4.0 Radiological Protection and Doses

This section provides information on the Hanford Site radiological program and doses as well as cleanup activities as DOE progresses toward site closure and the likely transfer of property to other entities. Additional information on radiation, dose rates, and dose terminology can be found in Appendix A, Helpful Information and Appendix B, Glossary.

4.1 External Radiation Monitoring

CJ Perkins

External radiation is defined as radiation originating from a source external to the human body. External radiation was monitored at the Hanford Site in relative proximity to known or potential radiation sources. Sources of external radiation at the Hanford Site include waste materials associated with the historical production of plutonium for defense; residual nuclear inventories in former production and processing facilities; radioactive waste handling, storage, and disposal activities; waste cleanup and remediation activities; atmospheric fallout from historical nuclear weapons testing; and natural sources such as cosmic radiation. During any given year, external radiation levels can vary from 15–25% at any location because of changes in soil moisture and snow cover (NCRP 1975).

The Harshaw™* thermoluminescent dosimeter (TLD) system is used to measure external radiation on the Hanford Site. This system includes the Harshaw 8800-series dosimeter and the Harshaw 8800 reader. The Harshaw 8800-series environmental dosimeter consists of two TLD-700 chips and two TLD-200 chips and provides both shallow- and deep-dose measurement capabilities using filters in the dosimeter. Data obtained from the two TLD-700 chips were used to determine the average total environmental dose at each location. The two TLD-200 chips were included to determine doses in the event of a radiological emergency and were not used in calculating average total environmental dose. The average daily dose rate was determined by dividing the average total environmental dose by the number of days the dosimeter was exposed. Daily dose equivalent rates (mrem/day) at each location were converted to annual dose equivalent rates (mrem/yr) by averaging the daily dose rates and multiplying by 365 days/yr. The TLDs were positioned approximately 3.3 ft (1 m) above ground and were collected and read quarterly.

Radiation surveys with portable instruments are conducted to monitor and detect contamination and to provide a coarse screening for external radiation fields. The types of areas surveyed included underground radioactive material areas, contamination areas, soil contamination areas, high-contamination areas, roads, and fence lines.

4.1.1 External Radiation Measurements

External radiation fields were monitored in 2015 at 115 locations (Table 4.1) near Hanford Site facilities and operations. The TLD results were used individually or averaged to determine dose rates in a given area for a specific sampling period. Individual TLD results and detailed maps of monitoring locations are available upon request.

* Harshaw is a trademark of Thermo Fisher Scientific, Inc., Waltham, MA.

Table 4.1. Thermoluminescent Dosimeter Locations, 2015

Location	No. of Dosimeters
100-K Area	14
100-N Area	1
200 East Area	42
200 West Area	24
200 North Area	1
300 Area	8
300 TEDF	6
400 Area	7
618-10 Burial Ground	4
CVDF	4
ERDF	3
IDF	1
Total	**115**

CVDF=Cold Vacuum Drying Facility (100 K Area), ERDF=Environmental Restoration Disposal Facility (200 West Area), IDF=Integrated Disposal Facility (200 East Area), TEDF=300 Area Treated Effluent Disposal Facility

In early 2015, the Hanford External Dosimetry Program's (HEDP) laboratory was relocated from its long-time location near the 300 Area and to a location between the 200 East and 200 West Areas. This relocation introduced two substantial variances within the 2015 data set.

One significant difference was the higher background dose rate levels (approximately 50% higher) attributable to elevated radon levels inherent within the new HEDP facility (Figure 4.1). These background values are subtracted from the ambient dose rate levels measured in the environs to determine site-specific dose rate levels above background. This simple calculation produced artificially decreased dose rate values for 2015 when compared to previous years' values.

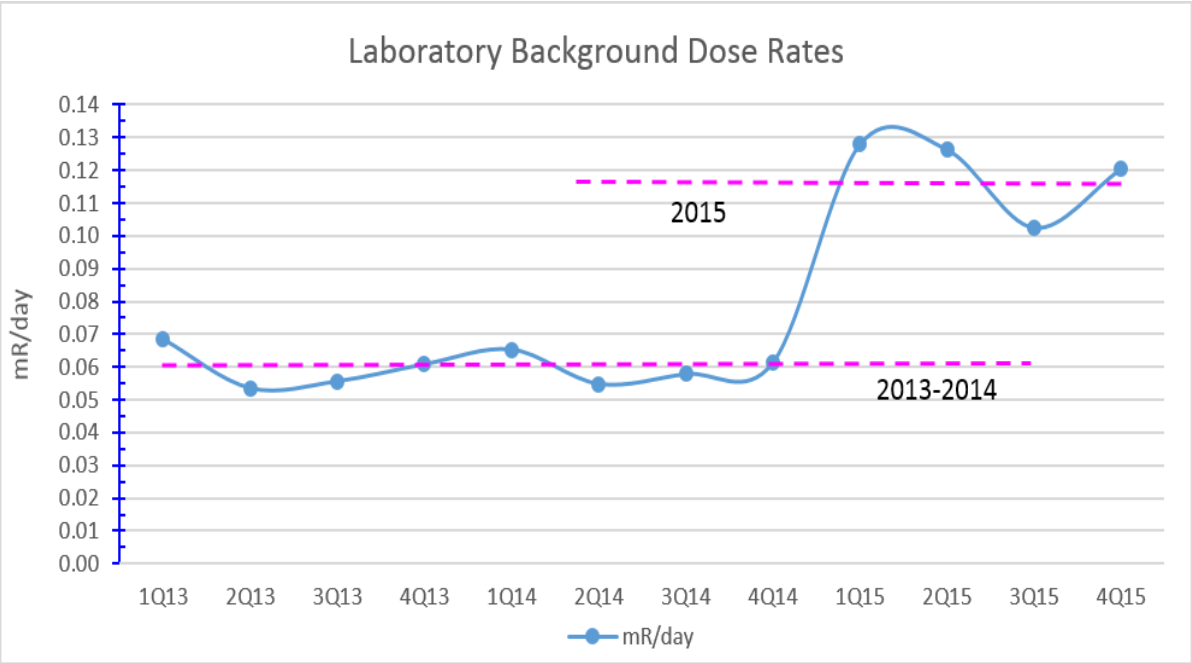

Figure 4.1. Background Dose Rates at the Hanford External Dosimetry Program Laboratory

The second significant difference that occurred during 2015 was the material used for shielding the dosimeters during their residency in the HEDP facility. Prior to 2015, the shielding material used was lead which is substantially better than the steel shielding used in 2015. The effect of this change was to expose the dosimeters to the significantly higher background levels discussed in the previous paragraphs and ultimately cause a higher dose rate reading.

Due to the complexities and uncertainties imparted on the 2015 TLD data by these changes at the HEDP facility, annual data comparisons are impractical and are not being reported. Comparative data reporting will resume once the HEDP laboratory background and shielding values are stable.

100-K Area. As in years past, the 2015 dose rate levels near the load-out area of the 105-KW (reactor) building where radioactive contaminated sludge and debris from the cleanout of the 100-K West Basin was transported were noticeably higher than other TLD locations at 100-K.

100-N Area Shoreline (N Springs). Dose rates were measured along the Columbia River shoreline in the 100-N Area (N Springs) to determine potential external radiation doses to onsite workers and to the public accessing the river. Cleanup activities at the retired 116-N-1 and 116-N-3 Trenches (located near the Columbia River) have decreased dose rates notably over the past few years.

200-East Area. Dose rate levels measured during 2015 near the "A" and "C" Tank Farms were higher than other 200 East area locations.

200-West Area. Dose rate levels measured during 2015 near the "S" and "T" Tank Farms and at the Solid Waste Operations Complex were higher than other 200 West area locations.

200-North. Dose rates measured in 2015 were low, and all four quarterly measurements were similar.

300 Area. Dose rate levels measured during the second quarter of 2015 near the North Process Trench were slightly higher than any other period or at other 300 Area locations.

400 Area. Dose rates measured in 2015 at all seven monitoring locations were low and similar.

ERDF. Dose rates measured in 2015 at all three monitoring locations were low and similar.

618-10 Burial Ground. Dose rates measured in 2015 at all four monitoring locations were low and similar.

Integrated Disposal Facility. Dose rates measured in 2015 were low, and all four quarterly measurements were similar.

4.1.2 Waste Disposal Sites Radiological Surveys

JW Wilde

During 2015, 886 environmental radiological surveys were reported as performed at active and inactive waste disposal sites and the surrounding terrain to detect and characterize radioactive surface contamination. Radiation surveys with portable instruments are conducted to monitor and detect contamination and to provide a coarse screening for external radiation fields. The types of areas surveyed included underground radioactive material areas, contamination areas, soil contamination areas, high-contamination areas, roads, and fence lines. Vehicles equipped with radiation detection devices, and Global Positioning Systems (GPS) were used to measure accurately the extent of contamination. Area measurements were entered into the Hanford Geographical Information System, a computer database maintained by MSA. Routine radiological survey locations included former waste disposal cribs and trenches, retention basin perimeters, ditch banks, solid waste disposal sites (e.g., burial grounds), unplanned release sites, tank farm perimeters, stabilized waste disposal sites, roads, and firebreaks in and

around the Hanford Site operational areas. These sites were posted as underground radioactive material areas, contamination areas, and soil contamination areas. The external dose rate at 80% of the outdoor contamination areas was estimated to be less than 1 mrem (0.01 mSv) per hour, although direct dose-rate readings from isolated radioactive specks could have been higher.

Underground radioactive material areas are regions where radioactive materials occur below the soil surface. These areas are typically stabilized cribs, burial grounds, covered ponds, trenches, and ditches. Barriers have been placed over the contamination sources to inhibit radionuclide transport to the surface. These areas are surveyed at least annually to assess the effectiveness of the barriers.

Contamination areas and soil contamination areas may or may not be associated with an underground structure containing radioactive material. A breach in the surface barrier of a contaminated underground area may result in the growth of contaminated vegetation. Insects or animals may burrow into the soil and bring contamination to the surface. Vent pipes or risers from an underground structure may be sources of speck contamination (particles with a diameter less than 0.25 in. [0.6 cm]). Areas of contamination not related to subsurface structures can include sites contaminated with fallout from effluent stacks or with materials from unplanned releases (e.g., contaminated tumbleweeds and animal feces).

All contaminated areas may be susceptible to contaminant migration and are surveyed at least annually to assess their current radiological status. In addition, onsite paved roadways on which radioactive materials are transported to ERDF are surveyed annually.

4.2 Potential Radiological Doses

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Potential radiological doses to the public and biota from Hanford Site operations in 2015 were evaluated to determine compliance with pertinent regulations and limits. Potential sources of radionuclide contamination included gaseous emissions from stacks and ventilation exhausts, contaminated groundwater seeping into the Columbia River, and fugitive emissions from areas of contaminated soil and operating facilities. A summary of the methods and results of the public and biota dose assessments is provided here. Details of the methods used to calculate radiological doses are provided in Appendix D.

The radiological impacts of Hanford Site operations were assessed in terms of the following:

- Dose to a hypothetical, maximally exposed individual (MEI) at an off-site location, evaluated by using a multimedia pathway assessment DOE O 458.1 (Section 4.2.1)
- Collective dose to the population residing within 50 mi (80 km) of Hanford Site operation areas (Section 4.2.2)
- Doses for air pathways calculated using regulation-specified EPA methods for comparison to the *Clean Air Act* standards in 40 CFR 61, Subpart H (Section 4.2.3)
- Doses from recreational activities, including hunting and fishing (Section 4.2.4.1)
- Dose to a worker consuming drinking water on the Hanford Site (Section 4.2.4.2)
- Dose to a visitor of the Manhattan Project National Historical Park (Section 4.2.4.3)
- Doses from non-DOE industrial sources on and near the Hanford Site (Section 4.2.5)

- Absorbed dose received by biota exposed to radionuclide releases to the Columbia River and to radionuclides in on-site surface water bodies (Section 4.2.6).

