decon Areas	15	0.5	0	5310	SW	5310	SW
X-STP	7.6	0.203	7.39	4590	SW	4590	SW

Table 7.1 (continued)

Source ID	Stack height (m)	Stack diameter (m)	Effective exit gas velocity (m/s) [a]	Distance (m) and direction to the maximally exposed individual			
				Plant maximum		Oak Ridge Reservation maximum	
East Tennessee Technology Park							
K-1407-AL CWTS	2.74	0.15	0	460	WSW	5710	SSE
K-2500-H-B	8.23	0.61	12.9	550	SE	6350	SE
K-2500-H-C	8.23	0.61	12.9	550	SE	6340	SE
K-2500-H-D	8.23	0.91	12.9	520	SE	6320	SE
Y-12 National Security Complex							
Y-Monitored	20	0.5	0	2270	NE	13340	SW
Y-Unmonitored Processes	20	0.5	0	2270	NE	13340	SW
Y-Unmonitored Lab Hoods	20	0.5	0	2270	NE	13340	SW

[a] Exit gas temperatures are "ambient air" unless noted otherwise.

Acronyms
CIP = Capacity Increase Project
CWTS = Chromium Water Treatment System
STP = Sewage Treatment Plant

For occupants of residences, the dose calculations assume that the occupant remained at home during the entire year and obtained food according to the rural pattern. This pattern specifies that 70% of the vegetables and produce, 44.2% of the meat, and 39.9% of the milk consumed are produced in the local area (e.g., a home garden). The remaining portion of each food category is assumed to be produced within 80 km (50 miles) of the ORR. The same assumptions are used for occupants of businesses, but the resulting doses are divided by 2 to compensate for the fact that businesses are occupied for less than half a year and less than half of a worker's food intake occurs at work. For collective ED estimates, production of beef, milk, and crops within 80 km (50 miles) of ORR was calculated using the production rates provided with CAP-88 PC Version 4.

Table 7.2. Meteorological towers and heights used to model atmospheric dispersion from source emissions

Tower	Height (m)	Source
		Y-12 National Security Complex
MT6 (West Y-12)	30	All Y-12 sources
	60	X-8915 Spallation Neutron Source (ORNL)
		East Tennessee Technology Park
MT7 (K1209)	10	K-1407-AL CWTS, K-2500-H- A, B, C, and D
		Oak Ridge National Laboratory
MT4 (Tow A)	15	X-7830, x-7935 Glove Box, X 7966,and X-7000 Lab Hoods
	30	X-7503, X-7856-CIP, X-7877, X-7880, X-7911, X-7935 Building
MT3 (Tow B)	15	X-5505, X-6000 Lab Hoods
MT2 (Tow D)	15	X-2099, X-3544, X-3608 FP, X-3608 AS, STP, X-Decon Hoods, X-1000, X-2000, X-3000, and X-4000 Lab Hoods
	35	X-2026
	60	X-3018, X-3020, and X-3039

Acronyms
CIP = Capacity Increase Project
CWTS = Chromium Water Treatment System
ORNL = Oak Ridge National Laboratory
STP = Sewage Treatment Plant

7.1.2.1.1 Results

Calculated EDs from radionuclides emitted to the atmosphere from the ORR are listed in Table 7.3 (maximum individual) and Table 7.4 (collective). The hypothetical maximally exposed individual for the ORR was located about 13,340 m southwest of the main Y-12 release point, about 5,240 m west-southwest of the 7911 stack at ORNL, and about 5,710 m south-southeast of the K-1407-AL Chromium Water Treatment System (CWTS) at ETTP. This individual could have received an ED of about 0.2 mrem, which is well below the National Emission Standards for Hazardous Air Pollutants for Radionuclides standard of 10 mrem and is about 0.7% of the roughly 300 mrem that the average individual receives from natural sources of radiation. Based on the 2010 population census data, the calculated collective ED to the entire population within 80 km (50 miles) of the ORR (about 1,172,530 persons) was about 6.4 person-rem, which is about 0.002% of the 351,759 person-rem that this population received from natural sources of radiation (based on an individual dose of about 300 mrem/year). CAP-88 PC Version 4 was used in 2016 to calculate both individual and collective doses. Due to improved time-in-flight calculations (implementation of full chain decay of isotopes in flight for each sector), collective doses associated with short-lived radionuclides are lower than would have been calculated using CAP-88 PC Version 3 (EPA 2015).

Table 7.3. Calculated radiation doses to maximally exposed off-site individuals from airborne releases, 2016

Plant	Effective dose, mrem (mSv)	
	At plant maximum	At Oak Ridge Reservation maximum
Oak Ridge National Laboratory	0.2 (0.002)[a]	0.2 (0.002)
East Tennessee Technology Park	0.004(0.00004)[b]	9×10^{-6} (9×10^{-8})
Y-12 National Security Complex	0.04 (0.0004)[c]	0.004 (0.00004)
Entire Oak Ridge Reservation	*d*	0.2 (0.002)[e]

[a]The maximally exposed individual was located 5,060 m SW of X-3039 and 5,240 m WSW of X-7911.
[b]The maximally exposed individual was located 460 m WSW of K-1407-AL Chromium Water Treatment System.
[c]The maximally exposed individual was located 2,270 m NE of the Y-12 National Security Complex release point.
[d]Not applicable.
[e]The maximally exposed individual for the entire Oak Ridge Reservation is also the Oak Ridge National Laboratory maximally exposed individual.

Table 7.4. Calculated collective effective doses from airborne releases, 2016

Plant	Collective effective dose[a]	
	Person-rem	Person-Sv
Oak Ridge National Laboratory	5.7	0.057
East Tennessee Technology Park	0.0003	3×10^{-6}
Y-12 National Security Complex	0.7	0.007
Entire Oak Ridge Reservation	6.4	0.064

[a]Collective effective dose to the 1,172,530 persons residing within 80 km (50 miles) of the Oak Ridge Reservation (based on 2010 census data).

The maximally exposed individual for the Y-12 Complex was located at a residence about 2,272 m (1.4 miles) northeast of the main Y-12 release point. This individual could have received an ED of about 0.04 mrem from Y-12 airborne emissions. Inhalation and ingestion of uranium radioisotopes (i.e., ^{233}U, ^{234}U, ^{235}U, ^{236}U, and ^{238}U) accounted for about 97%, and technetium-99 (^{99}Tc) accounted for about 1.6% of the dose (Fig. 7.1). The contribution of Y-12 emissions to the 50-year committed collective ED to the population residing within 80 km (50 miles) of the ORR was calculated to be about 0.7 person-rem, which is about 11% of the collective ED for the ORR.

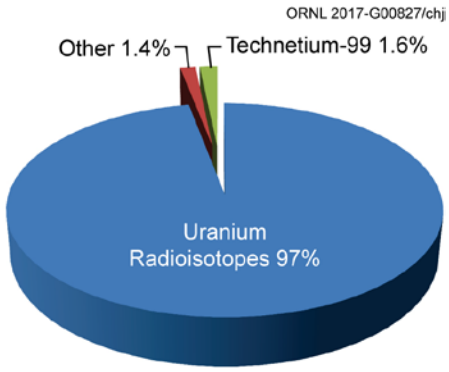

Fig. 7.1. Nuclides contributing to the effective dose at the Y-12 National Security Complex.

