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PNNL-30466

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September 2020

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Richland, Washington 99354

Summary

Low-energy beta-emitting radionuclides that were released historically during reactor operations and plutonium separations activities at some U.S. Department of Energy sites have migrated into the groundwater, forming contaminant plumes that are subject to federally regulated remediation actions. At the Hanford Site, the low-energy beta-emitting radionuclides include iodine-129, technetium-99, chlorine-36, carbon-14, and tritium (H-3). All are highly mobile in the subsurface, and except for tritium, and have very long half-lives—thousands to millions of years. The geochemistry and transport behavior of these contaminants in the subsurface present significant challenges for remediation of groundwater to federal drinking water standards (DWS)—the appropriate or relevant and applicable requirements (ARARs) for cleanup. For some of the low-energy beta-emitter contaminants, particularly iodine-129, cleanup and restoration of groundwater to DWS may not be attainable within a reasonable timeframe using currently available treatment technologies.

When restoration of groundwater to DWS cannot be attained in a reasonable timeframe, risk-based cleanup levels and risk-informed prioritization are potential approaches for managing remediation. Assessing the human health risks associated with contaminants in the environment is one of the first steps in identifying the scope and need for environmental remediation and the results can be used in forming risk-based cleanup levels and making risk-informed decisions. At sites falling under the Comprehensive Environmental Response, Compensation, and Liability Act[1] such as Hanford, the U.S. Environmental Protection Agency requires that cleanup should generally achieve a level of risk within the 10^{-4} to 10^{-6} carcinogenic risk range based on the reasonable maximum exposure for an individual.

The current U.S. standards for low-energy beta radioisotopes in drinking water are based on health parameters for dose and risk that were developed more than 50 years ago and are now considered conservative with respect to human health impacts. The federal DWS[2] for low-energy beta emitting radionuclides are derived concentrations based on limiting the annual cumulative dose equivalent for anthropogenic beta particles to less than 4 mrem/y to the total body or any internal organ to be protective of human health (assuming a 2 L/day water intake for adults). The 4 mrem/y cumulative dose is determined using the methodology and assumptions published in the National Bureau of Standards Handbook 69, which was last revised in 1963.[3] During the past 50 years, the science of health physics has advanced, and the recommended parameters and assumptions for calculating and evaluating dose and risk to humans have been updated. This report provides a summary and evaluation of how advancements in the understanding of health physics and the recommended changes for dose and risk calculations impact estimates of dose and human health risk from the five low-energy beta emitting radionuclides in groundwater.

As part of this evaluation, the dose and risk for each of the five low-energy beta radionuclides were estimated for a resident tap water scenario with the following exposure pathways to groundwater sourced from a well: drinking water ingestion, irrigated crop ingestion, inhalation, and immersion. The dose and risk for each low-energy beta-emitting radionuclide were calculated based on the original Handbook 69 dose coefficients and methods and compared with dose and risk values estimated using updated recommendations. These comparisons allow consideration of how updated information on dosimetry,

[1] CERCLA.1980. Comprehensive Environmental Response, Compensation, and Liability Act. Public Law 96-510 (December 11) 94 Stat.2808 as amended (U.S. Government Printing Office, Washington DC.

[2] 40 CFR 141.16 - Maximum contaminant levels for beta particle and photon radioactivity from man-made radionuclides in community water systems. Code of Federal Regulations July 1, 2002

[3] NBS 1963—National Bureau of Standards, Handbook 69, Addendum 1 to Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure. Originally issued in 1959 by U. S. Department of Commerce.

effective dose, and biokinetics affect the magnitude of dose and risk for each contaminant. Comparisons include estimates of the derived concentration that would yield a 4 mrem/y cumulative dose for each contaminant and the concentration that would result in 10^{-4} risk level. These results can be used in management strategies for CERCLA evaluations where the cleanup and restoration of groundwater to DWS may not be attainable within a reasonable timeframe using currently available treatment technologies.

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Acknowledgments

We would like to thank Kitt Bagwell for his technical review of the report and suggestions. Thanks are also extended to Mary Hartman and Margo Aye of CH2M Hill Plateau Remediation Company for providing access to groundwater plume data for the Hanford Site. Technical review and insights received from Margaret MacDonell of Argonne National Laboratory are also very much appreciated.