Radiological dose assessments related to environmental releases are ideally based on direct measurements of radionuclide concentrations in specific exposure media; however, amounts of many radioactive materials released to the Columbia River or the atmosphere from Hanford Site sources are too small to be measured in environmental media after they are dispersed in the offsite environment. For the radionuclides present in measurable amounts, it can be difficult to distinguish the small contribution of Hanford Site sources from contributions caused by fallout from historical nuclear weapons testing and naturally occurring radionuclides such as uranium and its decay products. As a result, computer models are employed to calculate offsite radionuclide concentrations based on measured and estimated releases. In specific instances, such as ambient air measurements of tritium at on- and off-site locations near the 300 Area, radionuclide concentrations may be distinguishable from background levels, and these measurements are used to support the dose assessment.

Calculations of radiation dose require the use of biological and radiological models of the behavior of radioactive material in the human body. Scientific understanding of these processes has improved over time. In the 1960s, the annual environmental reporting at the Hanford Site used the recommendations and methodologies of the ICRP Publication 2 (*Permissible Dose for Internal Radiation* [ICRP 1959]). In the 1970s, the annual reports began to follow the newer recommendations in ICRP Publication 26 (ICRP 1977]) and Publication 30 (*Limits for Intakes of Radionuclides by Workers*, Part 1 and Supplement to Part 1 [IRCP 1979a and 1979b, respectively]) incorporated in the dose factors from the EPA in Federal Guidance Reports 11 and 12 (EPA 1988 and EPA 1993, respectively). The GENII Version 1 computer code at the Hanford Site beginning in 1988 used ICRP Publications 26 and 30 as well as EPA dose factors. The GENII Version 2 computer code for the annual report dose calculations beginning in 2009 uses ICRP Publication 60 methods (ICRP 1991) and updated EPA dose factors (EPA 1999).

Off-site dose for a MEI (Section 4.2.1) and collective dose for population residing within 50 mi (80 km) of Hanford Site operation areas (Section 4.2.2) are calculated separately for liquid releases to the Columbia River and stack air emissions. Radiological doses from the water pathways are calculated based on differences in radionuclide concentrations between upstream and downstream sampling points on the Columbia River. Although the downstream minus upstream radionuclide concentrations potentially include groundwater-related contributions from other operating areas, they have been assigned to the 200 Area for tabulation of radiological dose. No direct discharge of radioactive materials from the 100 or 300 areas to the Columbia River was reported during 2015. Radiological doses from the air pathways are calculated based on stack emissions measurements from approximately 60 emission points in Hanford Site operation areas.

Columbia River shoreline spring and seep water-containing radionuclides is known to enter the river along the portion of the Hanford Site shoreline extending from the 100-BC Area downstream to the 300 Area. Tritium and uranium isotopes were measured in the Columbia River downstream of the Hanford Site (Richland Pumphouse station, HRM 46.4) in 2015 at concentrations statistically greater than upstream (Priest Rapids Dam station) levels (Appendix D). Radioactive air emissions are discussed in Section 6.1 and summarized in Table 6.1. For the GENII Version 2.10 (PNNL-14583, Rev 3) calculations supporting this dose assessment, ingrowth of short-lived radioactive progeny during environmental transport was calculated to develop a complete set of radionuclide release estimates. Details on the development of air pathway and water pathway radioactive release estimates are provided in Appendix D.

4.2.1 Maximally Exposed Individual Dose (Off-site Resident)

The MEI is a hypothetical person whose location and lifestyle are such that it is unlikely any actual member of the public would have received a higher radiological dose from Hanford Site releases during 2015. This individual's exposure pathways were chosen to maximize the combined doses from all reasonable environmental routes of exposure to radionuclides in Hanford Site liquid effluents and air emissions using a multimedia pathway assessment (DOE O 458.1, Section 4.e). In reality, such a combination of maximized exposures to radioactive materials is highly unlikely to apply to any single person. The individual pathway dose calculations themselves also incorporate conservative assumptions intended to ensure that modeled concentrations of radionuclides in exposure media and resulting doses are protective. For these reasons, the dose assessment results for the MEI represent a hypothetical upper bound of potential individual dose rather than an anticipated dose to an actual individual.

The location of the hypothetical MEI varies depending on the relative contributions of radioactive air emissions and liquid effluent releases from Hanford Site operational areas. Four off-site locations were evaluated to determine the location of the MEI (Figure 4.2). The Ringold location receives maximal air pathway impacts from the 200 Area. Depending on annual differences in the prevailing wind direction, either the Sagemoor or Horn Rapids Road location may receive maximal air pathway impacts from the 300 Area. A small population of West Pasco residents obtains their drinking water from the Riverview location via a community water system, and the domestic drinking water pathway is applied to that location. Residences in the vicinity of Horn Rapids Road receive drinking water from the City of Richland, which has an intake downstream of the Hanford Site, so the domestic drinking water pathway is also applied here. Both Riverview and Horn Rapids Road are locations where Columbia River water is withdrawn for irrigation.

Dose calculations for 2015 releases indicate that the MEI is located at the PNNL Physical Sciences Facility, an off-site business just to the south of the Hanford Site 300 Area at 638 Horn Rapids Road. For the Horn Rapids Road receptor dose calculations, the following exposure routes were evaluated:

- Inhalation and external radiation exposure related to airborne radionuclides
- External radiation exposure and inadvertent soil ingestion for radionuclides deposited on the ground
- Ingestion of domestic drinking water from the Columbia River
- Ingestion of locally grown food products irrigated with Columbia River water and/or containing radionuclides deposited from the air
- External radiation exposure to radionuclides in Columbia River water and sediments near the Hanford Site during recreational activities (i.e., fishing, boating) and inadvertent ingestion of water while swimming
- Consumption of locally caught Columbia River fish.

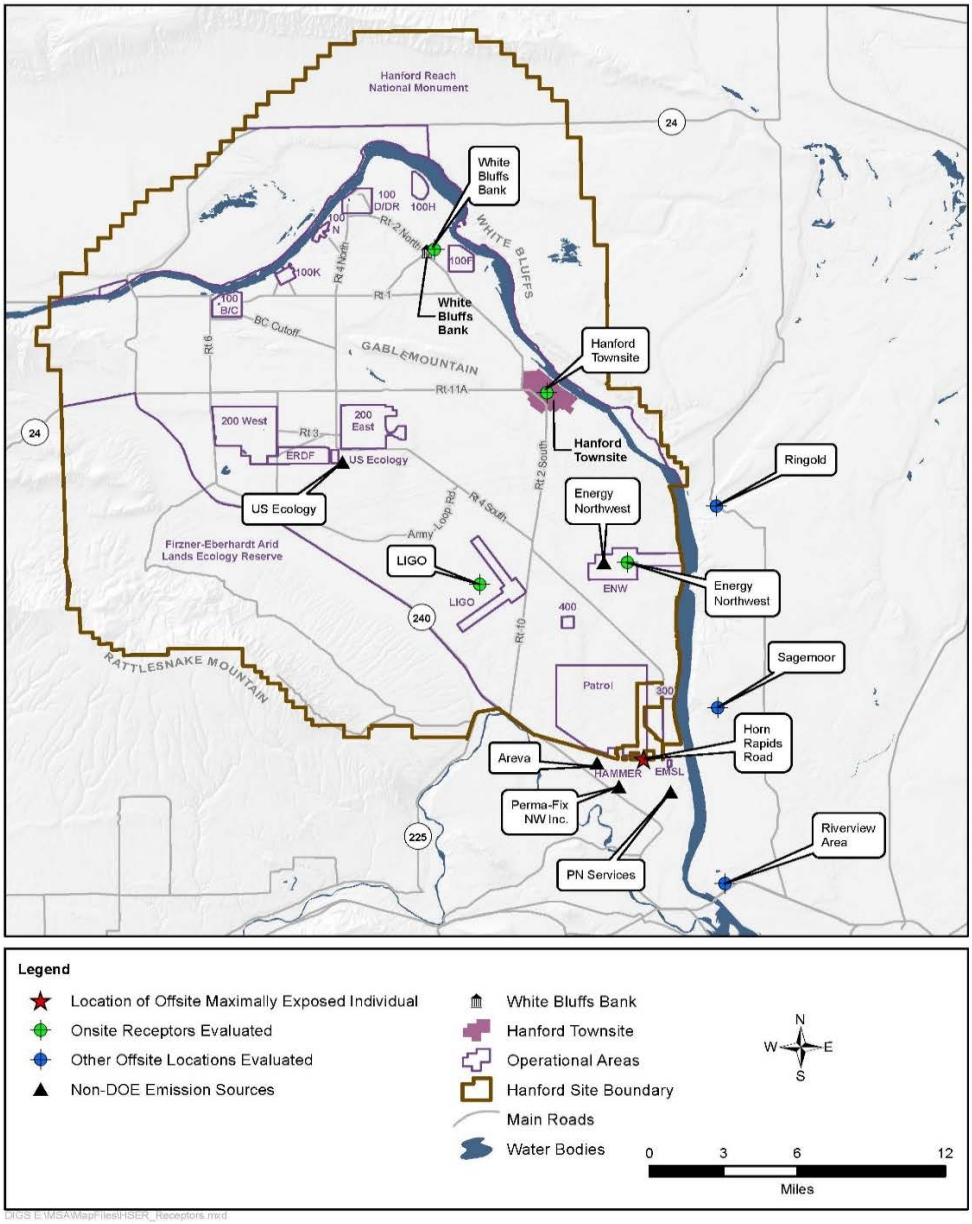

Figure 4.2. On-Site Receptors Evaluated

A graphical depiction of the conceptual site model showing all potentially complete exposure pathways for the Horn Rapids Road MEI evaluated using GENII Version 2.10 (PNNL-14583, Rev 3) is provided in Figure 4.3. Additional information related to selection of the MEI location for releases is included in Appendix D. Exposure variable input values related to residency and recreational exposure times, intake rates for water, foods, other media, and agricultural pathway assumptions for the MEI are provided in Appendix D.

The total dose to the MEI at Horn Rapids Road in 2015 was calculated to be 0.21 mrem (2.1 mSv)/yr (Table 4.2; Figure 4.4). This dose is 0.21% of the 100 mrem (1000 mSv) per year public dose limit specified in DOE O 458.1 and 0.84% of the 25-mrem (250-mSv)/yr threshold where a supplemental assessment of dose to the lens of the eye, skin, and extremities is required. Air pathway contributions from sources in the 300 Area contributed approximately 70% of the total dose of 0.21 mrem (2.1 mSv)/yr, with the remaining dose related to water pathway exposures.

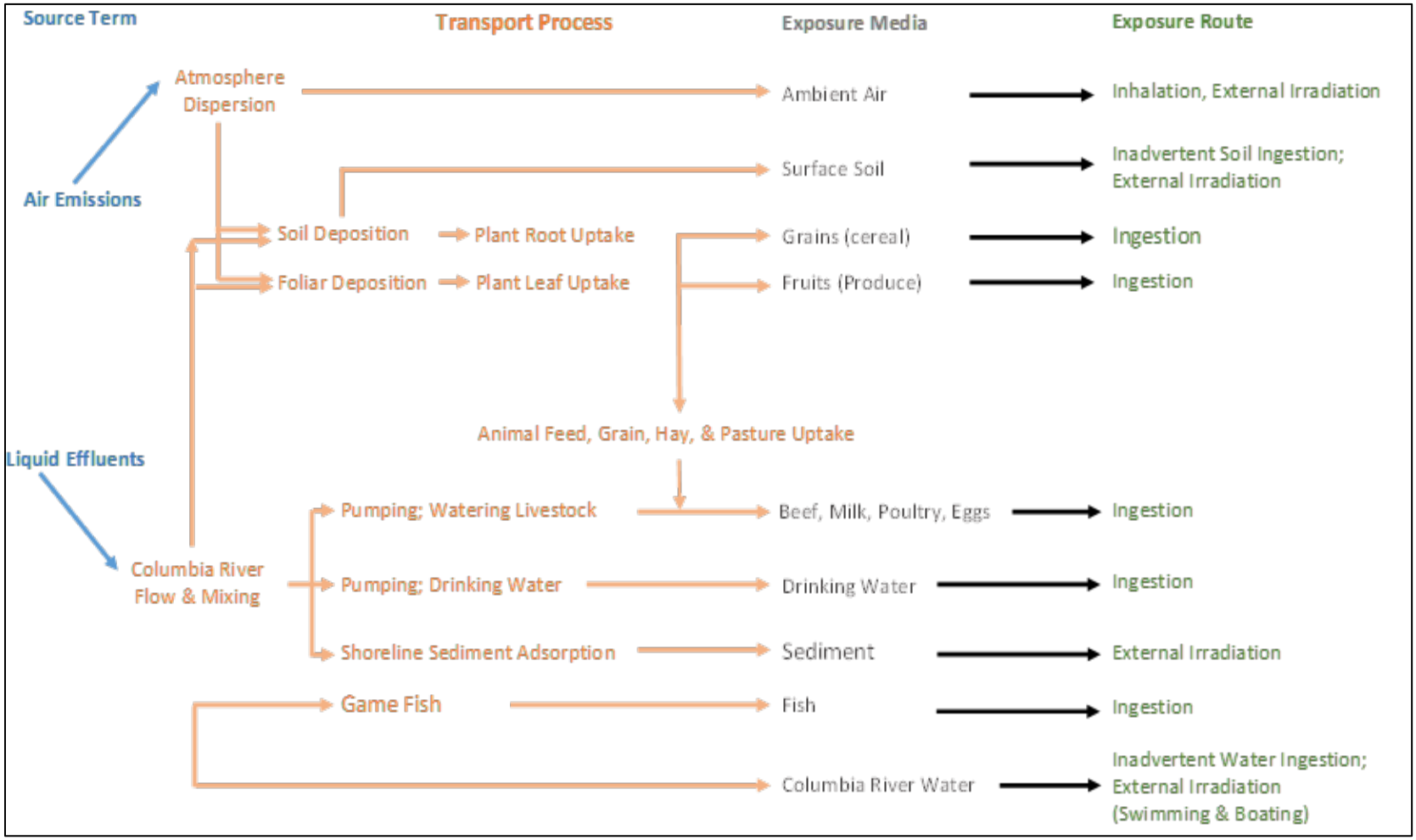

Figure 4.3. Conceptual Site Model of Exposure Pathways Evaluated in Dose Calculations (Horn Rapids Road MEI)