The maximally exposed individual for ORNL was located at a residence about 5,060 m (3.4 miles) southwest of the 3039 stack and 5,240 m (3.3 miles) west-southwest of the 7911 stack. This individual could have received an ED of about 0.2 mrem from ORNL airborne emissions. Radionuclides that contributed 10% or more to the dose were ^{11}C (34%), ^{234}U (21%), and ^{212}Pb (18%) (Fig. 7.2). The total contribution from uranium radioisotopes (i.e., ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{236}U, and ^{238}U) accounted for about 25% of the dose, and ^{234}U contributed about 21% of the dose. The contribution of ORNL emissions to the collective ED to the population residing within 80 km (50 miles) of the ORR was calculated to be about 5.7 person-rem or about 90% of the collective ED for the ORR.

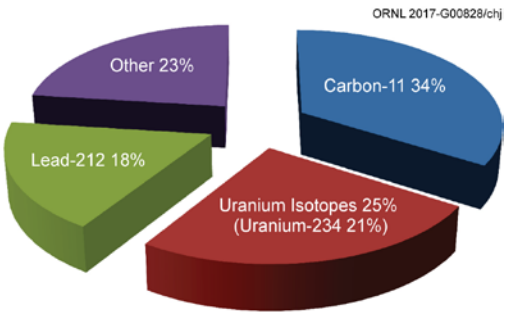

Fig. 7.2. Nuclides contributing to effective dose at Oak Ridge National Laboratory.

The maximally exposed individual for ETTP was located at a business about 460 m (0.3 miles) west southwest of the K-1407-AL CWTS. The ED received by this individual from airborne emissions was calculated to be about 0.0004 mrem. About 90% of the dose is from uranium radioisotopes (^{234}U, ^{235}U, ^{236}U, and ^{238}U), and 7% of the dose is from ^{99}Tc (Fig. 7.3). The contribution of ETTP emissions to the collective ED to the population residing within 80 km (50 miles) of the ORR was calculated to be about 0.0003 person-rem, or about 0.005% of the collective ED for the reservation.

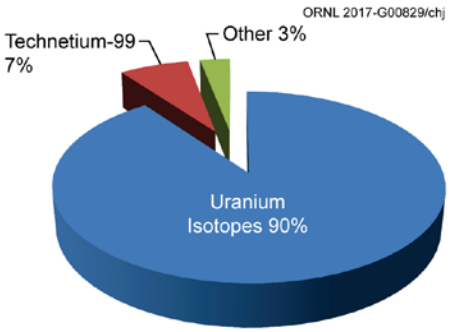

Fig. 7.3. Nuclides contributing to effective dose at East Tennessee Technology Park.

The reasonableness of the estimated doses can be inferred by comparing EDs calculated at the ORR perimeter area monitoring (PAM) stations from measured air concentrations of radionuclides, excluding naturally occurring ^{7}Be and ^{40}K, with air concentrations calculated using CAP-88 PC Version 4 and emissions data (Table 7.5). Based on measured air concentrations, hypothetical individuals assumed to reside at AAM1 and PAM stations 35–49 could have received EDs between 0.007 and 0.04 mrem/year. Based on emissions data using CAP-88 PC Version 4, the above individuals could have received EDs between 0.04 and 0.2 mrem/year. As shown in Table 7.5, EDs calculated using CAP-88 PC Version 4 and emissions data tend to be greater than or equivalent to EDs calculated using measured air concentrations.

Table 7.5. Hypothetical effective doses from living near the Oak Ridge Reservation, Oak Ridge National Laboratory, and the East Tennessee Technology Park ambient air monitoring stations, 2016

Station	Calculated effective doses			
	Using air monitor data		Using CAP-88[a] and emission data	
	mrem/year	mSv/year	mrem/year	mSv/year
1	0.02	0.0002	0.2	0.002
35	0.02	0.0002	0.04	0.0004
37	0.007	0.00007	0.08	0.0008
38	0.009	0.00009	0.02	0.0002
39	0.02	0.0004	0.2	0.002
40	0.01	0.0001	0.2	0.002
42	0.04	0.0002	0.02	0.0002
46	0.02	0.0002	0.1	0.001
48	0.009	0.00009	0.2	0.002
49	0.02	0.0002	0.09	0.0009
52	0.008	0.00008	0.009	0.00009
K2	0.05	0.0005	0.04	0.0004
K6	0.05	0.0005	0.02	0.0002
K11	0.03	0.0003	0.02	0.0002
K12	0.07	0.0007	0.02	0.0002

[a]CAP-88 PC Version 4 software, developed under US Environmental Protection Agency sponsorship to demonstrate compliance with 40 CFR 61, Subpart H.

Station 52, located remotely from the ORR, gives an indication of potential EDs from background sources. Based on measured air concentrations, the ED was estimated to be 0.008 mrem/year (the isotopes ^{7}Be and ^{40}K were not included in the background air monitoring station calculation), whereas the estimated ED based on calculated air concentrations using CAP-88 PC Version 4 was estimated to be 0.009 mrem/year. The measured air concentrations of ^{7}Be were similar at the PAM stations and at the background air monitoring station.

Of particular interest is a comparison of EDs calculated using measured air concentrations of radionuclides at PAM stations located near the maximally exposed individuals for each plant and EDs calculated for those individuals using source emissions data. K11 station is located near the on-site maximally exposed individual for ETTP. The ED calculated with measured air concentrations was 0.03 mrem/year, which is comparable to the ED of 0.02 mrem/year estimated using source emissions data. PAM station 46 is located near the off-site maximally exposed individual for the Y-12 Complex, and the ED calculated with measured air concentrations was 0.02 mrem/year, which is considerably less than the ED of 0.1 mrem/year estimated using source emissions data.

7.1.2.2 Waterborne Radionuclides

Radionuclides discharged to surface waters from the ORR enter the Tennessee River system by way of the Clinch River (see Section 1.3.4 for the surface water setting of the ORR). Discharges from Y-12 enter the Clinch River via Bear Creek and East Fork Poplar Creek (EFPC), 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 (WOC) and enter Melton Hill Lake via some small drainage creeks. Discharges from ETTP enter the Clinch River either directly or via Poplar Creek. This section discusses the potential radiological impacts of these discharges to persons who drink water; eat fish; and swim, boat, and use the shoreline at various locations along the Clinch and Tennessee Rivers.

For assessment purposes, surface waters potentially affected by the ORR are divided into seven segments:

1. Melton Hill Lake above all possible ORR inputs,
2. Melton Hill Lake,
3. Upper Clinch River (from Melton Hill Dam to confluence with Poplar Creek),
4. Lower Clinch River (from confluence with Poplar Creek to confluence with the Tennessee River),
5. Upper Watts Bar Lake (from near the confluence of the Clinch and Tennessee Rivers to below Kingston),
6. the lower system (the remainder of Watts Bar Lake and Chickamauga Lake to Chattanooga), and
7. Poplar Creek (including the confluence of EFPC).

Two methods 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) determined by laboratory analyses of water and fish samples (see Sections 6.4, 6.5, and 6.7). The second method calculates possible radionuclide concentrations in water and fish from measured radionuclide discharges and known or estimated stream flows. In both methods, reported concentrations of radionuclides were used if the reported value was statistically significant. The advantage of the first method is the use of radionuclide concentrations measured in water and fish; disadvantages are the inclusion of naturally occurring radionuclides (e.g., ^{40}K, uranium and its progeny, thorium and its progeny, and unidentified alpha and beta activities), the possible inclusion of radionuclides discharged from sources not part of the ORR, and the possibility that some radionuclides of ORR origin might be present in quantities too low to be measured. The advantages of the second method are (1) that most radionuclides discharged from the ORR will be quantified and (2) that naturally occurring radionuclides may not be considered or may be accounted for separately. The disadvantage is the use of models to estimate the concentrations of the radionuclides in water and fish. Both methods use the same models (Hamby 1991) to estimate radionuclide concentrations in media and at locations other than those that are sampled (e.g., downstream). However, utilizing the two methods to estimate potential doses takes into account both field measurements and discharge measurements.