Glossary

aquifer	Groundwater-bearing subsurface material
becquerel	1 disintegration per second (dps), or ~27 pCi
beta-emitting radioisotope	An isotope that emits a beta particle (β^- or β^+) during radioactive decay
beta particle	A high-energy, high-speed electron or positron emitted during radioactive decay
biokinetics	
carcinogen	Any substance, radionuclide, or radiation that promotes carcinogenesis, or the formation of cancer
Central Plateau	The 200 Area of the Hanford Site
consent order	A legal document that confirms agreement between two or more parties
curie	$2.22 \times 10^{+12}$ disintegrations per minute (dpm), or 37 giga becquerels (GBq)
dose equivalent, H	The product of D and Q at a point in tissue, where D is the absorbed dose and Q is the quality factor for the specific radiation at this point, thus: H =DQ. The unit of dose equivalent is joule per kilogram (J kg_1), and its special name is sievert (Sv).
effective dose, *E*	The tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression: $E = \sum w_T \sum w_R D_{T,R}$ where H_T or $w_R D_{T,R}$ is the equivalent dose from radiation R in a tissue or organ T, and w_T is the tissue weighting factor. The unit for the effective dose is the same as for absorbed dose, J kg^{-1}, and its special name is sievert (Sv).
equivalent dose, HT	The dose in a tissue or organ T given by: $H_T = \sum_R w_R D_{T,R}$ where $D_{T,R}$ is the mean absorbed dose from radiation R in a tissue or organ T, and w_R is the radiation weighting factor. Since w_R is dimensionless, the unit for the equivalent dose is the same as for absorbed dose, J kg_1, and its special name is sievert (Sv).
gamma radiation	Penetrating electromagnetic radiation arising from radioactive decay
half-life	The time required for the radioactivity of an isotope to fall to half its original value
millirem	One one-thousandth of a rem
operable unit	Within a complex site, a distinct area with respect to geography, problems, or medium (e.g., groundwater, soil) where a specific action is required

photon	A high-energy particle emitted during gamma decay of a radioactive isotope
pico-curie (pCi)	1 curie x 10^{-12}, or 2.22 dpm
radionuclide	An atom that emits radioactivity
rem (Roentgen equivalent man)	A unit of absorbed dose equal to 0.01 sievert (Sv)
risk	The chance of harmful effects to human health or to ecological systems
River Corridor	The Hanford areas adjacent to the Columbia River
sievert	A measure of the health effect of low levels of ionizing radiation on the human body equivalent to 100 rem
Tri-Party Agreement	A comprehensive Hanford cleanup and compliance agreement between U. S. Department of Energy, U. S. Environmental Protection Agency, and the Washington State Department of Ecology

Acronyms and Abbreviations

ARAR	appropriate or relevant and applicable requirement
BSS	Basic Safety Standards
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CHPRC	CH2M Hill Plateau Remediation Company
CEU	Council of the European Union
DCS	Derived Concentration Standards
DOE	U.S. Department of Energy
DWS	drinking water standards
ede	effective dose equivalent
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
GAO	General Accounting Office
GWIA	groundwater interest area
HEAST	Health Effects Assessment Summary Tables
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ID	indicative dose
MCL	maximum concentration level
NBS	National Bureau of Standards
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NRC	Nuclear Regulatory Commission
NCRP	National Council on Radiation Protection and Measurements
OIR	Occupational Intakes of Radionuclides
OSHA	Occupational Safety and Health Administration
OU	operable unit
P&T	pump and treat
RAIS	Risk Assessment Information System
RCRA	Resource Conservation and Recovery Act
ROD	Record of Decision
SAB	Science Advisory Board (EPA)
SDWA	Safe Drinking Water Act
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization
WMA	waste management area

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1.0 Introduction

Low-energy beta-emitting radioisotopes resulting from past nuclear production operations are found as contaminants in groundwater at several U.S. Department of Energy (DOE) sites, including Hanford, Savannah River, Idaho National Laboratory, and others. Risk-based cleanup levels and risk-informed prioritization are potential approaches for managing remediation of this contamination. An evaluation was conducted to examine these approaches using the case of low-energy beta-emitters in groundwater at Hanford. At the Hanford Site, low-energy beta-emitting radioisotopes in groundwater include iodine-129, technetium-99, chlorine-36, carbon-14, and tritium (H-3). These contaminants, except tritium, have long half-lives—thousands of years—and all these radioisotopes are highly mobile in the subsurface. Federal drinking water standards (DWS) are the appropriate or relevant and applicable requirements (ARARs) used to set the current cleanup levels for the low-energy beta radioisotopes in groundwater at Hanford, as specified by the Comprehensive Environmental Response, Compensation, and Liability Act (42 U.S.C. §9601). Cleanup and restoration of groundwater to federal DWS for some of the low-energy beta-emitter contaminants present significant challenges.