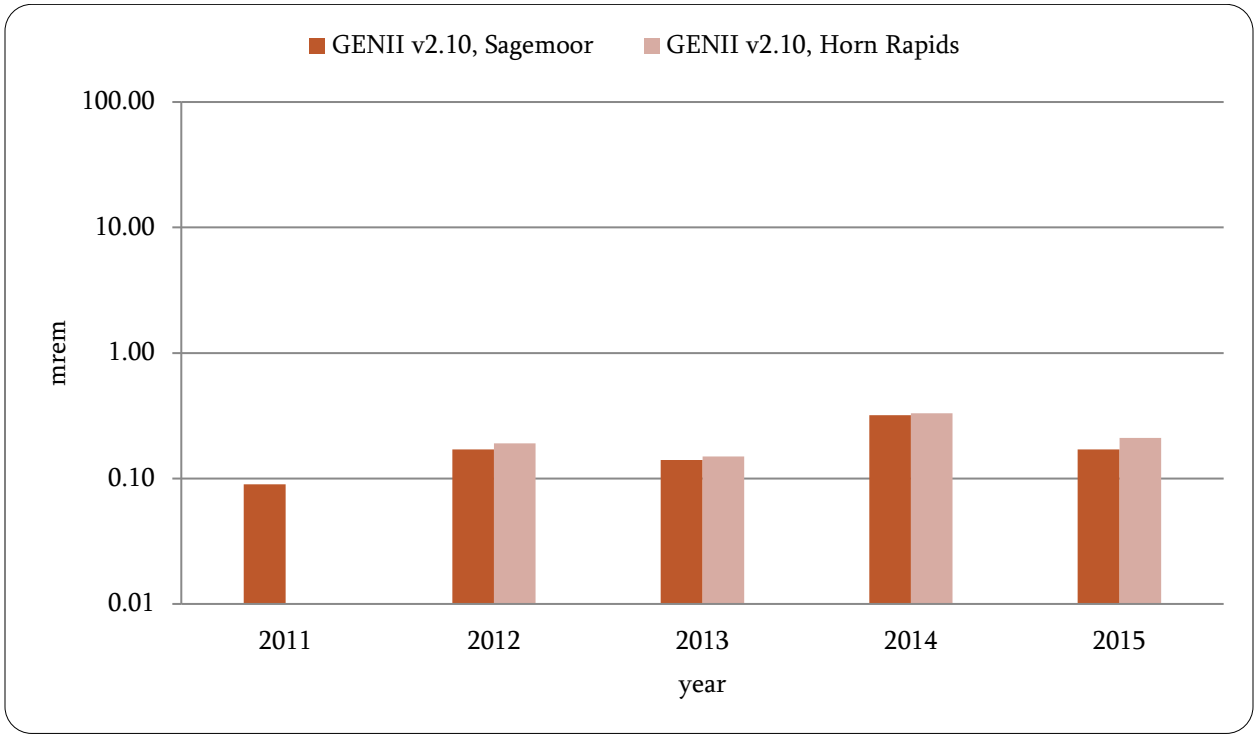

Figure 4.4. Total Dose for the Hypothetical MEI Over Time

Table 4.2. Pathway Doses for the Hypothetical MEI Residing at Horn Rapids Road

Release Type	Exposure Pathway	Dose Contributions from Operational Areas (mrem)* 100 Areas	200 Areas†	300 Area	400 Area	Pathway Total
Air	Food Ingestion	6.1E-07	4.8E-05	0.094	2.8E-07	0.094
	Inhalation	5.7E-06	8.4E-05	0.059	1.0E-06	0.059
	External, Soil Ingestion	5.4E-09	1.0E-06	0.0010	6.7E-09	0.0010
	Subtotal Air	6.3E-06	1.3E-04	0.15	1.3E-06	0.15
Water	Irrigation (food and soil ingestion; external)	NA‡	0.015	NA	NA	0.015
	Drinking Water Ingestion	NA‡	0.0053	NA	NA	0.0053
	Recreation (river water, sediments; external, ingestion)	NA‡	2.7E-04	NA	NA	2.7E-04
	Fish Ingestion	NA‡	0.032	NA	NA	0.032
	Subtotal Water	NA	0.052	NA	NA	0.052
	Air + Water Total	**6.3E-06**	**0.052**	**0.15**	**1.3E-06**	**0.21**

*To convert mrem to International System dose units (mSv), multiply by 10.
†Integrates releases from all operational areas based on difference between down and upstream Columbia River radionuclide concentrations.
‡No measured releases; the last 100 Area NPDES-permitted outfall (1908-K Outfall) ceased releases in March 2011.
NA=Not applicable. All liquid discharges reflected in the difference between upstream and downstream radionuclide concentrations are assigned to the 200 Area.

The primary radionuclides and exposure pathways contributing to the MEI dose are as follows:

Air Releases. Consumption of food products containing tritium released from the 300 Area contributed approximately 61% of the total air pathways dose of 0.15 mrem (1.5 mSv)/yr. Inhalation of the radioactivity progeny of radon-220 released from the 300 Area contributed approximately another 33% of the total air pathways dose.

Water Releases. Consumption of fish from the Columbia River contributed 0.032 mrem (0.32 mSv) or 61% of the total water pathways dose of 0.052 mrem (0.52 mSv)/yr. Consumption of food grown using Columbia River water withdrawn downstream from the Hanford Site contributed approximately another

29% of the total water pathways dose, and drinking water ingestion contributed the remaining 10%. Isotopes of uranium and their progeny, particularly uranium-234 and uranium-238, contribute approximately 60% of the total water pathways dose of 0.052 mrem (0.52 mSv)/yr. Most of the remaining 40% of the water pathways dose is related to strontium-90 and cesium-134, two radionuclides that were protectively included in dose calculations based on comparing downstream and upstream concentrations but not detected at concentrations above sample quantitation limits (Appendix D).

The MEI dose in 2015 of 0.21 mrem (2.1 mSv) is below the 0.33 mrem (3.3 mSv) MEI dose calculated in 2014 (DOE/RL-2014-52, *Hanford Site Environmental Report for Calendar Year 2014*). The difference between the 2015 and 2014 dose estimates is mostly attributable to the inclusion of naturally occurring potassium-40 in the 2014 water pathways dose calculations. Potassium-40 was included in the 2014 dose calculations for water releases because average downstream river concentrations were statistically greater than upstream concentrations, even though potassium-40 is a naturally-occurring radionuclide not of Hanford origin. In 2013 and 2015, downstream potassium-40 concentrations were not statistically different from those measured upstream.

The MEI dose estimate incorporates a number of conservative assumptions to ensure that pathway doses are protective and therefore calculated doses are likely to be overestimated. In the air pathways calculations, gross alpha and gross beta radiation measurements in stack emissions from the 100, 200, and 300 areas were protectively added to the measured emissions of plutonium-239/-240 (an alpha-emitting radionuclide related to Hanford operations) and cesium-137 (a beta-emitting radionuclide related to Hanford operations), respectively. The actual measured total air releases of plutonium-239/-240 and cesium-137 are a small fraction (35 and 14%, respectively) of assumed releases that include the contribution of gross radioactivity values. Although gross alpha and gross beta levels in stack emissions are similar to ambient air background levels, the addition of these values ensures that possible contributions from any unmeasured operations-related radionuclides are protectively incorporated in the estimated doses.

In the irrigation pathways calculations, all produce eaten by the MEI was protectively assumed to be locally grown and originate from areas irrigated with Columbia River water. For the fish consumption pathway, near-shore water samples were protectively used to represent Columbia River water generally, and it was assumed that all fish consumed by the MEI are resident species rather than anadromous fish, such as salmon or steelhead. Because anadromous fish spend most of their lives in the ocean they would have a much lesser exposure to contaminants associated with the Hanford Reach compared to species that spend their entire lives in the Hanford Reach, such as sturgeon.

Because releases of tritium from the 300 Area are the major source of calculated Hanford-related radiological dose for the hypothetical MEI, modeled annual-average tritium concentrations at locations near the 300 Area were compared to concentrations based on air monitoring station samples. Figure 4.5 shows the 2015 modeled annual average air concentrations of tritiated water vapor (HTO) at the Horn Rapids Road MEI location and 2015 annual averages based on measured values at two off-site locations south and east of the 300 Area (Battelle Complex and Byers Landing) and two on-site locations near the southern border of the 300 Area northeast of the Horn Rapids Road MEI location. Measured monthly tritium concentrations vary substantially at each monitoring location. The 95% upper and lower confidence intervals of the annual average values are shown on Figure 4.5 in addition to the annual average.

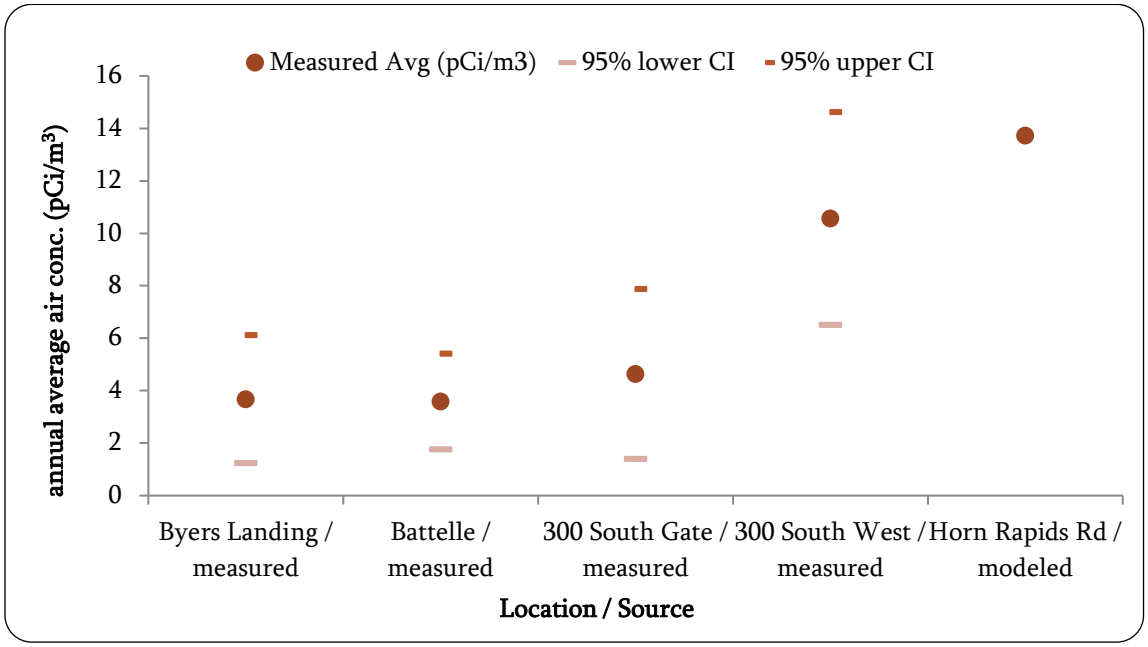

Figure 4.5. Comparison of Measured and Modeled Tritium Air Concentrations Near the 300 Area
Error bars are 95% confidence intervals of the mean

The modeled annual-average tritium concentration at the Horn Rapids Road MEI location is above the range of the 95% upper and lower confidence interval of the mean of the measured values at the two nearby off-site monitoring locations and the 300 South Gate on-site location. The Horn Rapids Road modeled annual-average tritium concentration is within the 95% upper and lower confidence interval of the mean of the measured values at the 300 South West monitoring station. A relationship between 300 Area monthly tritium air emissions and on-site 300 Area ambient air concentrations in 2006 was shown by Barfuss (2007), but there was little correlation of monthly emissions and air concentrations for a combined group of four nearby off-site monitoring locations. Figure 4.5 shows that the modeled MEI tritium air concentration is higher than the upper 95% confidence interval annual-average tritium concentrations measured at Battelle Complex (near the Horn Rapids Road MEI Location) and Byers Landing (near the Sagemoor MEI location) stations. This suggests that modeled tritium air concentrations may overestimate actual annual-average levels at these off-site locations.