In 2016, analyses of surface water samples collected for ORR-wide surveillance at Clinch River kilometers (CRKs) 66, 58, 32, 23, and 16 was transitioned from a commercial laboratory to the ORNL Radioactive Materials Analytical Laboratory (RMAL). Following the transition, reported concentrations radionuclides were higher than those typically reported by the commercial laboratory. The major reasons for the increases are thought to be the result of higher radiation background in the RMAL counting laboratory, cross-contamination found in RMAL laboratory equipment, and the contributions of naturally occurring short-lived radionuclides that likely decayed significantly during transport to commercial laboratories. Corrective actions have been identified and implemented to address these issues.

In 2016, surface water samples were also collected at CRKs 23 and 16 for ETTP site-specific monitoring. The results from these samples were used in dose calculations instead of those obtained via the ORR-wide program to reduce bias from the higher laboratory backgrounds and cross-contamination.

7.1.2.2.1 Drinking Water Consumption

Surface Water

Several water treatment plants that draw water from the Clinch and Tennessee River systems could be affected by discharges from ORR. No in-plant radionuclide concentration data are available for these plants; all of the dose estimates given below likely are high because they are based on radionuclide concentrations in water before it enters a processing plant. Based on a nationwide food consumption survey (EPA 2011) and weighted based on the combined population of Anderson, Knox, Loudon, and Roane counties, the drinking water consumption rate for the maximally exposed individual is 680 L/year (180 gal/year), and the drinking water consumption rate for the average person is 330 L/year (87 gal/year). The average drinking water consumption rate is used to estimate the collective ED. At all locations in 2016, estimated maximum EDs to a person drinking water were calculated using both measured radionuclide concentrations in and measured radionuclide discharges to off-site surface water, excluding naturally occurring radionuclides such as ^{40}K.

- **Upper Melton Hill Lake above all possible ORR inputs.** Based on samples from Melton Hill Lake above possible ORR inputs (at CRK 66 near the City of Oak Ridge Water Intake Plant), a maximally exposed individual drinking water at this location could have received an ED of about 0.09 mrem. The collective ED to the 48,042 persons who drink water from the City of Oak Ridge water plant would be 2.0 person-rem.

- **Melton Hill Lake.** The only water treatment plant located on Melton Hill Lake that could be affected by discharges from the ORR is a Knox County plant. This plant is located near surface water sampling location CRK 58. A maximally exposed individual could have received an ED of about 0.09 mrem; the collective dose to the 63,779 persons who drink water from this plant could have been 2.7 person-rem.

- **Upper Clinch River.** The ETTP (Gallaher) water plant, which drew water from the Clinch River near CRK 23 was deactivated; therefore doses from drinking water are no longer calculated. ETTP and the Rarity Ridge community receive drinking water from the City of Oak Ridge water plant, which is located near CRK 66.

- **Lower Clinch River.** There are no known drinking water intakes in this river segment (from the confluence of Poplar Creek with the lower Clinch River to the confluence of the lower Clinch River with the Tennessee River).

- **Upper Watts Bar Lake.** The Kingston and Rockwood municipal water plants draw water from the Tennessee River not very far from its confluence with the Clinch River. A maximally exposed individual could have received an ED of about 0.03 mrem. The collective dose to the 30,355 persons who drink water from these plants could have been about 0.5 person-rem.

- **Lower system.** Several water treatment plants are located on tributaries of Watts Bar Lake and Chickamauga Lake. Persons drinking water from these plants could not have received EDs greater than the 0.03 mrem calculated for drinking water from the Kingston or Rockwood municipal water plants. The collective dose to the 311,223 persons who drink water within the lower system could have been about 3.4 person-rem.

- **Poplar Creek/Lower EFPC.** No drinking water intakes are located on Poplar Creek or lower EFPC.

Groundwater

A series of off-site monitoring wells were installed across the Clinch River from ORNL west of the Melton Valley waste management areas in 2010. Sampling of the off-site wells occurred semiannually through FY 2016, and results were compared to EPA MCLs. The analyses show that beta trends have remained stable over the past 5 years. For detailed information on results see 2016 Remediation Effectiveness Report for the U.S. Department of Energy (DOE 2016). Currently, no water is consumed from these off-site groundwater wells.

7.1.2.2.2 Fish Consumption

Fishing is quite common on the Clinch and Tennessee River systems. Based on a nationwide food consumption survey (EPA 2011) and weighted based on the combined population of Anderson, Knox, Loudon, and Roane counties, it was assumed that avid fish consumers would have eaten 27 kg (60 lb) of fish during 2016. For the average person used for collective dose calculations, it was assumed that 11 kg (24 lb) of fish was consumed in 2016. The estimated maximum ED will be based on either the first method, measured radionuclide concentrations in fish, or by the second method, which calculates possible radionuclide concentrations in fish from measured radionuclide discharges and known or estimated stream flows. The EDs estimated by both methods, in each of the surface water segments, are provided in Appendix E. The number of individuals who could have eaten fish is based on lake creel surveys conducted annually by the Tennessee Wildlife Resources Agency (TWRA 2016).

- **Upper Melton Hill Lake above All Possible ORR Inputs.** For reference purposes, a hypothetical avid fish consumer who ate fish caught at CRK 66, which is above all possible ORR inputs, could have received an ED of about 0.04 mrem. This dose was estimated from a composite fish sample collected near CRK 70, and a major contributor to dose was ^{90}Sr. The collective ED to the 25 persons who could have eaten such fish was about 4×10^{-4} person-rem.

- **Melton Hill Lake.** An avid fish consumer who ate fish from Melton Hill Lake could have received an ED of about 1.3 mrem. The collective ED to the 222 persons who could have eaten such fish could be about 0.1 person-rem.

- **Upper Clinch River.** An avid fish consumer who ate fish from the upper Clinch River could have received an ED of about 1.3 mrem. The collective ED to the 365 persons who could have eaten such fish could have been about 0.2 person-rem.

- **Lower Clinch River.** An avid fish consumer who ate fish from the lower Clinch River (CRK 16) could have received an ED of about 1.3 mrem. The collective ED to the 853 persons who could have eaten such fish could have been about 0.4 person-rem.

- **Upper Watts Bar Lake.** An avid fish consumer who ate fish from upper Watts Bar Lake could have received an ED of about 0.2 mrem. The collective ED to the 2,436 persons who could have eaten such fish could be about 0.2 person-rem.

- **Lower System.** An avid fish consumer who ate fish from the lower system could have received an ED of about 0.2 mrem. The collective ED to the about 18,873 persons who could have eaten such fish could have been about 1.5 person-rem.

- **Poplar Creek/Lower East Fork Poplar Creek.** An avid fish consumer who ate fish from Poplar Creek could have received an ED of about 0.2 mrem. Assuming that 100 people could have eaten fish from lower EFPC and from Poplar Creek, the collective ED could have been about 0.01 person-rem.