This evaluation focuses on review and discussion of the latest science-based approaches that may be appropriate to apply when evaluating protectiveness for environmental management and remediation. The current U.S. standards for low-energy beta radioisotopes in drinking water are based on health parameters developed more than 50 years ago that are now shown to be conservative with respect to health impacts. Updated information on dosimetry, effective dose, and biokinetics can be implemented to develop a risk-based approach to evaluating protectiveness for environmental management of low-energy beta radioisotopes in groundwater. For this report, “risk” is defined in terms of the probability and adverse consequences to human health.

The intent of this evaluation is to provide defensible information about science-based protectiveness criteria that may be appropriate for use in risk management strategies, consistent with applying risk-informed decisions. As management strategies are developed, considering risk-based protectiveness can aid in targeting resources to mitigate risks and help determine cost-effective remedial approaches as part of risk-informed remedial decision-making. DOE is required to follow certain laws, agreements, federal guidelines, and court decisions [e.g., CERCLA, Resource Conservation and Recovery Act (RCRA), and Tri-Party agreements with the U.S. Environmental Protection Agency (EPA) and states] that establish standards, procedures, or requirements for DOE’s cleanup mission. A recent report by the General Accounting Office (GAO 2019) notes that several organizations—including the DOE Inspector General and GAO—have recommended that DOE adopt a risk-informed approach to making cleanup decisions. Specifically, the report recommends that DOE adopt a decision-making approach that considers trade-offs among risks to human health and the environment, cost, and other factors in the face of uncertainty and diverse stakeholder perspectives. Although DOE currently does not have a framework for implementing the requirements and guidance to make cleanup decisions in a risk-informed manner (GAO 2019), development of a risk-based protectiveness approach for low-energy beta radioisotopes is an important step toward use of risk-informed decisions in remediation of these contaminants.

The objectives of this evaluation are as follows:

- Describe and evaluate the technical bases for developing risk-based cleanup levels that are protective of human health and the environment for low-energy beta radioisotopes and evaluate technical gaps.
- Document the range of national and international health parameters used to calculate dose and assess risk.

- Calculate and compare risk-based cleanup levels based on current federal and international regulations governing dose limits and human-health risk.
- Demonstrate technical advantages to a risk-based approach for low-energy beta radioisotopes with relevant analyses at Hanford.

Within this report, Section 2.0 provides background information on the extent of low-energy beta radioisotopes in groundwater at Hanford and summarizes the current remediation approaches. Section 3.0 provides an overview of national and international radiation protection guidelines with respect to regulatory targets and human health risks. The pathway-specific dose and human health risks associated with these five low-energy beta radioisotopes are evaluated and summarized in Section 4.0:

- Section 4.1 describes the history and evolution of dosimetry and how radiation protection recommendations have changed over the past 60 years to reflect scientific advances
- Section 4.2 describes the assumptions and parameters for the Resident Tap Water Scenario, which is applied to determine the pathway-specific and total human health dose and risk for each of the five radionuclides
- Section 4.3 provides the pathway-specific and total dose and risk calculated for each radionuclide using the Resident Tap Water Scenario and compares these values with current ARARs for the remediation of groundwater at Hanford.

These sections are followed by summary and conclusions in Section 5.0, references in Section 6.0, and supporting information on dose and risk coefficients in Appendix A.

2.0 Background

Under CERCLA at Hanford, DOE has entered into a federal facility agreement and consent order with EPA and the Washington State Department of Ecology—termed the Tri-Party Agreement (DOE, Ecology, and EPA 2017). DOE must consider the state's position and key concerns related to the cleanup approaches and the state's comments on requirements that are applicable or relevant and appropriate into its selection of a cleanup approach. CERCLA and the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (40 CFR Part 300) specify the following:

- Remediation goals shall be protective of human health and the environment and shall be developed with federal and state drinking water standards established under the Safe Drinking Water Act specified as ARARs for remediation of groundwater that is or could be a potential source of drinking water and considering the ARARs established under other federal or state environmental laws.
- The lifetime cancer risk calculated from all substances and all exposure pathways for known or suspected carcinogens, including radionuclides, shall have an upper bound between 10^{-6} to 10^{-4} risk level.

Based on the anticipated yield and natural water quality, the State of Washington has determined that the aquifer setting for Hanford groundwater meets the Washington Administrative Code 173-340-720 definition for potable groundwater. This is the highest beneficial use definition for potable groundwater and protection of drinking water (excluding other uses such as irrigation). Under EPA's groundwater classification program, Hanford groundwater would be designated Class II-B, which is groundwater that is not a current source of drinking water but is a potential future source (EPA 1992). Federal and Washington state DWS for low-energy beta emitters are equivalent and are used to set the current cleanup levels for the low-energy beta radioisotopes in groundwater at Hanford.