Note that exact correspondence between modeled and measured annual average values would not be expected because the episodic nature of HTO releases is not captured in the GENII air dispersion modeling, which assumes a constant rate of HTO emissions. However, the modeled tritium values do not account for regional background levels of tritium, which would add between 1.5 and 4 pCi/m^3 to the modeled values (Figure 11 in Barfuss 2007) and exacerbate the difference between modeled and measured tritium values at off-site locations near the 300 Area.

Samples of locally raised foodstuffs were collected in 2015 from four locations including the Sagemoor, Riverview, Sunnyside, and East Wahluke areas. Sampled foodstuffs included fruits (apples, cherries, melons, and tomatoes), leafy vegetables, potatoes, corn, milk, and wine. Gamma-emitting radionuclides and strontium-90 were measured in all foodstuffs, and tritium was also measured in tomatoes, milk and wine. Measured concentrations of the Hanford-related radionuclides strontium-90, cesium-137, and tritium in foods were compared to modeled concentrations calculated for the MEI receptor using the

GENII computer code. These comparisons encompassed fruits, leafy vegetables, grain (corn), root vegetables (potatoes), and milk. Modeled concentrations of tritium and cesium-137 are related primarily to air emissions, whereas modeled concentrations of strontium-90 are related to irrigation with Columbia River water. The following observations are drawn from the comparisons:

- Cesium-137 was not detected in any food sample. Analytical detection limits were approximately a factor of 1,000 to 10,000 times larger than the worst-case modeled concentrations but comparable to or below environmental surveillance project dose-based reporting limits (DOE/RL-91-50) calculated using a 1 mrem (10 μSv)/yr threshold. Cesium-137 routine air releases are far below levels of detection or radiological concern in foodstuffs.
- Strontium-90 was detected only in leafy vegetable samples from the Sagemoor, Sunnyside, and East Wahluke areas. Strontium-90 concentrations of approximately 0.006 pCi/g in the samples were approximately 30 times larger than the worst-case modeled concentration (0.0002 pCi/g) and also larger than the detection limit of the sample collected in the Riverview area (0.0004 pCi/g). However, low levels of strontium-90 in the environment are widespread to past above-ground weapons testing, and measured concentrations in leafy vegetables from the Sagemoor, Sunnyside, and East Wahluke areas are consistent with trends based on observations in off-site vegetation samples (PNNL-20577, *Radionuclide Concentrations in Terrestrial Vegetation and Soil Samples On and Around the Hanford Site, 1971 Through 2008*). Detected concentrations of approximately 0.006 pCi/g in leafy vegetables are almost 100 times below the environmental surveillance project dose-based reporting limit (DOE/RL-91-50).
- Tritium was measured in samples of tomatoes from the Sunnyside and Riverview areas but was not detected at either location, with analytical detection limits of approximately 0.08 and 0.03 pCi/g, respectively. Tritium was also detected in samples of milk at average concentrations of approximately 19 pCi/L (Sunnyside), 28 pCi/L (East Wahluke), and 35 pCi/L (Sagemoor). The relative tritium concentrations in milk from these three locations is consistent with expectations for air dispersion from releases in the 300 Area. However, these concentrations are well below the modeled worst-case tritium concentration in milk for cows grazing at the MEI location of Horn Rapids Road (approximately 600 pCi/L) and far less than the environmental surveillance project dose-based reporting limit of 17,000 pCi/L (DOE/RL-91-50).

4.2.2 Collective Dose

Collective dose is defined as the sum of doses to all individual members of the public within a defined distance of a specific release location. The regional collective dose from 2015 Hanford Site operations was estimated by calculating the radiological dose to the population residing within a 50-mi (80-km) radius of on-site operating areas (DOE O 458.1; Section 4.e(d)). The collective doses reported are based on regional population data from the 2010 census, as described in Appendix D.

The conceptual site model of potentially complete exposure pathways for the Horn Rapids Road MEI shown in Figure 4.3 is also applicable to the collective dose calculations. Like the Horn Rapids Road MEI, the collective dose calculation also incorporates the drinking water exposure pathway because the cities of Richland and Pasco obtain all or part of their municipal water directly from the Columbia River downstream from the Hanford Site, and the City of Kennewick obtains its municipal water indirectly from wells adjacent to the river. A primary distinction between the MEI and collective dose calculations is the

use of population-average values for certain exposure variables in place of reasonable upper bound values. Exposure variable input values related to residency and recreational exposure times, intake rates for foods and other media, and agricultural pathway assumptions for the collective dose calculations are provided in Appendix D. The air pathways collective dose calculations employ population data from the 2010 census broken out according to direction and distance to coincide with air dispersion and deposition modeling conducted within the GENII Version 2.10 computer code (PNNL-14583, Rev 3).

The annual collective dose is reported in units of person-rem (person-sievert), which is the sum of doses to all individual members of the exposed population. The total collective dose calculated for this population in 2015 was 1.7 person-rem (0.017 person-Sv)/yr (Table 4.3), below the collective dose calculated in 2014 and approximately equal to that calculated in 2013 (Figure 4.6). Air pathway contributions from releases in the 300 Area contributed approximately 65%, and water pathway contributions assigned to the 200 Area contributed approximately 35% to the total collective dose of 1.7 person-rem (0.017 person-Sv) in 2015.

Table 4.3. Collective Pathway Doses within a 50-mi (80-km) Radius

Release Type	Exposure Pathway	Dose Contributions from Operational Areas, person-rem* 100 Areas	200 Areas	300 Area	400 Area	Pathway Total
Air	Food Ingestion	1.0E-04	0.0045	0.64	1.1E-05	0.64
	Inhalation	0.0018	0.014	0.39	6.0E-05	0.41
	External, Soil Ingestion	1.1E-06	4.0E-05	0.0061	2.6E-07	0.0062
	Subtotal Air	0.0019	0.019	1.0	7.1E-05	1.1
Water	Irrigation (food and soil ingestion; external)	NA†	0.016‡	NA	NA	0.016
	Drinking Water Ingestion	NA†	0.0020‡	NA	NA	0.0020
	Recreation (river water, sediments; external, ingestion)	NA†	0.012‡	NA	NA	0.012
	Fish Ingestion	NA†	0.58‡	NA	NA	0.58
	Subtotal Water	NA	0.61	NA	NA	0.61
	Air + Water Total	**0.0019**	**0.63**	**1.0**	**7.1E-05**	**1.7**

NA=not applicable. All liquid discharges reflected in difference between up- and downstream radionuclide concentrations assigned to 200 Area.
*To convert person-rem to International System dose units (person-Sv), divide by 100.
†No measured releases; the last 100 Areas NPDES-permitted outfall (1908-K Outfall) ceased releases in March 2011.
‡Integrates releases from all operational areas based on difference between down- and upstream Columbia River radionuclide concentrations.

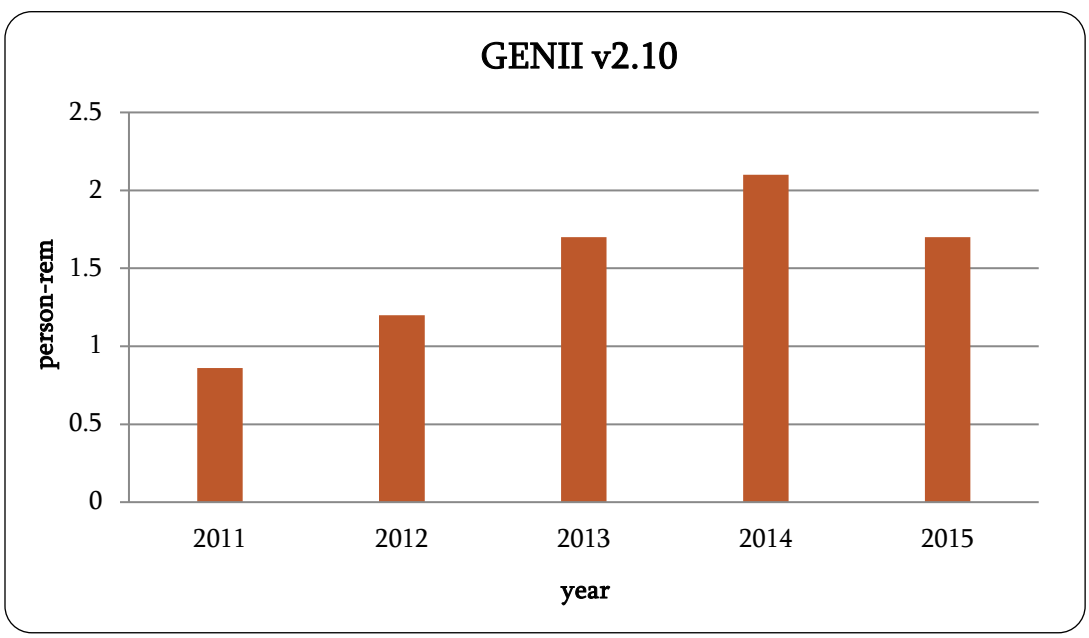

Figure 4.6. Collective Total Dose within a 50-mi (80-km) Radius

The primary radionuclides and exposure pathways contributing to the collective dose are as follows.

Air Releases. Consumption of food products grown downwind of the 300 Area contributed approximately 60% of the of the air pathways collective dose of 1.1 person-rem (0.011 person-Sv). The remaining air pathways collective dose is primarily related to inhalation. About 70% of these food and inhalation air pathways doses are due to releases of tritium from the 300 Area. Approximately another 25% of the total air pathways collective dose is associated with inhalation of the radioactive progeny of radon-220 released from the 300 Area. Air releases from the 100, 200, and 400 areas had negligible contributions to the air pathways collective dose.

Water Releases. Consumption of drinking water drawn from the Columbia River downstream of the Hanford Site contributed approximately 95% of the total water pathways collective dose of 0.61 person-rem (0.0061 person-Sv). Naturally occurring isotopes of uranium (-234 and -238) and their progeny from releases assigned to the 200 Area were the largest contributors (approximately 80%) to the drinking water collective dose.

The collective dose in 2015 of 1.7 person-rem (0.017 person-Sv) is below the 2.1 person-rem (0.021 person-Sv) collective dose calculated in 2014 (DOE/RL-2014-52) and approximately equal to the 2013 collective dose. There is no specific collective dose metric analogous to the 100 mrem (1,000 mSv) per year public dose limit for individual exposures described in Section 4.2.