7.1.2.2.3 Other Uses

Other uses of 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. The average individual, who is used for collective dose estimates, was assumed to swim or wade for 10 h/year, boat for 21 h/year, and use the shoreline for 20 h/year. The potential EDs from these activities were estimated from measured and calculated concentrations of radionuclides in water; the equations that were used were derived from the LADTAP XL code (Hamby 1991) and were modified to account for radioactive data and shoreline use. At all locations in 2016, the estimated maximally exposed individual EDs were based on measured off-site surface water radionuclide concentrations and excluded naturally occurring radionuclides such as ^{7}Be and ^{40}K.

The number of individuals who could have been other users is different for each section of water because the data sources differ. For Watts Bar parts (upper Clinch River through lower Watts Bar), the assumption for other users is five times the number of people who harvest fish. For Chickamauga and Melton Hill, the number for other users is based on surveys conducted by the Tennessee Valley Authority.

- **Upper Melton Hill Lake above all possible ORR inputs.** A hypothetical maximally exposed other user of upper Melton Hill Lake above possible ORR inputs (CRK 66) could have received an ED of about 7×10^{-7} mrem. The collective ED to the 19,643 other users could have been 2×10^{-6} person-rem.

- **Melton Hill Lake.** An individual other user of Melton Hill Lake could have received an ED of about 0.01 mrem. The collective ED to the 52,085 other users could have been about 0.06 person-rem.

- **Upper Clinch River.** An individual other user of the upper Clinch River could have received an ED of about 0.007 mrem. The collective ED to the 9,322 other users could have been about 0.01 person-rem.

- **Lower Clinch River.** An individual other user of the lower Clinch River could have received an ED of about 0.007 mrem. The collective ED to the 10,875 other users could have been about 0.02 person-rem.

- **Upper Watts Bar Lake.** An individual other user of upper Watts Bar Lake could have received an ED of about 0.002 mrem. The collective ED to the 31,072 other users could have been about 0.02 person-rem.

- **Lower system.** An individual other user of the lower system could have received an ED of about 0.002 mrem. The collective ED to the 693,978 other users could have been about 0.1 person-rem.

- **Poplar Creek/Lower EFPC.** An individual other user of Lower EFPC, above its confluence with Poplar Creek, could have received an ED of about 1×10^{-5} mrem. The collective ED to the 200 other users of Poplar Creek and Lower EFPC could have been about 4×10^{-8} person-rem.

7.1.2.2.4 Irrigation

Although there are no known locations that use water from water bodies around the ORR to irrigate food or feed crops, it was decided to determine whether irrigation could contribute to radiation doses to one or

more members of the public. To make this determination, the method described by the Nuclear Regulatory Commission (NRC 1977) was used. Cross-contamination in analytical equipment used to quantify radionuclides in ORR-wide surface water samples from CRKs 66, 58, 32,23, and 16 led to biased results for several 2016 sampling events. However, sampling was also performed at CRK 23 and CRK 16 for ETTP site-specific monitoring. To reduce bias in dose calculations, the results from the ETTP program sampling at CRKs 23 and 16 were used instead of those obtained via the ORR program. Based on measured and calculated concentrations of radionuclides at CRK 16, which is a location on the lower Clinch River and downstream of the ORR, the maximum potential dose (excluding the naturally occurring radionuclides ^{7}Be and ^{40}K) to an individual due to irrigation ranged from 7×10^{-10} to 0.05 mrem in 2016. The individual was assumed to consume 24 kg of leafy vegetables, 90 kg of produce, 321 L of milk and 671 kg of meat (beef) during the year.

7.1.2.2.5 Summary

Table 7.6 is a summary of potential EDs from identified waterborne radionuclides around the ORR. Adding worst-case EDs for all pathways in a water-body segment gives a maximum individual ED of about 1 mrem to a person obtaining his or her full annual complement of fish from and participating in other water uses on Melton Hill Reservoir/Clinch River. The maximum collective ED to the 80 km (50 mile) population could be as high as 11 person-rem. These are small percentages of individual and collective doses attributable to natural background radiation, about 0.4% of the average individual background dose of roughly 300 mrem/year and 0.003% of the 351,759 person-rem that this population received from natural sources of radiation.

Table 7.6. Summary of annual maximum individual (mrem) and collective (person-rem) effective doses (EDs) from waterborne radionuclides, 2016[a,b]

	Drinking water	Eating fish	Other uses	Total[c]
Upstream of all Oak Ridge Reservation discharge locations (CRK 66, City of Oak Ridge Water Plant)				
Individual ED	0.09	0.04	7×10^{-7}	0.1
Collective ED	2.0	4×10^{-4}	2×10^{-6}	2.0
Melton Hill Lake (CRK 58, Knox County Water Plant)				
Individual ED	0.09	1.3	0.01	1.4
Collective ED	2.7	0.1	0.06	2.8
Upper Clinch River (CRK 23,32)				
Individual ED	NA[d]	1.3	0.007	1.3
Collective ED	NA[d]	0.2	0.01	0.2
Lower Clinch River (CRK 16)				
Individual ED	NA[d]	1.3	0.007	1.3
Collective ED	NA[d]	0.4	0.02	0.5
Upper Watts Bar Lake, Kingston Municipal Water Plant				
Individual ED	0.03	0.2	0.002	0.3
Collective ED	0.5	0.2	0.02	0.7
Lower system (Lower Watts Bar Lake and Chickamauga Lake)				
Individual ED	0.03	0.2	0.002	0.2
Collective ED	3.4	1.5	0.1	5

Table 7.6 (continued)

	Drinking water	Eating fish	Other uses	Total[c]
Lower East Fork Poplar Creek and Poplar Creek				
Individual ED	NA[d]	0.2	1×10^{-5}	0.2
Collective ED	NA[d]	0.01	4×10^{-8}	0.01

[a]1 mrem = 0.01 mSv.
[b]Doses based on measured radionuclide concentrations in water or estimated from measured discharges and known or estimated stream flows.
[c]Total doses and apparent sums over individual pathway doses may differ because of rounding.
[d]Not at or near drinking water supply locations.

Acronyms
CRK = Clinch River kilometer.

7.1.2.3 Radionuclides in Other Environmental Media

The CAP-88 PC computer codes are used to calculate radiation doses from ingestion of meat, milk, and vegetables that contain radionuclides released to the atmosphere. These doses are included in the dose calculations for airborne radionuclides. However, some environmental media, including milk and vegetables, are sampled as part of the surveillance program. The following dose estimates are based on environmental sampling results and may include contributions from radionuclides occurring in the natural environment, released from the ORR, or both.

7.1.2.4 Food

7.1.2.4.1 Milk

During 2016, milk samples were collected from a nearby dairy (in Claxton, Tennessee) and from a reference location in Maryville. Based on a nationwide food consumption survey (EPA 2011), a hypothetical person (weighted based on the combined population of Anderson, Knox, Loudon, and Roane counties) who drank milk was assumed to have consumed a maximum of about 321 L (85 gal) of milk annually. Statistically significant concentrations of ^{40}K were detected in all samples from the nearby dairy and reference location. Annual EDs attributable to ^{40}K found in dairy and composite samples were estimated to be about 13 mrem. The naturally occurring radionuclide ^{40}K was excluded. The doses associated with tritium and strontium were estimated to be 0.04 mrem for the Claxton dairy and 0 mrem for the reference location.