The federal DWS (40 CFR 141.16) are derived concentrations based on limiting the annual cumulative dose equivalent for anthropogenic beta particles to less than 4 mrem to the total body or any internal organ to be protective of human health. This limit was established by the National Interim Primary Drinking Water Regulations (EPA 1976) and became effective in 1977. The estimated concentration for each of the low-energy beta emitters at Hanford that would yield a 4 mrem/y dose based on 2-L per day water intake (i.e., used to derive an equivalent DWS) is shown in Table 2.1 along with characteristics of the radionuclides.

Table 2.1. Characteristics of Low-Energy Beta Radioisotopes at Hanford and Current Federal Drinking Water Standards (Peterson et al. 2007)

Isotope	Half-life (y)	Natural Abundance	Specific Activity (Ci/g)	Decay Mode	Radiation Energy (MeV)		DWS-Equivalent Derived Activity Concentrations (pCi/L)[a]
					Beta (β)	Gamma (γ)	
H-3	12	<< 1	9,800	β	0.0057	--	20,000
C-14	5,700	<< 1	4.5	β	0.049	--	2,000
Cl-36	301,000	--	0.033	β, EC	0.027	< 0.001	200
Tc-99	210,000	--	0.017	β	0.1	--	900
I-129	16,000,000	--	0.00018	β	0.19	--	1

(a) The EPA DWS for radionuclides listed in Table 2.1 were derived based on a 4 mrem/y dose standard using maximum permissible concentrations in water specified in National Bureau of Standards (NBS) Handbook 69, *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (40 CFR 141.16). NBS Handbook 69 is based on the recommendations of ICRP Publication 2 (ICRP 1960).

2.1 Sources and Extent of Low-Energy Beta Contamination in Groundwater at Hanford

The sources and extent of groundwater contamination from low-energy beta radioisotopes vary across the Hanford Site (DOE/RL-2018-66, DOE 2019a). Within the River Corridor, contaminant sources in the 100 Areas included cooling water conditioning and handling facilities, underground pipe leaks, liquid and solid waste disposal sites, and unplanned releases. Large volumes of effluent were discharged in the 100 Area during reactor operation, resulting in contamination of the aquifer, creation of large groundwater mounds, and modification of groundwater flow. On the Central Plateau, contamination resulted primarily from planned releases of the process liquid wastes and wastewater to the soil via discharge to engineered structures (cribs, trenches, ditches, ponds, leach fields, or injection wells). Releases to these engineered structures occurred during the 1940s through the 1990s. This section discusses the main sources of the low-energy beta radioisotopes in Hanford groundwater and describes the extent and magnitude of the resulting groundwater plumes as shown in Figure 2.1.