4.2.3 Compliance with *Clean Air Act* Standards

Historically at the Hanford Site, there has been one primary expression of radiological risk to an off-site individual, the MEI dose; however, it is currently calculated by two different methods in response to two different requirements. One MEI dose computation is required by DOE O 458.1 and is calculated using the GENII computer code as described in Section 4.2.1 of this report. This calculation considers all potential environmental exposure pathways (e.g., from releases to both air and water) that maximize a hypothetical off-site individual's exposure to the Hanford Site's radiological liquid effluents and air emissions. A second estimate of MEI air pathways dose is required by the *Clean Air Act* and must be calculated using an EPA air dispersion and dose modeling computer code (CAP-88; EPA 2000) or other methods accepted by the EPA under the *Clean Air Act* to demonstrate compliance with 40 CFR 61, Subpart H requirements. This regulation specifies that no member of the public shall receive a dose greater than 10 mrem (100 mSv)/yr from exposure to airborne radionuclide emissions (other than radon) released at DOE facilities. The Hanford Site stack emissions and emissions from diffuse and unmonitored sources (e.g., windblown dust) are considered in the off-site dose for the *Clean Air Act* and are based solely on an airborne radionuclide emissions pathway.

The assumptions embodied in the CAP-88 computer code differ slightly from standard air pathways assumptions used with the GENII computer code; therefore, air-pathway doses calculated by the two codes may differ somewhat. In principle, the MEI for air pathways assessed under 40 CFR 61, Subpart H may be evaluated at a different location from the all-pathways MEI if dose from the water pathways exceeds that from air pathways (Appendix D).

The *Clean Air Act* regulation also requires that an annual report for each DOE facility be submitted to EPA that supplies information about atmospheric emissions for the preceding year and any potential contributions to off-site dose. For more detailed information about 2015 air emissions at the Hanford Site, refer to DOE's report to EPA (DOE/RL-2016-10).

4.2.3.1 Dose from Stack Emissions to an Off-site Maximally Exposed Individual

Using CAP-88, the maximally exposed off-site individual for air pathways in 2015 was at PNNL's Laboratory Supply Warehouse, an offsite business located in north Richland, Benton County, WA directly south of the Hanford Site 300 Area and proximal to the Horn Rapids Road MEI location (Figure 4.2). The potential air pathway dose from stack emissions to a MEI at that location calculated using the CAP-88 computer code was determined to be 0.067 mrem (0.67 mSv)/yr, less than 1% of the EPA standard of 10 mrem (100 mSv)/yr. The CAP-88 result is approximately one-half of the air pathway dose of 0.15 mrem (1.5 mSv) for stack emissions calculated with GENII (Table 4.2).

Dose related to radon-220 is not included in the dose calculated for EPA compliance in 40 CFR 61, Subpart H but is regulated by the 10-mrem (100-mSv)/yr standard established in WAC 246-247. A release of 385 curies of radon-220 was calculated from engineering estimates for stack emissions from Building 325 in the 300 Area. A radon-220 dose of 0.064 mrem (0.64 mSv)/yr was calculated using the CAP-88 computer code for the Laboratory Supply Warehouse MEI, far below the WAC 246-247 standard. The sum of MEI dose for radon-220 and dose calculated for compliance with 40 CFR 61, Subpart H using the CAP-88 computer code is approximately 0.13 mrem (1.3 mSv), practically equivalent to the Horn Rapids Road air pathways MEI dose of 0.15 mrem (1.5 mSv) calculated using the GENII computer code.

4.2.3.2 Dose from Diffuse and Fugitive Radionuclide Emissions to an Off-site Maximally Exposed Individual

The December 15, 1989, revisions to 40 CFR 61, Subpart H required DOE facilities to estimate the dose to a member of the public for radionuclides released from all potential sources of airborne radionuclides. DOE and EPA interpreted the regulation to include diffuse and fugitive (nonpoint source) emissions, as well as emissions from monitored point sources (i.e., stacks) described in Section 4.2.3.1. EPA has not specified or approved standardized methods to estimate diffuse airborne emissions because of the wide variety of sources at DOE sites. The method developed at the Hanford Site to estimate potential diffuse emissions is based on environmental monitoring measurements of airborne radionuclides at the site perimeter (DOE/RL-2016-10). Modeled contributions from monitored stack emissions and contributions from background levels of radionuclides are subtracted from perimeter ambient air concentrations measured for each radionuclide and positive differences are attributed to a virtual fugitive source located near the center of the Hanford Site.

The Laboratory Supply Warehouse location immediately south of the 300 Area was chosen for purposes of demonstrating compliance with the MEI dose standard for diffuse and fugitive emissions (DOE/RL-2016-10). The estimated dose from diffuse emissions to a MEI was calculated using the CAP-88 computer code to be 0.022 mrem (0.22 mSv)/yr. Therefore, the potential combined dose from stack emissions, radon-220 emissions, and diffuse emissions (excluding radon) during 2015 at the Laboratory Supply Warehouse location was 0.15 mrem (1.5 mSv)/yr, far below the 10 mrem (100 mSv) per year federal and state standards described above.

4.2.3.3 Maximum Dose to Non-U.S. Department of Energy Workers at the Hanford Site

DOE has recently allowed private businesses to locate their activities and personnel on some regions of the Hanford Site. The EPA Region 10 Office and the WDOH provided guidance to DOE-RL that, when demonstrating compliance with 40 CFR 61 standards, it should evaluate potential doses to non-DOE

employees who work at facilities within the Hanford Site but who are not under direct DOE control. This situation has created the need to calculate a maximum dose for an on-site individual employed by a non-DOE business who works within the boundary of the Hanford Site.

Doses to members of the public employed at non-DOE facilities at locations outside access-controlled areas on the Hanford Site (those requiring DOE-access authorization for entry) were evaluated in the 2015 EPA air emissions report (DOE/RL-2016-10) as possible MEI locations included the Columbia Generating Station operated by Energy Northwest and Laser Interferometer Gravitational Wave Observatory (LIGO) operated by the University of California (Figure 4.2). The non-DOE worker dose due to stack emissions at these facilities was calculated using the CAP-88 computer code assuming full-time occupancy because EPA guidance does not allow for adjustment of such doses to account for less than full-time occupancy. The highest estimated dose to a member of the public from fugitive emissions was at LIGO. The total dose attributable to 2015 stack emissions, fugitive source emissions, and radon-220 at LIGO was calculated using CAP-88 to be 0.075 mrem (0.75 mSv; DOE/RL-2016-10). Even assuming that a LIGO employee is continuously present, the estimated total dose to non-DOE on-site workers in 2015 was lower than the 0.15 mrem (1.5 mSv)/yr total dose calculated with CAP-88 to an off-site MEI at the Laboratory Supply Warehouse.

4.2.4 Special Case Dose Estimates

The exposure assumptions used to calculate the dose to the MEI were selected to provide a scenario yielding a reasonable upper bound dose estimate. The MEI dose calculations are based on measurements of radionuclide releases from stack emissions (air pathways) and differences between downstream and upstream radionuclide concentrations in the Columbia River (water pathways), followed by modeling of environmental transport related to a number of different exposure pathways (Figure 4.3). Exposure pathways using other radionuclide measurements also exist that could have resulted in radiological exposures. Three such scenarios include an outdoor recreationalist who consumed meat from contaminated wildlife that migrated from the Hanford Site; an individual who drank water from one of four DOE-owned water treatment facilities at the Hanford Site; and a visitor to the Manhattan Project National Historical Park. The potential doses resulting from these scenarios are examined in the following sections.

4.2.4.1 Outdoor Recreationalist Dose

Wildlife has access to Hanford Site areas that are contaminated with radioactive materials and have the potential to acquire radioactive contamination and migrate off site. Wildlife sampling was conducted at the Hanford Site to estimate radionuclide tissue concentrations in animals from the site that could potentially have been hunted off site. An outdoor recreationalist is also potentially exposed to contaminated soil and sediment along the river corridor if they access this area from the Columbia River. However, concentrations of radionuclides measured in soil (cesium-137, plutonium-238, plutonium-239/-240, and strontium-90) at far field sampling locations are not readily distinguishable from background levels, and soil concentrations are less susceptible to yearly variation than sediment and wildlife. An evaluation of radionuclide soil concentrations and trends over time is provided in PNNL-20577. Review of the 2015 sediment data indicates that concentrations of key radionuclides frequently detected in sediment (including cesium-137, plutonium-239/-240, and uranium isotopes) have approximately equal concentrations at upstream (Priest Rapids Dam) and downstream (McNary Dam) locations. Also, sediment concentrations at the dam locations are generally as large as or larger than concentrations at locations along the Hanford Site in the 100 Area and at Hanford Townsite. The 2015 sediment data do not indicate the presence of a Hanford contribution to sediment

radionuclide concentrations. Therefore, the screening assessment of outdoor recreationalist dose will focus on wildlife samples obtained in 2015.

Gamma-emitting radionuclides were analyzed in muscle tissue samples collected in 2015 from Canada goose and cottontail rabbit. In addition to muscle tissue, bone samples were collected from these animals and analyzed for strontium-90, a radionuclide that accumulates in bone tissue. For estimating dose from ingestion of game meat, radionuclide concentrations in muscle tissue are most applicable. Ten muscle tissue samples were collected and analyzed in 2015 for Canada goose, and four for cottontail rabbit. The only radionuclide detected in the muscle tissue of either animal was potassium-40, a naturally occurring primordial radioisotope not of Hanford Site origin.

Four fillet tissue samples and four carcass samples were obtained from sturgeon in the Hanford Reach in 2015. Five fillet tissue samples and four carcass samples were obtained from whitefish in the 100 Area region of the Columbia River. Additionally, five fillet tissue samples and three carcass samples were obtained from whitefish in an upstream reference area. Fillet samples were analyzed for gamma-emitting radionuclides, tritium, strontium-90, and isotopes of plutonium and uranium. Carcass samples were only analyzed for strontium-90. Detected radionuclides in fillet samples were limited to cesium-137, potassium-40, uranium-234, uranium-235, and uranium-238. Potassium-40 is a naturally occurring radionuclide that is not of Hanford Site origin. However, cesium-137 and uranium isotopes are associated with Hanford Site operations.

Cesium-137 was detected in three of the four sturgeon fillet samples from the Hanford Reach. Uranium-234, -235, and -238 were detected in one white fish fillet sample from the 100 Area and two fillet samples from the reference area. However, isotopic uranium concentrations detected in the reference area whitefish fillet samples were all higher than the values detected in the 100 Area fillet sample. These uranium isotope results for whitefish are in contrast to sampling results for uranium isotopes in carp fillet samples collected in 2014, where concentrations of uranium-234 and uranium-238 were observed to increase in carp fillet samples with downstream distance from an upstream reference area to the 100 Area to the 300 Area. Differences in sampling locations and species may explain these differences between 2014 carp and 2015 whitefish fish fillet results; Hanford Site uranium releases to the Columbia River estimated from downstream and upstream river concentrations were approximately equivalent in these 2 years.

The potential radiation dose received from consumption of fish fillets with cesium-137 concentrations similar to those measured in sturgeon in 2015 would be negligible. Assuming annual fish consumption of 88 lbs (40 kg) for an MEI (Table D.4), the annual radiation dose related to fish ingestion for fish that contains 0.0065 pCi/g [2.4×10^{-4} Bq/g] of cesium-137 is estimated to be 0.012 mrem (0.12 mSv)/yr.

The dose estimate was derived using a cesium-137 ingestion dose factor of 4.8×10^{-5} mrem/pCi (1.3×10^{-2} mSv/Bq) from ICRP Publication 72 (ICRP 1995) in the following manner:

$$0.0065 \text{ pCi cesium-137/g} \times 40 \text{ kg} \times 1{,}000 \text{ g/kg} \times 4.8 \times 10^{-5} \text{ mrem/pCi} = 0.012 \text{ mrem (0.12 mSv)/yr}$$

4.2.4.2 Hanford Site Drinking Water Dose

Drinking water was sampled and analyzed for tritium, strontium-90, gross alpha radiation, and gross beta radiation during 2015 in accordance with applicable regulations (40 CFR 141); water samples were collected from the 100-K Area, 200-West Area, and two sources in the 400 Area. The water supply for the

100-K and 200-West Areas is the Columbia River, whereas the primary and backup water supplies for the 400 Area are groundwater wells (see Section 7.1).

A comparison of analytical results for the 100-K, 200 Area, and 400 Area drinking water samples to state and federal standards is provided in Section 7.1. Tritium and strontium-90 are both man-made soluble beta radiation emitters; there are also naturally occurring beta emitters in the uranium, actinium, and thorium decay series. Potential on-site drinking water dose from Hanford-related beta-emitting radionuclides is addressed in this section by evaluating drinking water data for tritium and strontium-90.