7.1.2.4.2 Vegetables

The food-crop sampling program is described in Chapter 6. Samples of tomatoes and lettuce were obtained from six gardens, five local and one distant. In 2016, turnip samples were not available from these gardens. These vegetables represent fruit-bearing and leafy vegetables. All radionuclides detected in the food crops can be found in the natural environment, and all but ^{7}Be and ^{40}K also may also have originated from activities or facilities on the ORR. Dose estimates are based on hypothetical consumption rates of vegetables that contain statistically significant amounts of detected radionuclides that could have come from the ORR. Based on a nationwide food consumption survey (EPA 2011), a hypothetical home gardener (weighted based on the combined population of Anderson, Knox, Loudon, and Roane counties) was assumed to have eaten a maximum of about 72 kg (158 lb) of homegrown tomatoes and 24 kg (53 lb) of homegrown lettuce. The hypothetical gardener could have received a 50-year committed ED of between 0.05 and 0.07 mrem, depending on garden location. Of this total, between 0.03 and 0.05 mrem could have come from eating tomatoes and between 0.01 and 0.02 mrem from eating lettuce. The highest

dose to a gardener could have been about 0.07 mrem from consuming both types of homegrown vegetables. A person eating food from the distant (background) garden could have received a committed ED of 0.1 mrem from consumption of both vegetables.

An example of a naturally occurring and fertilizer-introduced radionuclide is ^{40}K, which is specifically identified in the samples and accounts for most of the beta activity found in them. The presence of ^{40}K in the samples adds, on average, about 8 mrem to the hypothetical home gardener's ED. In 2016, the gardeners were asked about water sources and fertilizers used, and it was reported for tomatoes, none irrigated or used fertilizers. For lettuce, most did not irrigate and did not use fertilizers. One lettuce gardener irrigated with river water and also fertilized; another used mushroom dirt. It is believed ^{40}K and most of the excess unidentified alpha activities are due to naturally occurring radionuclides, not radionuclides discharged from the ORR.

7.1.2.4.3 Hay

Another environmental pathway that was evaluated was eating beef and drinking milk obtained from hypothetical cows that ate hay harvested from one location on the ORR. Statistically significant concentrations of ^{7}Be, ^{40}K, and ^{238}U were detected at that sampling location. Excluding the doses from ^{7}Be and ^{40}K (both naturally occurring), the average ED from drinking milk and eating beef was estimated to be 0.0009 mrem.

7.1.2.4.4 White-Tailed Deer

TWRA conducted three 2-day deer hunts during 2016 on the Oak Ridge Wildlife Management Area, which is part of the ORR (see Chapter 6). During the hunts, 361 deer were harvested and were brought to the TWRA checking station. At the station, a bone sample and a muscle tissue sample were taken from each deer. The samples were field-counted for radioactivity to ensure that the deer met wildlife release criteria [less than net counts not greater than 1½ times background (~20 pCi/g $^{89/90}Sr$) of beta activity in bone or 5 pCi/g of ^{137}Cs in edible tissue]. Two deer exceeded the limit for beta-particle activity in bone and were retained. The remaining 359 deer were released to the hunters.

The average ^{137}Cs concentration in muscle tissue of the 359 released deer, as determined by field counting, was 0.4 pCi/g; the maximum ^{137}Cs concentration in released deer was 0.7 pCi/g. Most of the ^{137}Cs concentrations were less than minimum detectable levels. The average weight of released deer was approximately 40 kg (88 lb); the maximum weight was 81 kg (179 lb). The EDs attributed to field-measured ^{137}Cs concentrations and actual field weights of the released deer ranged from about 0.005 to 1.1 mrem, with an average of about 0.4 mrem.

Potential doses attributed to deer that might have moved off the ORR and been harvested elsewhere were also evaluated. In this scenario, an individual who consumed one hypothetical average-weight 40 kg (88 lb) deer (assuming 55% field weight is edible meat) containing the 2016 average field-measured concentration of ^{137}Cs (0.4 pCi/g) could have received an ED of about 0.5 mrem. The maximum field-measured ^{137}Cs concentration was 0.7 pCi/g, and the maximum deer weight was 81 kg (179 lb). A hunter who consumed a hypothetical deer of maximum weight and ^{137}Cs content could have received an ED of about 1 mrem.

Muscle tissue samples collected in 2016 from 10 deer (8 released and 2 retained) were subjected to laboratory analyses. Requested radioisotopic analyses included ^{137}Cs, ^{90}Sr, and ^{40}K radionuclides. Comparison of the released-deer field results to analytical ^{137}Cs concentrations found that the field concentrations were either equal to or greater than the analytical results and that all were less than the administrative limit of 5 pCi/g. In one case, the field concentration may have been slightly lower than the

analytical concentration; however, the analytical value was less than the minimum detectable activity. Using analytically measured ^{137}Cs and ^{90}Sr (excluding ^{40}K, a naturally occurring radionuclide) and actual deer weights, the estimated doses for the eight released deer ranged from 0 to 0.4 mrem. The highest estimated dose for a human consuming the retained deer would have been 0.5 mrem.

The maximum ED to an individual consuming venison from two or three deer was also evaluated. Twenty-eight hunters harvested either two or three deer from the ORR. Based on ^{137}Cs concentrations determined by field counting and actual field weight, the ED range to a hunter who consumed two or more harvested deer was estimated to be between 0.2 and 1.2 mrem.

The collective ED from eating all the harvested venison from the ORR with a 2016 average field-derived ^{137}Cs concentration of 0.4 pCi/g and an average weight of 40 kg (88 lb) is estimated to be about 0.2 person-rem. The collective dose is based on number of hunters that harvested deer. It is possible that additional individuals may also consume the harvested venison; however, the collective dose would remain the same.

7.1.2.4.5 Canada Geese

Fifty geese (20 adults and 30 goslings) were captured during the 2016 goose roundup. Twenty-seven geese (20 adults, 7 goslings) were subjected to live whole-body gamma scans. The geese were field-counted for radioactivity to ensure that they met wildlife release criteria (< 5 pCi/g of ^{137}Cs in tissue). The average ^{137}Cs concentration was 0.24 pCi/g, with a maximum ^{137}Cs concentration in the released geese of 0.7 pCi/g. All of the ^{137}Cs concentrations were below minimum detectable activity levels. The average weight of the geese screened during the roundup was about 3.5 kg (7.7 lb), and the maximum weight was about 5.1 kg (11.3 lb).

The EDs attributed to field-measured ^{137}Cs concentrations and actual field weights of the geese ranged from 0.007 to 0.02 mrem. However, for bounding purposes, if a person consumed a released goose with an average weight of 3.5 kg (7.7 lb) and an average ^{137}Cs concentration of 0.24 pCi/g, the estimated ED would be approximately 0.02 mrem. It is assumed that about half the weight of a Canada goose is edible. The estimated ED to an individual who consumed a hypothetical goose with the maximum ^{137}Cs concentration of 0.7 pCi/g and maximum weight of 5.1 kg (11.3 lb) is about 0.08 mrem.

It is possible that a person could eat more than one goose that spent time on the ORR. The average seasonal goose bag per active hunter from Tennessee in the Mississippi Flyway has ranged from 1.9 to 3.0 geese per hunting season between 1999 and 2010 (TWRA 2010). If one person consumed two hypothetical geese of maximum weight with the highest measured concentration of ^{137}Cs, that person could have received an ED of about 0.2 mrem.

Between 2000 and 2009, 22 samples of goose tissue were analyzed. An evaluation of potential doses was made based on laboratory-determined concentrations of the following radionuclides: ^{40}K, ^{137}Cs, ^{90}Sr, thorium (^{228}Th, ^{230}Th, ^{232}Th), uranium ($^{233/234}$U, ^{235}U, ^{238}U), and transuranic elements (^{241}Am, $^{243/244}$Cm, ^{238}Pu, $^{239/240}$Pu). The total dose, less the contribution of ^{40}K, ranged from 0.01 to 0.5 mrem, with an average of 0.2 mrem (EP&WSD 2010).