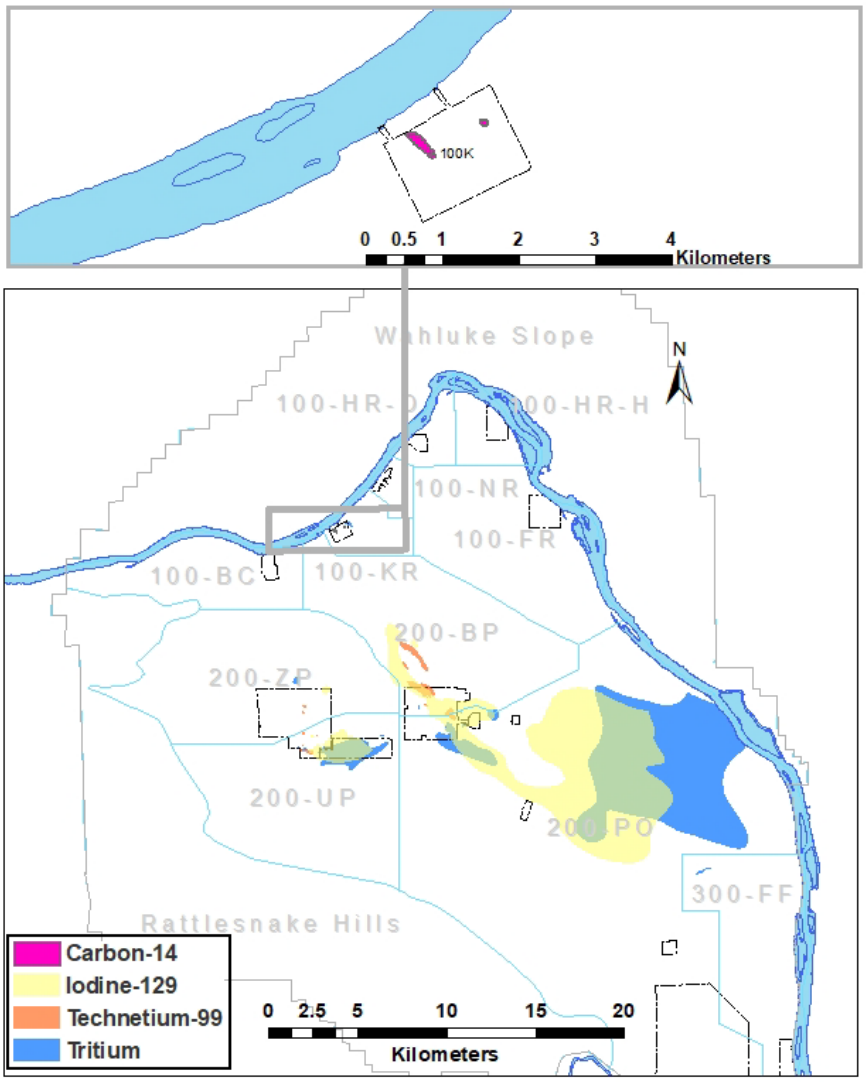

Figure 2.1. 2018 Estimated Groundwater Plumes for Low-Energy Beta Radioisotopes. [Contaminant plume data from CH2M Hill Plateau Remediation Company (CHPRC) used in the Hanford Site Groundwater Monitoring Report for 2018, DOE-RL-2018-66.]

2.1.1 Iodine-129 in Hanford Groundwater

Sources of iodine-129 occur on the Central Plateau, where process waste fluids were generated by the separations process, and the iodine scrubber waste from acid dissolver overheads subsequently was disposed to engineered structures (Nichols et al. 2018). The waste streams resulting from the separations processes in the 200 Area were discharged to the various cribs and trenches along with tritium, nitrate, and other waste products. Early estimates indicate approximately 4.7 Ci of iodine-129 was discharged to liquid disposal sites (Corbin et al. 2005). Ongoing iodine-129 mass-balance analyses related to the Hanford Site Composite Analysis indicate preliminary estimates of 5.01 to 13.9 Ci of iodine-129 in liquid discharged to soil (Cobb et al. 2017; CP-60195).

Part of these discharges included a large volume of liquid waste discharged to the PUREX cribs in the 200-PO groundwater interest area (GWIA), resulting in an iodine-129 plume at concentrations equal to or greater than 1 pCi/L extending south and east of the 200 Area cribs with an areal extent of approximately

64 km^2 (DOE-RL-2018-66). Other smaller plumes where concentrations of iodine-129 are greater than 1 pCi/L occur in GWIAs associated with 200 East and 200 West, including the 200-BP (6.1 km^2), 200-UP (4.0 km^2), and 200-ZP (0.3 km^2) (DOE-RL-2018-66). The largest plume area where iodine-129 concentrations are greater than 10 pCi/L is located in 200-UP (Figure 2.2), where the iodine-129 plumes originated from the U Plant and REDOX waste site.