Strontium-90 was analyzed in one sample from each of the four drinking water sources in 2015 and was not identified above its analytical detection limit in any drinking water sample. Tritium was analyzed in one sample from both the 100-K and 200-West Areas and was not detected above its analytical detection limit in either sample. Tritium was detected in all four drinking water samples collected from the primary drinking water sources for the 400 Area (well P-16) and also in the single sample from backup well P-14. Based on the four quarterly samples from the primary well, the annual average 400 Area drinking water tritium concentration was 1,275 pCi/L (47 Bq/L). Assuming a consumption rate of 0.26 gal (1 L)/day for 250 working days at the FFTF in the 400 Area, the potential annual worker dose in 2015 would be approximately 0.21 mrem (0.21 mSv). A single tritium sample was also collected from Well P-14 in the 400 Area, where a value of 13,000 pCi/L was reported. Based on this single measurement, an annual worker drinking water dose for water obtained exclusively from this backup supply well would be 0.22 mrem (2.2 mSv). These estimates are well below EPA's drinking water dose limit of 4 mrem (40 mSv)/yr for beta-emitting radionuclides in public drinking water supplies.

The dose estimates were derived using a tritium ingestion dose factor of 6.7×10^{-8} mrem/pCi (1.8×10^{-5} mSv/Bq) from ICRP Publication 72 (ICRP 1995) in the following manner:

$$1{,}275 \text{ pCi tritium/L} \times 1 \text{ L/day} \times 250 \text{ d/year} \times 6.7 \times 10^{-8} \text{ mrem/pCi} = 0.021 \text{ mrem/yr}$$

4.2.4.3 Manhattan Project National Historical Park Visitor Dose

The Manhattan Project National Historical Park at Hanford includes guided tours of the B Reactor as well as access to several pre-Manhattan Project locations, two of which (Hanford Townsite and White Bluffs Bank) are situated to the east of 100-K and the 200 Area. These historical locations are geographically closer to these air emissions sources than the off-site MEI locations evaluated in Section 4.2.1. However, unlike an off-site residential MEI receptor, visitors to these locations would not be exposed from agricultural and drinking water exposure pathways, nor would they be continually exposed over the course of a year, as might be anticipated for some residents. For these reasons, potential doses at these locations are likely to be considerably below those calculated for the hypothetical off-site MEI.

Inhalation dose related to 100-K and 200 Area stack emissions was calculated for a hypothetical individual at the Hanford Townsite and White Bluffs Bank locations using the GENII Version 2 computer code. Although Historical Park visitors would be present only briefly and on a single occasion at these locations, individuals conducting tours could be present for greater lengths of time. Additionally, these locations are adjacent to the Columbia River where recreationalists might be exposed while boating, fishing, or engaged in other activities. For this screening calculation, continuous exposure at the Hanford Townsite and White Bluffs Bank locations was assumed. The results of these dose calculations are presented in Table 4.4.

Table 4.4. Annual Doses for a Hypothetical Individual at the Hanford Townsite and White Bluffs Bank Locations (2015)

Release Type	Exposure Pathway	Location	Dose Contributions from Operational Areas, mrem* 100 Areas	200 Areas	Pathway Total
Air	Inhalation	Hanford Townsite	4.2E-05	1.7E-04	2.1E-04
		White Bluffs Bank	2.0E-04	1.4E-04	3.4E-04

*To convert mrem to International System dose units (mSv), multiply by 10.

Radiological doses assuming continuous inhalation exposure at either the Hanford Townsite or White Bluffs Bank locations are far below the hypothetical off-site MEI air pathways dose of 0.15 mrem (1.5 mSv; Table 4.2) at Horn Rapids Road.

4.2.5 Doses from Non-U.S. Department of Energy Sources

Doses from non-DOE sources were not quantified in 2015 because the MEI dose of 0.33 mrem (3.3 mSv)/yr from DOE-related sources (section 4.2.1) was far below the threshold of 25 mrem (250 mSv)/yr at which the contribution of non-DOE sources must be included. DOE O 458.1 paragraph 4.e.(1)(c) states that dose evaluations to demonstrate compliance with the public dose limit must include:

> [t]he dose to members of the public from DOE-related exposure sources only, if the projected DOE-related dose to the representative person or MEI is 25 mrem (250 mSv) in a year or less. If the DOE-related dose is greater than 25 mrem (250 mSv) in a year, the dose to members of the public must include major non-DOE sources of exposure and dose from DOE-related sources.

Before it was superseded by the release of DOE O 458.1 in 2011, DOE O 5400.5 provided the applicable requirements for radiation protection of members of the public. Chapter II, Paragraph 7 of DOE O 5400.5, Chg 2 has a reporting requirement for a combined dose due to DOE and other manmade sources. Therefore, Hanford Site environmental reports prior to 2011 routinely evaluated dose contributions from various non-DOE industrial sources of radiation exposure on or near the Hanford Site. These included a commercial, low-level radioactive waste burial ground at the Hanford Site operated by Ecology; a nuclear power-generating station at the Hanford Site operated by Energy Northwest; a nuclear-fuel production plant operated near the site by AREVA NP, Inc.; a commercial, low-level radioactive waste treatment facility operated near the site by Perma-Fix Northwest, Inc.; and a commercial decontamination facility operated near the site by PN Services (Figure 4.2). The total individual dose from non-DOE source activities in 2010 was conservatively estimated at about 0.004 mrem (0.04 mSv)/yr (PNNL-20548).

4.2.6 Dose to Non-Human Biota

Dose assessments for non-human biota evaluate the potential for exposures from Columbia River sediment and water, soils (near facilities and off site), and exposures associated with West Lake. Upper estimates of the radiological dose to aquatic organisms were made in accordance with the DOE O 458.1 interim requirement for management and control of liquid discharges and air emissions. The current dose limit for aquatic animal organisms is 1 rad (10 milligray [mGy]) per day. Rad is a unit of absorbed dose of ionizing radiation equal to an energy of 100 ergs/g of irradiated material. In addition to the dose limit for aquatic organisms there is a dose limit for riparian or terrestrial wildlife of 0.1 rad (1 mGy)/day.

Concentration guides for assessing doses to biota are very different from the DOE-derived concentration standards used to assess radiological doses to humans. A tiered approach is used to estimate radiological

doses to aquatic and terrestrial biota. This method uses the RESidual RADioactive (RESRAD)-BIOTA computer code (DOE/EH-0676, *User's Guide, Version 1, RESRAD-BIOTA: A Tool for Implementing a Graded Approach to Biota Dose Evaluation*; DOE-STD-1153-2002, *A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota*) to compare radionuclide concentrations measured by routine monitoring programs to a set of biota concentration guides.

Biota concentration guides are the soil, water, or sediment concentrations of a radionuclide that would produce 1 rad (10 mGy)/day for aquatic biota or terrestrial plants or 0.1 rad (1 mGy)/day for riparian or terrestrial wildlife. For samples containing multiple radionuclides, a sum of fractions is calculated to account for the contribution to dose from each radionuclide relative to the dose limit. If the sum of fractions exceeds 1.0, then the dose limit has been exceeded. If the initial estimated screening value (Tier 1) exceeds the guideline (sum of fractions more than 1.0), additional screening calculations are performed (Tier 2 or Tier 3) to evaluate more accurately exposure of the biota to the radionuclides. The process may culminate in a site-specific assessment requiring additional sampling and study of exposure. Biota-dose screening assessments were conducted using surveillance data collected in 2015 from on and around the Hanford Site.

Researchers used the RESRAD-BIOTA computer code to evaluate potential effects on biota from the maximum concentrations of radionuclides measured in Columbia River sediment and water as tabulated in Appendix C. The detected radionuclides evaluated across all locations in the Columbia River sediment and water biota dose assessment are carbon-14, cobalt-60, cesium-137, plutonium-238, plutonium-239/-240, strontium-90, technetium-99, tritium, uranium-234, uranium-235, and uranium-238. Potassium-40 was also detected in sediments upstream, on site, and downstream of the Hanford Site. Potassium-40 is a naturally occurring radionuclide and is not associated with releases from the reactors or any groundwater plumes entering the Columbia River. Therefore, dose associated with potassium-40 is not included in the biota dose assessment. Most of the locations located on the Columbia River had samples collected from riverbank springs or seeps that carry groundwater contaminants into the Columbia River. Concentrations in springs or seeps are greater than those observed in the river water; therefore, the dose assessment results for these discrete areas of elevated concentrations are protective relative to the potential for impacts on populations of biota in the Columbia River. For an initial screen of ecological populations, the sediment and water data were split into five subareas: upstream, 100 Areas, Hanford Townsite, 300 Area, and downstream and the maxima concentrations evaluated in these locations. If risks to biota were identified in the initial screen, then further assessments using average concentration over smaller spatial units would be evaluated. The results of the screening calculations listed in Table 4.5 show the concentrations in all Columbia River sediment and water samples passed the Tier 1 screen and indicate that the calculated doses were below dose limits (sum of fractions less than one). Most of the estimated dose in the 100 Areas is from carbon-14 (89%) and strontium-90 (9%) and dose in the 300 Area is basically entirely associated with uranium isotopes. Biota doses upstream at the Hanford Townsite and downstream were all similar and likely related to background concentrations in water and sediment. Further documentation of the Columbia River biota dose calculations is provided in Appendix D.

Table 4.5. Estimated Doses to Biota Associated with Columbia River Sediment and Water*

Location	Media Sampled for Key Radionuclides†	Tier 1 Screen Sum of Fractions‡	Pass or Fail
Upstream	Sediment, Water	0.015	Pass
100 Areas	Sediment, Water	0.64	Pass
Hanford Townsite	Sediment, Water	0.016	Pass
300 Area	Water	0.30	Pass
Downstream	Sediment, Water	0.016	Pass

*Using RESRAD-BIOTA computer code, a screening method to estimate radiological doses to aquatic and riparian biota.
†A sum of fractions is calculated to account for the contribution to dose from each radionuclide. If the sum of fractions exceeds 1.0, then the dose guideline has been exceeded and further screening (Tier 2 or 3) is required. The sum of fractions has been rounded to two figures with a maximum of three decimal points. Maximum concentrations and the Biota Concentration Guides are presented in Appendix D.
‡The biota dose assessment requires concentration data for both sediment and water. If one of these media is not measured then it is estimated by using the default water to sediment partition coefficient. If water was measured, then sediment was estimated from water and if sediment was measured then water was estimated from sediment. In some cases where both sediment and water were measured a radionuclide was only measured in one medium (e.g., tritium in water), and the concentration for that radionuclide in the other medium was estimated. See Appendix D for details on what was measured.

Biota dose calculations also were completed for West Lake, located on the Central Plateau of the Hanford Site. West Lake is a vernal pool or ephemeral wetland that fills with water during the winter and generally becomes smaller or dries up entirely in other seasons. West Lake is part of the 200 Area Unplanned Release Waste Group Operable Unit (200-UR-1 Operable Unit), and is planned for supplemental characterization (DOE/RL-2009-121, *Sampling and Analysis Plan for the West Lake Site*). The results of these planned investigations will be presented in the appropriate CERCLA remedial action document for the 216-N-8 waste site. In parallel with these planned CERCLA studies, this program has been collecting sediment data annually. In addition, other media (water and biota) have been collected from West Lake on a less regular schedule. Both sediment and water samples were collected in 2015 and data tabulated (Appendix C, Tables C.2, C.3, and C.4).

The results of the 2015 screening calculations listed in Table 4.6 show the West Lake sediment and water concentrations failed the Tier 1 and 2 screens. The Tier 1 screen was based on the maximum concentration, and the Tier 2 screen was based on the average concentrations of five water and three sediment samples. The estimated biota dose for Tiers 1 and 2 was almost entirely due to the measured concentration of uranium in water and the assumed potential for uptake from water to aquatic biota using a default bioaccumulation factor.

Table 4.6. Estimated Doses to Biota Associated with West Lake*

Tier	Exposure Assumptions	Sum of Fractions† 2014	Sum of Fractions† 2015	Pass or Fail
1	Maximum Sediment, Water Concentration and Default Bioaccumulation	62	16	Fail
2	Average Sediment, Water Concentration and Default Bioaccumulation	31	3.7	Fail
3	Average Sediment, Water Concentration and Site-specific Bioaccumulation	0.34	0.05	Pass

*Using RESRAD-BIOTA computer code, a screening method to estimate radiological doses to aquatic and riparian biota.
†A sum of fractions is calculated to account for the contribution to dose from each radionuclide. If the sum of fractions exceeds 1.0, then the dose guideline has been exceeded and further screening (Tier 2 or 3) is required.