7.1.2.4.6 Eastern Wild Turkey

Participating hunters are allowed to harvest one turkey from the reservation in a given season unless a harvested turkey is retained, in which case, the hunter is allowed to hunt for another turkey. Two wild turkey hunts took place on the reservation in 2016: April 9–10 and April 16–17. Twenty-seven male turkeys were harvested during that time frame; no harvested turkeys were retained. In addition, two

turkeys were harvested October 29 during the deer hunts, and neither was retained. The average ^{137}Cs concentration measured in the released turkeys was 0.1 pCi/g, and the maximum ^{137}Cs concentration was 0.2 pCi/g. All of the ^{137}Cs concentrations were below minimum detectable activity levels. The average weight of the released turkeys was about 8.1 kg (17.8 lb). The maximum turkey weight was about 10.7 kg (23.6 lb).

The EDs attributed to the field-measured ^{137}Cs concentrations and the actual field weights of the released turkeys ranged from about 0.02 to 0.03 mrem with an average dose of 0.02 mrem. Potential doses were also evaluated for turkeys that might have moved off the ORR and were then harvested elsewhere. In that scenario, if a person consumed a wild turkey with an average weight of 8.1 kg (17.8 lb) and an average ^{137}Cs concentration of 0.1 pCi/g, the estimated ED would be about 0.02 mrem. The maximum estimated ED to an individual who consumed a hypothetical released turkey with the maximum ^{137}Cs concentration of 0.2 pCi/g and the maximum weight of 10.7 kg (23.6 lb) was about 0.05 mrem. It is assumed that approximately half the weight of a wild turkey is edible. No tissue samples were analyzed in 2016.

The collective ED from consuming all the harvested wild turkey meat (29 birds) with an average field-derived ^{137}Cs concentration of 0.1 pCi/g and an average weight of 8.2 kg (18.1 lb) is estimated to be about 0.0006 person-rem. The collective dose is based on number of hunters that harvested turkey. It is possible that additional individuals may also consume the harvested turkey meat; however, the collective dose would remain the same.

Earlier evaluations of doses based on laboratory-determined concentrations of radionuclides included ^{40}K, ^{137}Cs, ^{90}Sr, ^{230}Th, ^{3}H, ^{234}U, ^{235}U, ^{238}U, and transuranic elements (^{241}Am, ^{244}Cm, ^{237}Np, ^{239}Pu). The total dose, less the contribution of ^{40}K, ranged from 0.06 to 0.2 mrem (EP&WSD 2010).

7.1.2.5 Direct Radiation

The principal sources of natural external exposure are the penetrating gamma radiations emitted by ^{40}K and the series originating from ^{238}U and ^{232}Th (NCRP 2009). Due to radiological activities on the ORR, external radiation exposure rates are measured at perimeter and on-site ambient air monitoring stations. External gamma exposure rates were continuously recorded by dual-range Geiger-Müller tube detectors colocated with ORR ambient air stations. In 2016, exposure rates averaged about 10.7 μR/h and ranged from 9.0 to 16 μR/h. These exposure rates correspond to an annual average dose of about 65 mrem with a range of 55 to 98 mrem. At the remote PAM station, the exposure rate averaged about 9.7 μR/h and ranged from 8 to 11 μR/h. The resulting average annual dose was about 59 mrem with a range of 49 to 70 mrem. The annual dose based on measured exposure rates at or near the ORR boundaries were typically within the range of the doses measured at the remote location; slightly higher exposure rates were observed at PAM station 39.

7.1.3 Current-Year Summary

A summary of the maximum EDs to individuals by pathway of exposure is given in Table 7.7. In the unlikely event that any person was irradiated by all of those sources and pathways for the duration of 2016, that person could have received a total ED of about 2 mrem. Of that total, 0.2 mrem would have come from airborne emissions and approximately 0.3 mrem from waterborne emissions (0.09 mrem from drinking water, 1 mrem from consuming fish, 0.01 mrem from other water uses along the Clinch River, and 0.05 mrem from irrigation at CRK16) and about 1 mrem from consumption of wildlife. Current direct radiation measurements at PAM stations are at or near background levels. There are no known significant doses from discharges of radioactive constituents from the ORR other than those reported.

Table 7.7. Summary of maximum estimated effective doses to an adult by exposure pathway

Pathway	Dose to maximally exposed individual		Percentage of DOE mrem/year limit (%)	Estimated collective dose		Population within 80 km	Estimated background radiation collective dose (person-rem)[a]
	mrem	mSv		person-rem	person-Sv		
Airborne effluents							
All pathways	0.2	0.002	0.2	6.4	0.064	1,172,530[b]	
Liquid effluents							
Drinking water	0.09	0.0009	0.09	8.5	0.085	453,399[c]	
Eating fish	1	0.01	1	2.4	0.024	22,974[d]	
Other activities	0.01	0.0001	0.001	0.2	0.002	816,975[d]	
Irrigation	0.05	0.005	0.05				
Other Pathways							
Eating deer	1[e]	0.01	1	0.2	0.002	359	
Eating geese	0.2[f]	0.0008	0.08	*g*	*g*		
Eating turkey	0.05[h]	0.0005	0.05	0.0006	0.000006	29	
Direct radiation	NA[i]	NA					
All pathways	**3**	**0.003**	**3**	**18**	**0.18**	**1,172,530**	**363,484**

[a]Estimated background collective dose is based on the roughly 300 mrem/year individual dose and the population within 80 km (50 miles) of the Oak Ridge Reservation.
[b]Population based on 2010 census data.
[c]Population estimates based on community and non-community drinking water supply data from the Tennessee Department of Environment and Conservation, Division of Water.
[d]Population estimates based on population within 80 km (50 miles) and fraction of fish harvested from Melton Hill, Watts Bar, and Chickamauga reservoirs. Melton Hill and Chickamauga recreational use information was obtained from the Tennessee Valley Authority (Stephens et al. 2006 and Stephens et al. 2007). These populations should not be added together since a member of the each population associated with one activity may also be included in the population of other activities (e.g, fishing and boating).
[e]From consuming one hypothetical worst-case deer, a combination of the heaviest deer harvested and the highest measured concentrations of ^{137}Cs in released deer on the ORR; collective dose based on number of hunters that harvested deer.
[f]From consuming two hypothetical worst-case geese, each a combination of the heaviest goose harvested and the highest measured concentrations of ^{137}Cs in released geese.
[g]Collective doses were not estimated for the consumption of geese since no geese were harvested for consumption during the goose roundup.
[h]From consuming one hypothetical worst-case turkey, a combination of the heaviest turkey harvested and the highest measured concentrations of ^{137}Cs in released turkey. The collective dose is based on the number of hunters who harvested turkey.
[i]Current exposure rate measurements at PAM stations are at or near background levels.

The dose of 3 mrem is about 1% of the annual dose (roughly 300 mrem) from background radiation. The ED of 3 mrem includes the person who received the highest EDs from eating wildlife harvested on the ORR. If the maximally exposed individual did not consume wildlife harvested from the ORR, the estimated dose would be about 2 mrem. DOE O 458.1 limits the ED that an individual may receive from all exposure pathways from all radionuclides released from the ORR during 1 year to no more than 100 mrem. The 2016 maximum ED should not have exceeded about 3 mrem, or about 3% of the limit given in DOE O 458.1. (For further information, see Appendix E, which summarize dose levels associated with a wide range of activities.)