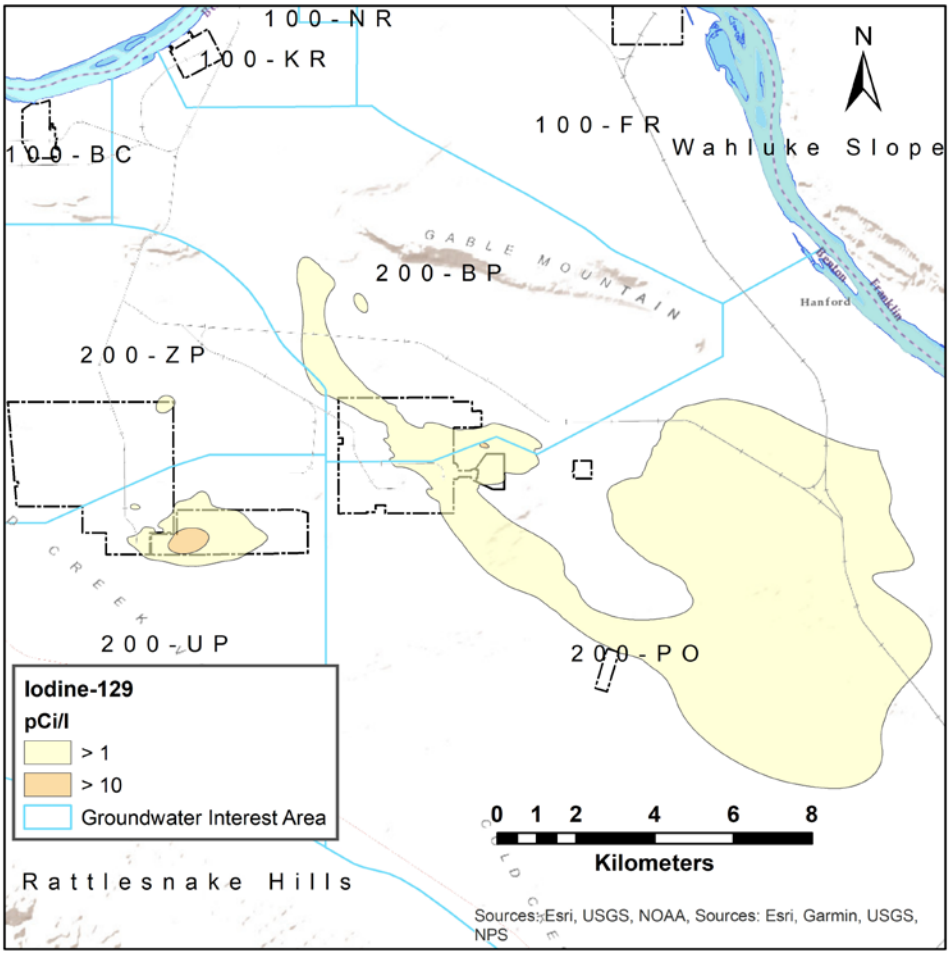

Figure 2.2. Estimated Extent of Iodine-129 Groundwater Plumes on Hanford in 2018. (Contaminant plume data from CHPRC used in the Hanford Site Groundwater Monitoring Report for 2018, DOE-RL-2018-66.)

2.1.2 Technetium-99 in Hanford Groundwater

Technetium-99 is a relatively common by-product of the plutonium and uranium processing operations that occurred at Hanford, and small groundwater plumes of technetium-99 (Figure 2.3) formed from the releases to various ponds and cribs and tank-farm releases within the Central Plateau. Recent estimates from the Hanford soil inventory model indicate that approximately 728 Ci of technetium-99 was released in direct liquid discharges, unplanned releases, and tank leaks located on the Central Plateau (Nichols et al. 2018). Slightly more than half of that inventory was released to the 200-BC-1 Operable Unit (OU), and significant releases also occurred to the 200-DV-1 OU, Waste Management Area (WMA)-BX-BY OU, and the WMA-T. In the 200-BP GWIA, the origins of the plumes (totaling 1.5 km^2) can be traced to the B Complex and WMAs. The sources of technetium-99 in the 200-PO GWIA are in WMA C and WMA A-AX and the plume area in 2018 was estimated to be 0.12 km^2 (DOE-RL-2018-66). In 200-UP, the

technetium-99 plume in 2018 was estimated to be 0.15 km^2 and has sources from WMA S-SX, 216-U-1 and 216-U-2 Cribs, and WMA U (DOE-RL-2018-66). In 200-ZP, plumes of technetium-99 are 0.05 km^2 and located at WMA TX-TY and WMA T. The sources of these two plumes were leaks in single-shell tanks and pipelines, and liquid waste disposal near the WMAs (DOE/RL-2016-67). Pump-and-treat (P&T) systems are implemented under CERCLA to remove technetium-99 and other contaminants from groundwater.