The RESRAD-BIOTA default bioaccumulation factor for uranium isotopes from water to aquatic biota is 1,000. This means that the concentration in tissues would be 1,000 times that measured in water. Site-specific data from West Lake support a much lower uranium bioaccumulation factor. Aquatic biota

(only brine flies have been sampled, and they are also the most relevant organisms) and water were sampled concurrently in 2000 and 2007 (PNNL-13487, *Hanford Site Environmental Report for Calendar Year 2000*; DOE/RL-2007-50, *Central Plateau Ecological Risk Assessment Data Package Report*). The maximum concentration of any of the uranium isotopes in brine flies was 0.77 pCi/g for uranium-233/-234 in 2007. The minimum uranium-233/234 water concentration was 940 pCi/L in 2007. The bioaccumulation factor is calculated by dividing the biota concentration (in pCi/g) by the water concentration (in pCi/ml); therefore, the maximum bioaccumulation factor for uranium would be less than one. A bioaccumulation factor of one was used for the Tier 3 biota dose calculation as a somewhat protective measure of site-specific uranium uptake into the food chain. The Tier 3 biota dose calculations resulted in sum of fractions less than one, indicating that the calculated doses were below dose limits related to the biota concentration guides. This result was similar to those calculated for 2012, but the 2014 doses were about 10 times greater than those calculated for 2013 (Table 4.6). The reason is that the maximum concentrations in West Lake pond water samples varied quite widely, and isotopic uranium is typically detected in West Lake pond water. The last 3 years of concentrations were 2013 (uranium-234 at 256 pCi/L, uranium-235 at 13.8 pCi/L, uranium-238 at 250 pCi/L); 2014 (uranium-234 at 6,580 pCi/L, uranium-235 at 248 pCi/L, uranium-238 at 6,380 pCi/L); and 2015 (uranium-234 at 1,650 pCi/L, uranium-235 at 87.1 pCi/L, uranium-238 at 1,570 pCi/L). The maximum concentration measured in 2014 was about 25 times greater than that measured in 2013. Further documentation of the West Lake biota dose calculations, including the Tier 3 Biota Concentration Guides, is provided in Appendix D.

Biota dose calculations were implemented for terrestrial biota based on exposures to soils collected on and distant to the Hanford Site. The RESRAD-BIOTA computer code evaluates potential effects on biota from the maximum concentrations of radionuclides measured in near field and far field soil samples as tabulated in Appendix C. The radionuclides evaluated in soil are cesium-137, plutonium-238, plutonium-239/-240, and strontium-90. The results of 2015 screening calculations listed in Table 4.7 show the near- and far-field soil concentrations passed the Tier 1 screen, based on the maximum concentration. Basically, the entire estimated dose for near-field locations is from cesium-137 (94%) and strontium-90 (6%). Biota doses at far field locations are likely related to background concentrations in soil. For a long-term trend in soil concentrations and associated biota doses on and off the Hanford Site, see PNNL-20577.

Table 4.7. Estimated Doses to Terrestrial Biota Associated with On- and Off-site Soil*

Location	Tier 1 Screen Sum of Fractions†	Pass or Fail
Near field	0.72	Pass
Far field	0.024	Pass

*Using RESRAD-BIOTA computer code, a screening method to estimate radiological doses to aquatic and riparian biota.
†A sum of fractions is calculated to account for the contribution to dose from each radionuclide. If the sum of fractions exceeds 1.0, then the dose guideline has been exceeded and further screening (Tier 2 or 3) is required. The sum of fractions has been rounded to two figures with a maximum of three decimal points. Maximum concentrations and the Biota Concentration Guides are presented in Appendix D.

In addition to the dose assessments related to soils, sediments, and water, there are also fish and wildlife collected from the Hanford Site and reference locations. Although none of the biota dose assessments (except for West Lake) required any additional tiers of analyses, these supplemental calculations characterize more realistic doses based on measured concentrations. Dose to aquatic animals based on the maximum concentrations of carbon-14 (192 pCi/g), cesium-137 (7.48 pCi/g), and strontium-90 (0.835 pCi/g) in clams was 0.0009 rad/day. Dose to aquatic animals based on the maximum concentrations of cesium-137 (0.0145

pCi/g), uranium-234 (0.00055 pCi/g), uranium-235 (0.000272 pCi/g), and uranium-238 (0.000422 pCi/g), in fish was 0.00003 rad/day. Internal dose to terrestrial plants based on the maximum concentrations of cesium-137 (0.12 pCi/g), plutonium-238 (0.0014 pCi/g), plutonium-239 (0.0033 pCi/g), and strontium-90 (1.4 pCi/g) in plants was 0.0001 rad/day. Dose to terrestrial animals based on the maximum concentrations of strontium-90 (0.169 pCi/g) in rabbit bone was 0.00007 rad/day. Using the measured tissue data leads to lower doses then using the default bioaccumulation information assumed in the Tier 1 RESRAD-Biota calculations.

4.2.7 Radiological Dose in Perspective

The dose for the MEI in 2015 was 0.21 mrem (2.1 mSv; section 4.2.1). The average individual dose from Hanford Site operations in 2015, based on the 50-mi (80-km) radius population exposed to air emissions and the Tri-Cities populations exposed to water pathways releases to the Columbia River, was approximately 0.0058 mrem (0.058 mSv). To place the MEI and average individual estimated doses into perspective, the estimated doses may be compared with doses received from other routinely encountered sources of radiation. The NCRP issued a report in March 2009 estimating that the overall average exposure to ionizing radiation for the average American is 620 mrem (6,200 mSv) per year (NCRP 2009). Approximately 50% of the 620 mrem (6,200 mSv)/yr average annual dose is related to natural sources, with the remaining 50% attributable primarily to medical procedures.

The most relevant radiation sources for comparison to doses received from environmental media include natural terrestrial and cosmic background radiation, and inhalation of naturally occurring radon (Figure 4.7). Average annual individual background dose related to terrestrial radiation (19 mrem [190 mSv]), cosmic background radiation (30 mrem [300 mSv]), and radon (radon-222) and thoron (radon-220) gases (230 mrem [2,300 mSv]) are shown relative to Hanford Site operational doses in Figure 4.8. The calculated radiological doses from Hanford Site operations in 2015 were a small percentage of national average annual doses from these natural background sources. Note that annual dose is shown on a linear scale in Figure 4.8, and Hanford-related doses are too small to be observed. For example, the national annual average radiation dose from natural terrestrial sources (approximately 19 mrem [190 mSv]) is approximately 90 times larger than the 2015 Hanford Operations dose to the MEI receptor (0.21 mrem [2.1 mSv]).

Scientific studies (*Health Risks from Exposure to Low Levels of Ionizing Radiation, BEIR VII Phase 2* [National Research Council 2006]) have been performed to estimate the possible risk from exposure to low levels of radiation. These studies provide information to government and scientific organizations for use in recommending radiological dose limits and standards for public and occupational safety.

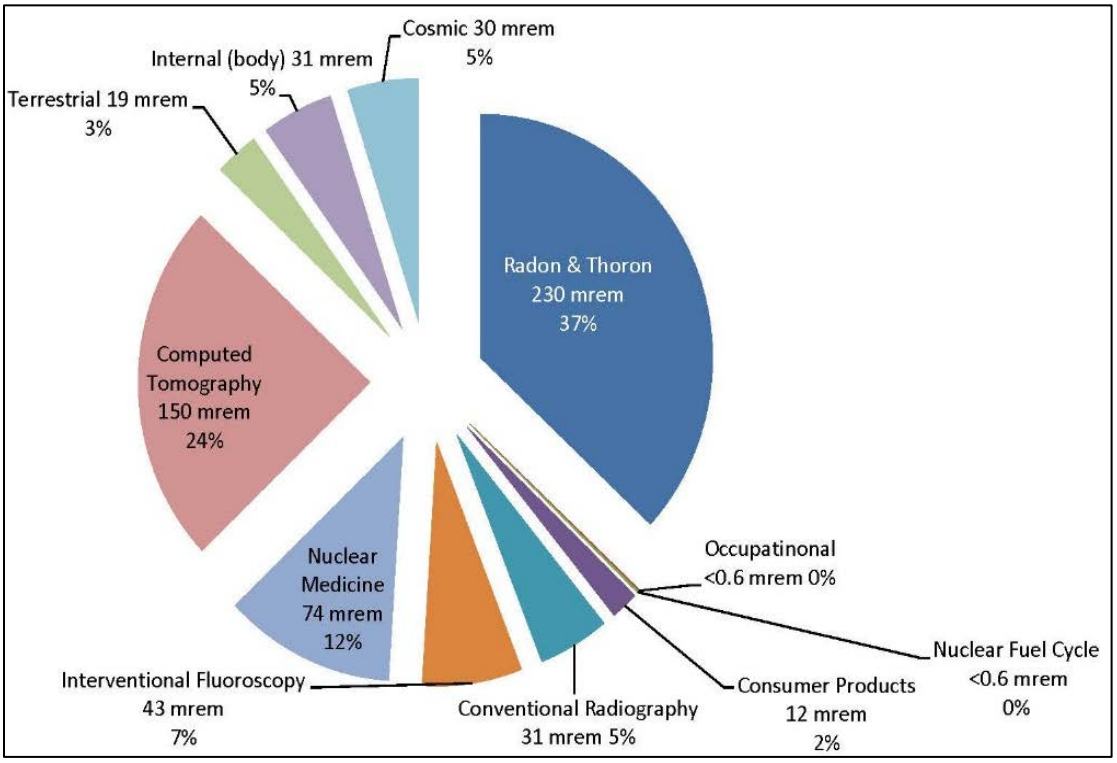

Figure 4.7. U.S. Annual Average Radiological Doses from Various Sources (2009 National Council on Radiation Protection and Measurements)

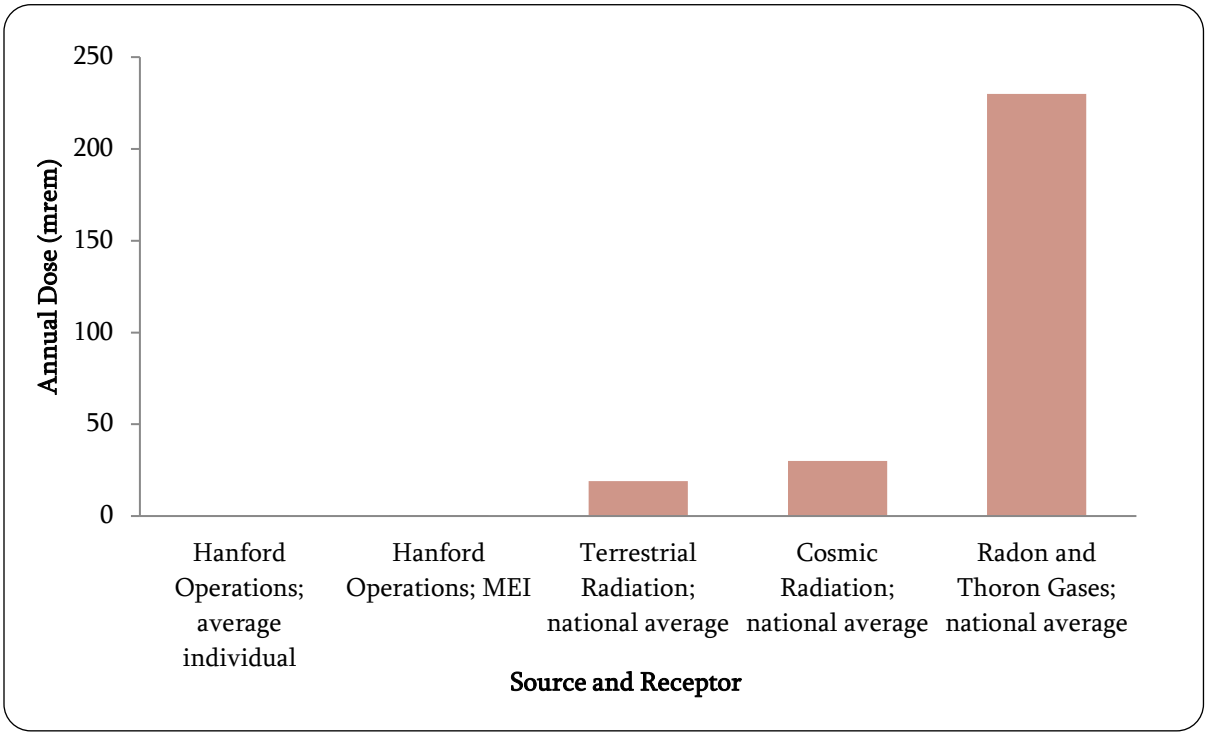

Figure 4.8. Radiological Doses from Hanford Site Operations Compared to Annual Average from Natural Sources

Although no increase in the incidence of health effects from low doses of radiation actually has been confirmed by the scientific community, regulatory agencies cautiously assume that the probability of these types of health effects occurring due to exposure to low doses (down to zero dose) is the same per unit dose as the health effects observed after an exposure to much higher doses (e.g., in atomic bomb survivors, individuals receiving medical exposure, or, historically, painters of radium dials). This concept is known as the "linear no-threshold" hypothesis. Under these assumptions, public exposure to radiation from current Hanford Site releases, exposure to natural background radiation (which is hundreds of times greater), and exposure to very high levels of radiation each increases an individual's probability or chance of developing a detrimental health effect (primarily cancer) proportional to the dose received.