The total collective ED to the population living within an 80 km (50 mile) radius of the ORR was estimated to be about 18 person-rem. This dose is about 0.005% of the 363,484 person-rem that this population received from natural sources during 2016.

7.1.4 Five-Year Trends

EDs associated with selected exposure pathways for the years 2012 to 2016 are given in Table 7.8. In 2016, the air pathway dose decreased somewhat due to taking into account terrain height for SNS, since it is located on a ridge above most of the ORR. The 2016 dose from fish consumption is comparable to the doses estimated in 2013 and 2014. The primary contributor to dose from fish consumption was ^{137}Cs associated with samples collected at CRK 58, which is upstream from most ORR discharges. In 2016, there some issues associated with cross-contamination in analytical equipment used to quantify radionuclides in ORR-wide surface water samples from CRK 66, 58, 32, 23, and 16 led to biased results for several 2016 sampling events. In 2013, an increase in the dose from fish consumption was observed; this increase in dose was primarily due to a composite fish sample collected near CRK 32, in which ^{137}Cs was the primary dose contributor. The increase in the 2014 fish consumption was due to a composite fish sample collected at CRK 16, in which ^{90}Sr was a primary dose contributor. There was a decrease in drinking water dose in 2014, but the doses in 2016 are comparable to earlier estimated doses. Recent direct radiation measurements along the Clinch River indicate doses near background levels. Doses from consumption of wildlife have been similar for the last 5 years with a slight increase in dose due to consumption of geese in 2016 and slight decrease in dose from consumption of venison in 2015 and 2016.

Table 7.8. Trends in effective dose (mrem)[a]

Pathway	2012	2013	2014	2015	2016
Air pathway (all routes)	0.3	0.4	0.6	0.4	0.2
Surface water pathway					
Fish consumption (Clinch River)	0.08	1.5	1.2	0.03	1.3
Drinking water (Kingston)	0.02	0.01	0.003	0.02	0.03
Wildlife consumption					
Deer	2	2	2	1	1
Geese	0.1	0.1	0.1	0.08	0.2
Turkey	0.06	0.08	0.04	0.05	0.05

[a] 1 mrem = 0.01 mSv.

7.1.5 Potential Contributions from Non-DOE Sources

DOE O 458.1 (DOE 2011) requires that if the DOE-related annual dose is greater than 25 mrem, the dose to members of the public must include major non-DOE sources of exposure as well as doses from DOE-related sources. In 2016, the DOE-related source doses were considerably below the 25 mrem criterion. However, DOE requested information from non-DOE facilities pertaining to potential radiation doses to members of the public. There are several non-DOE facilities on or near the ORR that could contribute radiation doses to the public. Eight facilities responded to the DOE request. Three facilities used COMPLY, a computerized screening tool for evaluating radiation exposure from atmospheric releases of radionuclides (EPA 2016). One facility reported annual doses from airborne emissions of 2.96×10^{-6} mrem at 30 m, one facility reported an annual dose of 0.26 mrem at fence line, and the other facility reported an annual dose < 10 mrem (COMPLY, level 1). Three non-DOE facilities reported liquid discharges that met license criteria. Doses from direct radiation ranged from none to an annual dose of

25 mrem, based on measurements at the facility and immediate surroundings. Therefore, annual doses from air and water emissions and external radiation from both non-DOE and DOE sources should be less than the DOE O 458.1 annual public dose limit of 100 mrem.

7.1.6 Doses to Aquatic and Terrestrial Biota

7.1.6.1 Aquatic Biota

DOE O 458.1 (DOE 2011) sets an absorbed dose rate limit of 1 rad/day to native aquatic organisms from exposure to radioactive material in liquid wastes discharged to natural waterways (see Appendix E for definitions of absorbed dose and rad). To demonstrate compliance with this limit, the aquatic organism assessment was conducted using the RESRAD-Biota code (1.8), a companion tool for implementing the DOE technical standard *A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota* (DOE 2002). The code serves as DOE's biota dose evaluation tool and uses the screening [i.e., biota concentration guides (BCGs)] and analysis methods in the technical standard. The BCG is the limiting concentration of a radionuclide in sediment or water that would not cause dose limits for protection of aquatic biota populations to be exceeded.

The intent of the graded approach is to protect populations of aquatic organisms from the effects of exposure to anthropogenic ionizing radiation. Certain organisms are more sensitive to ionizing radiation than others. Therefore, it is generally assumed that protecting the more-sensitive organisms will adequately protect other, less-sensitive organisms. Depending on the radionuclide, either aquatic organisms (e.g., crustaceans) or riparian organisms (e.g., raccoons) may be considered to be the more sensitive and are typically the limiting organisms for the general screening phase of the graded approach for aquatic organisms.

At ORNL, doses to aquatic organisms are based on surface water concentrations and sediment concentrations [Melton Branch, WOC, and White Oak Dam (WOD)] at the following instream sampling locations.

- Melton Branch [Melton Branch (X13)]
- WOC [WOC headwaters, WOC (X14), and WOD (X15)]
- First Creek
- Fifth Creek
- Northwest Tributary
- Clinch River CRKs 16 and 23

All locations, except WOD (X15) and CRK 23, passed the general screening phase (comparison of maximum radionuclide water concentrations to default BCGs). White Oak Dam (X15) and CRK 23 passed when average radionuclide water concentrations were compared to default BCGs. This resulted in absorbed dose rates to aquatic organisms below the DOE aquatic dose limit of 1 rad/day at all of the ORNL sampling locations.

At Y-12, doses to aquatic organisms were estimated from surface water concentrations and sediment concentrations (at Station 9422-1 and S24) at the following instream sampling locations.

- Surface Water Hydrological Information Support System Station 9422-1 (also known as station 17)
- Bear Creek at Bear Creek kilometer 9.2 (BCK 9.2)
- Discharge Point S24, Bear Creek at BCK 9.4

- Discharge Point S17 (unnamed tributary to the Clinch River)
- Discharge Point S19 (Rogers Quarry)

All locations passed the general screening phase (maximum water concentrations and default parameters for BCGs). This resulted in absorbed dose rates to aquatic organisms below the DOE aquatic dose limit of 1 rad/day at all of the Y-12 locations.

At ETTP, doses to aquatic organisms were estimated from surface water concentrations at the following instream sampling locations.

- Mitchell Branch at K1700; Mitchell Branch kilometers 0.45, 0.59, 0.71, and 1.4 (upstream location)
- Poplar Creek at K-716 (downstream)
- K1007-B and K-1710 (upstream location)
- K-702A and K901-A (downstream of ETTP operations)
- Clinch River (CRK 16 and CRK 23)

All of these locations passed the initial general screening (using maximum concentrations and default parameters for BCGs). This resulted in absorbed dose rates to aquatic organisms that were below the DOE aquatic dose limit of 1 rad/day at all of the ETTP sampling locations.

7.1.6.2 Terrestrial Biota

A terrestrial organism assessment was conducted to evaluate impacts on biota in accordance with requirements in DOE O 458.1 (DOE 2011). An absorbed dose rate of 0.1 rad/day is recommended as the limit for terrestrial animal exposure to radioactive material in soils. As for aquatic and riparian biota, certain terrestrial organisms are more sensitive to ionizing radiation than others, and it is generally assumed that protecting the more-sensitive organisms will adequately protect other, less-sensitive organisms. Initial soil sampling for terrestrial dose assessment was initiated in 2007 and was reassessed in 2014. This biota sampling strategy was developed by taking into account guidance provided in *A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota* (DOE 2002) and existing radiological information on the concentrations and distribution of radiological contaminants on the ORR. As in 2007, the soil sampling focused on unremediated areas, such as floodplains and some upland areas. Floodplains are often downstream of contaminant source areas and are dynamic systems where soils are eroding in some places and being deposited in others. Soil sampling locations are identified as follows.