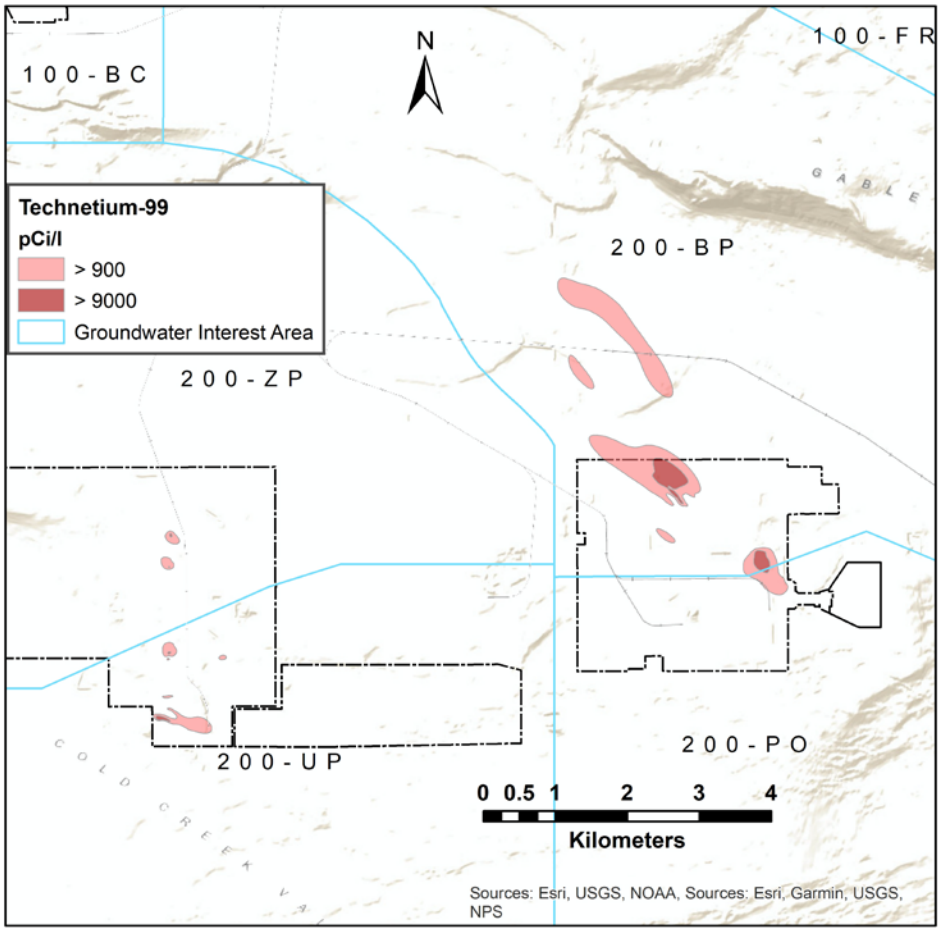

Figure 2.3. Estimated Extent of Technetium-99 Groundwater Plumes on Hanford in 2018. (Contaminant plume data from CHPRC used in the Hanford Site Groundwater Monitoring Report for 2018, DOE-RL-2018-66.)

2.1.3 Tritium in Hanford Groundwater

Previous estimates indicate that approximately 180,000 curies of tritium may exist in Hanford soil and groundwater as a result of past releases (Gephart 2010). On the Hanford Site, irradiation of uranium fuel elements in the plutonium production reactors produced tritium in the fuel by a process called ternary fission. Subsequent dissolution of the fuel released tritium into the dissolver water. A portion of the tritium was then released as process condensate disposal to cribs and ultimately to the soil. Most of the tritium in Hanford groundwater resulted from this type of process.

Tritium has been detected in several of the 100 Areas, in the 200 Areas, and in the 300-FF and 1100-EM GWIAs (Figure 2.4). In 2018, tritium concentrations in groundwater exceeding the 20,000 pCi/L DWS occurred in 100-KR, 100-NR, 300-FF, 200-BP, 200-PO, 200-UP, and 200-ZP GWIAs. The largest tritium

plumes are associated with sources in the 200 Areas. Cribs located in the 200-BP, 200-PO, and 200-UP areas were sources of tritium and the areal extents of the individual plumes are 0.10 km^2, 65.0 km^2, and 5.4 km^2, respectively (DOE/RL-2018-66). Tritium groundwater plumes in the 100 Areas originated from various sources (releases of reactor gas dryer and fuel storage basin water, contaminated solid waste that was disposed, unplanned releases, release of contaminated reactor cooling water to retention basins, and mobilization of residual tritium in the lower vadose zone as a result of adding water to the surface for dust-suppression during remediation). These plumes are smaller in extent, but some have significantly higher tritium concentrations. For example, the concentrations of tritium are high at 100-NR (383,000 pCi/L in 2018), but the total plume area is less than 0.01 km^2. The groundwater plume in 100-KR has decreased over time to an area of 0.09 km^2 (DOE/RL-2018-66). Tritium in the 300-FF GWIA was released as gas from buried radiological solid wastes resulting in a maximum groundwater concentration of 450,000 pCi/L at 618-11 Burial Ground (DOE-RL-2018-66). That plume area is decreasing and was estimated to be 0.11 km^2 in 2018 (DOE/RL-2018-66).