Scientists do not fully agree on how to translate the available epidemiological data on health effects from high radiological doses into the numerical probability (risk) of detrimental effects from low radiological doses (UNSCEAR 2012, *Biological Mechanisms of Radiation Actions at Low Doses*). Some scientific studies have indicated that low radiological doses may result in beneficial rather than adverse effects (Calabrese 2009). Because cancer is a common disease in the general population and may be attributable to many other causes besides radiation (e.g., genetic defects, natural and man-made chemicals, natural biochemical body reactions), some scientists doubt that the risk from low-level radiation exposure can be proven conclusively. In developing *Clean Air Act* regulations, EPA used a probability of approximately 4 per 10 million (4×10^{-7}) for the risk of developing a fatal cancer after receiving a dose of 1 mrem (10 mSv; EPA 1989). Additional data support the reduction of even this small risk value, possibly to zero, for certain types of radiation when the dose is spread over an extended time (National Research Council 2006). Guidance from the Interagency Steering Committee on Radiation Standards (ISCORS; *A Method for Estimating Radiation Risk from TEDE* [ISCORS 2002]) recommends that agencies assign a risk factor of 6 per 10 million (6×10^{-7}) for developing a fatal cancer after receiving a dose of 1 mrem (10 mSv).

One approach for providing perspective on calculated risks related to low-dose radiation exposures is to compare them to risks involved in other typical activities. Table 4.8 compares the estimated risks from various radiological doses to the risks of some activities encountered in everyday life.

Table 4.8. Estimated Risk from Various Activities and Exposures

Activity or Exposure Per Year	Risk of Fatality
Home accidents	100×10^{-6}*
Firearms (sporting accidents)	10×10^{-6}*
Flying as an airline passenger (cross-country roundtrip – accidents)	8×10^{-6} *
Recreational boating (accidents)	6×10^{-6}*
Riding or driving 300 mi (483 km) in a passenger vehicle	2×10^{-6}*
Dose of 1 mrem (10 mSv) for 70 yrs	0 to 0.6×10^{-6}†
Natural background radiological dose (310 mrem [3,100 µSv]) for 70 yrs	0 to 200×10^{-6}†
Dose to hypothetical MEI (2015 rate) of 0.21 mrem (2.1 mSv)/yr living near Hanford Site for 70 yrs	0 to 0.1×10^{-6}†

*Real actuarial values.
†Upper bound calculated using 6×10^{-7} risk of developing a fatal cancer after receiving a 1 mrem (10 mSv) dose (ISCORS 2002).

4.3 Radiological Clearance of Hanford Site Property

JW DeMers

Principal requirements for the control and clearance of DOE property containing residual radioactivity are found in DOE O 458.1. These requirements are designed to ensure the following:

- Property is evaluated, radiologically characterized and, where appropriate, decontaminated before release
- Residual radioactivity level in property to be released is as near background levels as reasonably practicable as determined through DOE's ALARA process requirements and authorized limits
- All property releases are appropriately certified, verified, documented, and reported; public participation needs are addressed; and processes are in place to maintain appropriate records.

4.3.1 Radiological Clearance for Potentially Contaminated Personal Property with Hard-to-Detect Radionuclides

In the process of performing environmental remediation or related support activities, Hanford Site contractors encounter a wide variety of contaminated personal property, including consumables, office items, tools and equipment, and debris. Over 19,000 items of personal property were cleared from radiological areas on the Hanford Site; however, the majority of the items did not leave the Hanford Site. The personal property items primarily consisted of small items such as flashlights, hard hats, radios, cameras, pens, pencils, respiratory protection, radiological control instruments, and industrial hygiene instruments. All of these items met DOE O 458.1 clearance criteria and therefore did not require additional radiological controls post-survey. In January 2000, DOE issued a moratorium prohibiting the release of volume-contaminated metals, and subsequently suspended the release of metals for recycling purposes from DOE radiological areas in July 2000. As a result, no volume of contaminated metals or metals for recycling purposes were released from Hanford in 2015.

Final disposition of potentially contaminated personal property with hard-to-detect radionuclides depends on whether the property is considered radiologically contaminated, and whether the disposal of such property is subject to CERCLA requirements. Radiologically contaminated property is disposed at ERDF if subject to CERCLA requirements, and if not, at the CWC in the 200-West Area. Personal property that has contamination levels below approved DOE control and clearance guidelines (DOE O 458.1) are considered for release if the property can be reused. Hanford Site contractors routinely encounter a wide variety of radionuclide mixtures ranging from essentially pure plutonium to fission and activation products. Included in these fission and activation products are low-energy beta emitters, such as carbon-14, iron-55, nickel-59, nickel-63, selenium-79, technetium-99, palladium-107, and europium-155 that are difficult or impossible to detect with routine field-survey methods (i.e., hard-to-detect radionuclides).

Traditionally, field detectable or easy-to-detect radionuclides have been used as an analog for the entire mixture of radionuclides encountered during work activities. The control and release criteria (DOE O 458.1) have been adjusted downward to account for the portion of the activity that is not detectable by field survey methods. As the ratio of hard-to-detect radionuclides to easy-to-detect radionuclides increases, the criteria are reduced to a point where the adjusted limits are difficult or impossible to verify with field survey instruments. Decades of radioactive decay have reduced the contributions of easy-to-detect radionuclides to such low levels that current control and release methodologies are no longer sufficient for verifying that contaminant levels comply with the existing approved DOE property release guidelines in DOE O 458.1.

Accordingly, a request to DOE in May 2006 was submitted by WCH (DOE contractor for the River Corridor Closure Contract) to increase the release criteria (authorized limits) for hard-to-detect radionuclides. The requested authorized limits would apply only to beta-gamma surface contamination on potentially contaminated equipment and materials, and exclude volumetric contamination (contamination that is distributed throughout the volume of the property), contamination in or on persons, unrestricted release of

metals, and alpha-surface contamination. Detailed radiological analyses were performed to demonstrate these authorized limits would be protective of human health and the environment. Based on these analyses, the authorized limits would result in a dose of less than 1 mrem (10 mSv) in any year to the MEI and a collective dose of less than 10 person-rem (0.1 person-Sv) to any exposed population. These authorized limits (Table 4.9) were reviewed by RL and HQ personnel and approved for use by WCH in May 2007. In 2008, RL provided conditional approval to CHPRC and Fluor Hanford, Inc. to use these hard-to-detect authorized limits. In addition to this request, in 2013 CHPRC requested and was approved an authorized limit to apply the general beta-gamma limits to the low energy beta emitter, plutonium-241 (1,000 dpm/100 cm^2 removable limit and 5,000 dpm/100 cm^2 total contamination limit). In June 2009, WRPS submitted a request to ORP for approval to use these hard-to-detect authorized limits. ORP provided conditional approval for this request in June 2009. MSA submitted a request to RL in October 2009 for approval to use these hard-to-detect authorized limits. RL provided conditional approval for this request in November 2009.

Table 4.9. Approved Release Criteria (Authorized Limits) for Select Hard-to-Detect Radionuclides* for Residual Beta-Gamma Surface Contamination

Average	Maximum	Removable
50,000 dpm/100 cm^2	150,000 dpm/100 cm^2	10,000 dpm/100 cm^2

*Carbon-14, iron-55, nickel-59, nickel-63, selenium-79, technetium-99, palladium-107, and europium-155

4.3.2 Granular Activated Carbon for Offsite Shipment and Regeneration Radiological Clearance

Carbon tetrachloride was found in the unconfined aquifer beneath the 200 West Area in the mid-1980s. Groundwater monitoring indicated the carbon tetrachloride plume was widespread, and concentrations were increasing. An expedited response action was initiated in 1992 to extract carbon tetrachloride from the vadose zone in the 200-ZP-2 Operable Unit, currently designated as the 200-PW-1 Operable Unit, in the 200 West Area. The 200-PW-1 Operable Unit soil-vapor extraction system includes vapor-phase granular activated carbon canisters to remove carbon tetrachloride from the extracted vapors prior to discharge. This facility was in full operation by 1995.

Workers installed a groundwater pump-and-treat system in 1996 in a second operable unit (200-ZP-1 Operable Unit) to treat contaminated groundwater in the unconfined aquifer. The system includes an air-stripping unit that volatilizes carbon tetrachloride in the groundwater and then discharges the carbon tetrachloride vapors through granular activated carbon canisters that are identical to the large, carbon-steel granular activated carbon canisters in the 200-PW-1 Operable Unit soil-vapor extraction system.

Each of these systems uses granular activated carbon canisters to capture the volatile organic compounds removed during the extraction process. When a granular activated carbon canister has reached volatile organic compound saturation, it is removed from the system, and the granular activated carbon is prepared for shipment to an off-site facility for regeneration and reuse. Regeneration of the granular activated carbon requires heating it in a hearth furnace to remove the captured volatile organic compounds.

Based on past Hanford Site activities, and the results of characterization sampling, this granular activated carbon could contain residual radioactivity. Characterization sampling results were used to determine specific radionuclides of concern for this residual radioactivity. For any potential residual radioactivity, DOE O 458.1 requires that the residual radioactivity not exceed established guidelines or that radiological release criteria (i.e., authorized limits) be developed and submitted to the applicable DOE field office.

Following review by RL and HQ personnel in October 2008, approved authorized limits for offsite shipment and regeneration of granular activated carbon was approved for use by CHPRC.

In anticipation of placing the new 200-West Area Pump and Treat facility online, increasing the volume of spent granular activated carbon being sent off site, a request to modify the authorized limits was made by CHPRC and approved by DOE in October 2010 (Table 4.10). This modification to the authorized limits does not change the expected dose to the public.

Table 4.10. Approved Modified Authorized Limits for Off-site Shipment and Regeneration of Granular Activated Carbon

Radionuclide	Authorized Limit (pCi/g)
Americium-241	29
Carbon-14	3,000
Cesium-137	80
Cobalt-60	21
Europium-152	40
Europium-154	40
Europium-155	700
Iodine-129	50
Neptunium-237	50
Nickel-63	100
Plutonium-238	26
Plutonium-239	24
Plutonium-240	24
Protactinium-231	10
Selenium-79	2,000
Strontium-90	100
Technetium-99	500
Thorium-232 plus progeny	6
Tritium	300,000
Uranium-234	100
Uranium-235	100
Uranium-238 plus short-lived progeny	100

Approximately 150,000 lbs (68,000 kg) of granular activated carbon was shipped off site in 2015 for regeneration under these approved modified authorized limits.

4.3.3 Tri-Cities Development Council (TRIDEC) Land Conveyance

The DOE O 458.1 authorized limits for radiological release of proposed land conveyance to TRIDEC were approved in December 2013. In 2015, field work was completed, and sample and survey results determined that authorized limits were met. Independent verification contractor Oak Ridge Associated Universities completed verification field and close-out activities. In 2015, approximately 1,640 ac (664 ha) were cleared and transferred to the local community reuse organization for development.