- WOC floodplain and upland location
- Bear Creek Valley floodplain
- Mitchell Branch floodplain
- Two background locations: Gum Hollow and near Bearden Creek

The soil samples were collected in similar locations as in 2007. With the exception of samples collected on the WOC floodplain (collected on the WOC floodplain upstream from WOD), samples taken at all other soil sampling locations passed either the initial-level screening (comparison of maximum radionuclide soil concentrations to default BCGs) or second-level screening, for which BCG default parameters and average soil concentrations were used. Cesium-137 is the primary dose contributor in the soil samples collected on the WOC floodplain.

Biota sampling in the WOC floodplain was conducted in 2009. White-footed mice (*Peromyscus leucopus*), deer mice (*Peromyscus maniculatus*), and hispid cotton rats (*Sigmodon hispidus)* were selected for sampling because they live and forage in these areas, are food for other mammals, and have relatively small home ranges. The biota sampling locations were at the confluence of Melton Branch and WOC and in the floodplain upstream of White Oak Lake. Based on the current measured concentrations in soil and tissue concentrations collected, the absorbed doses to the terrestrial organisms collected along the confluence of Melton Branch and WOC and in the floodplain upstream of White Oak Lake were less than 0.1 rad/day.

The next evaluation of exposure to terrestrial organisms would be within the next 5 years or if an abnormal event occurs that could have adverse effects on terrestrial organisms.

7.2 Chemical Dose

7.2.1 Drinking Water Consumption

7.2.1.1 Surface Water

To evaluate the drinking water pathway, hazard quotients (HQs) were estimated downstream of ORNL and downstream of ORR discharge points (Table 7.9). The HQ is a ratio that compares the estimated exposure dose or intake to the reference dose. Based on a nationwide food consumption survey (EPA 2011) and weighted based on the combined population of Anderson, Knox, Loudon, and Roane counties, it was assumed that the drinking water consumption rate for the maximally exposed individual is 680 L/year (180 gal/year). This is the same drinking water consumption rate used in the estimation of the maximum exposed radiological dose from consumption of drinking water. Chemical analytes were measured in surface water samples collected at CRK 23 and CRK 16. The water intake for ETTP used to be located near CRK 23 but was deactivated in 2014. Therefore it is not considered in this evaluation. CRK 16 is located downstream of all DOE discharge points. Although CRK 16 is not a source of drinking water, data from this location were used as an indicator of the potential effect of drinking water from the Clinch River. As shown in Table 7.9, HQs were less than 1 for detected chemical analytes for which there are reference doses or a maximum contaminant level.

Acceptable risk levels for carcinogens typically range in magnitude from 10^{-4} to 10^{-6}. A risk value slightly less than 10^{-5} was calculated for the intake of mercury in water collected at CRK 16.

Table 7.9. Chemical hazard quotients and estimated risks for drinking water, 2016

Chemical	Hazard quotient
	CRK 16[a]
Metals	
Antimony	0.01
Arsenic	0.05
Lead	0.1
Mercury	0.0006
Uranium	0.003
Zinc	0.0009
Risk for carcinogens	
Arsenic	9×10^{-6}

[a]Clinch River downstream of all US Department of Energy inputs.

Acronyms
CRK = Clinch River kilometer.

7.2.1.2 Groundwater

As discussed in Section 7.1.2.2.1, groundwater monitoring is conducted west of the Clinch River across from the Melton Valley waste management areas. These wells have been sampled semiannually from 2010 through 2016. Data are summarized in *2016 Remediation Effectiveness Report for the U.S. Department of Energy* (DOE 2016).

7.2.2 Fish Consumption

Chemicals in water can be accumulated by aquatic organisms that may be consumed by humans. To evaluate the potential health effects from the fish consumption pathway, HQs were estimated for the consumption of noncarcinogens, and risk values were estimated for the consumption of carcinogens detected in sunfish and catfish collected both upstream and downstream of the ORR discharge points. Based on a nationwide food consumption survey (EPA 2011) and weighted based on the combined population of Anderson, Knox, Loudon, and Roane counties, it was assumed that avid fish consumers would have eaten 27 kg (60 lb) of fish during 2016. This fish consumption rate of 74 g/day (27 kg/year) is assumed for both the noncarcinogenic and carcinogenic pollutants. This is the same fish consumption rate used in the estimation of the radiological dose from consumption of fish.

As shown in Table 7.10, for consumption of sunfish and catfish, HQ values of less than 1 were calculated for all detected analytes except for Aroclor-1260, a polychlorinated biphenyl (PCB), also referred to as PCB-1260. An HQ greater than 1 for Aroclor-1260 was estimated in both sunfish and catfish at all three locations (CRKs 16, 32, and 70).

For carcinogens, risk values at or greater than 10^{-5} were calculated for the intake of Aroclor-1260 in sunfish and catfish collected at all three locations. TDEC has issued a fish advisory that states that catfish should not be consumed from Melton Hill Reservoir (in its entirety) because of PCB contamination. TDEC has issued a precautionary fish consumption advisory for catfish in the Clinch River arm of Watts Bar Reservoir (TWRA 2012).

Table 7.10. Chemical hazard quotients and estimated risks for carcinogens in fish, 2016[a]

Carcinogen	Sunfish			Catfish		
	CRK 70[b]	CRK 32[c]	CRK 16[d]	CRK 70[b]	CRK 32[c]	CRK 16[d]
Hazard quotients for metals						
Antimony	0.3	0.2	0.5	0.2	0.4	0.3
Barium	0.0001	0.0001	0.0002	0.007	0.001	0.003
Cadmium	0.03			0.03		
Chromium	0.02	0.03	0.03	0.1	0.04	0.08
Manganese	0.003	0.002	0.003	0.07	0.01	0.03
Mercury	0.09	0.5	0.2	0.03	0.09	0.2
Nickel	0.002	0.002	0.002	0.001	0.001	0.002
Selenium	0.2	0.2	0.2	0.3	0.3	0.4
Strontium	0.0002	0.0002	0.00007	0.02	0.003	0.008
Thallium	0.05	0.06	0.02	0.08	0.1	0.09
Uranium	0.0002	0.0002	0.001	0.0007	0.0002	0.0004
Vanadium	0.003			0.004		
Zinc		0.03	0.02	0.06	0.06	0.06
Hazard quotients for pesticides and Aroclors						
Aroclor-1260	2	15	11	8	1	2
Risks for carcinogens						
Aroclor-1260	4E-5	3E-4	2E-4	1E-4	2E-5	3E-5
PCBs (mixed)[e]	4E-5	3E-4	2E-4	1E-4	2E-5	3E-5

[a]A blank space for a particular location indicates that the parameter was undetected.
[b]Melton Hill Reservoir, above the City of Oak Ridge Water Plant.
[c]Clinch River downstream of Oak Ridge National Laboratory.
[d]Clinch River downstream of all US Department of Energy inputs.
[e]Mixed polychlorinated biphenyls (PCBs) consist of the summation of Aroclors detected or estimated.

Acronyms
CRK = Clinch River kilometer

7.3 References

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