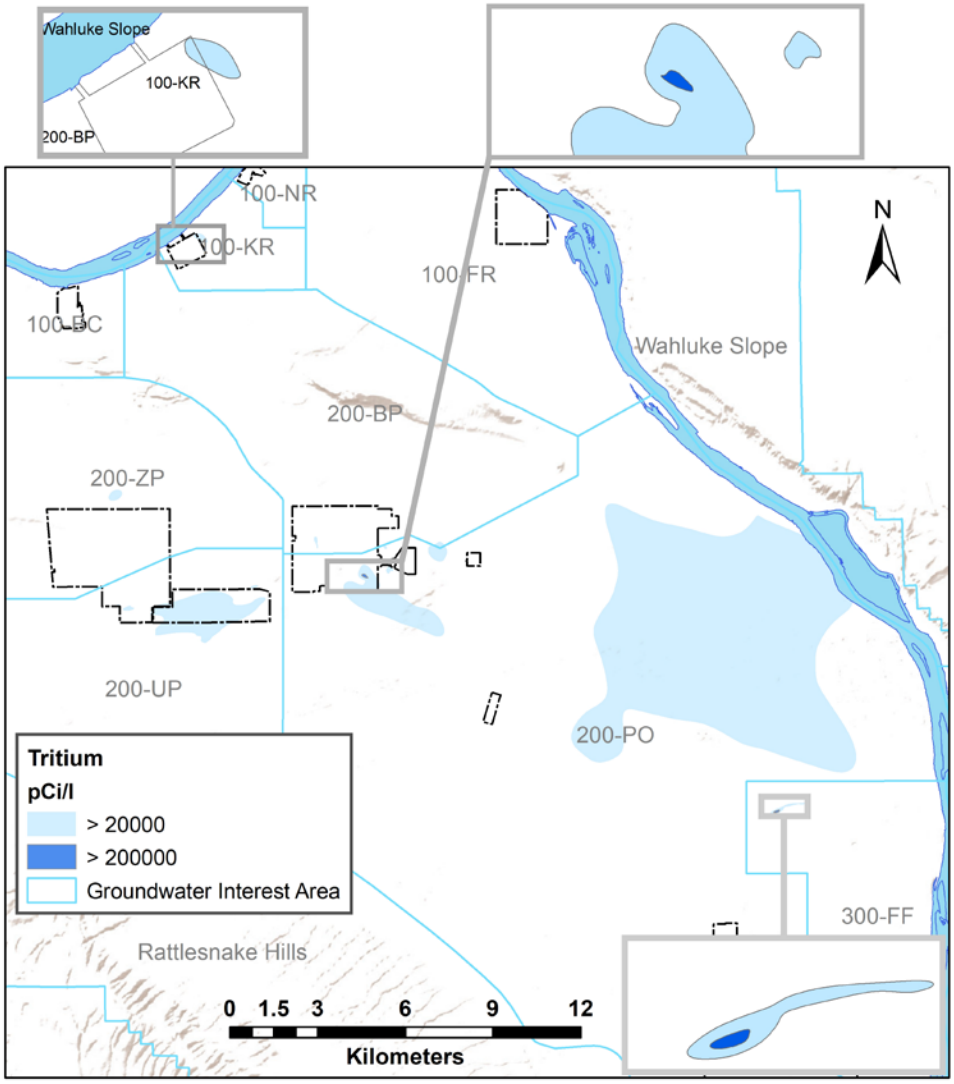

Figure 2.4. Estimated Extent of Tritium Groundwater Plumes on Hanford in 2018. (Inset maps show small plumes and the location and estimated extent of tritium plumes with concentrations >200,000 pCi/L. Contaminant plume data from CHPRC used in the Hanford Site Groundwater Monitoring Report for 2018, DOE-RL-2018-66.)

2.1.4 Carbon-14 in Hanford Groundwater

Carbon-14 at Hanford was produced in the operating reactors by the neutron activation of oxygen-17 in heavy water, and subsequently released from reactor gas dryer regeneration condensate and from fuel storage basins. Carbon-14 also was produced from nitrogen-14 in graphite according to the equation $^{14}N + n \rightarrow {}^{14}C + p$ (Gray and Morgan 1988). Most of the nitrogen in the graphite moderators of the Hanford plutonium production reactors was chemisorbed on the graphite surfaces, and ^{14}C formed predominantly on the graphite surfaces (Gray and Morgan 1988). This radionuclide exists on the Hanford Site in various chemical forms—commonly as carbon dioxide and its solution forms (bicarbonate, carbonate, and carbonic acid), which can readily interchange with soil materials.

There are two carbon-14 groundwater plumes in 100-KR GWIA with an area of 0.05 km^2 and a maximum concentration of 32,900 observed in 2018 (DOE/RL-2018-66). The sources of these plumes were discharges of reactor gas dryer regeneration condensate in gas condensate cribs 116-KE-1 and 116-KW-1 (DOE/RL-2016-67).

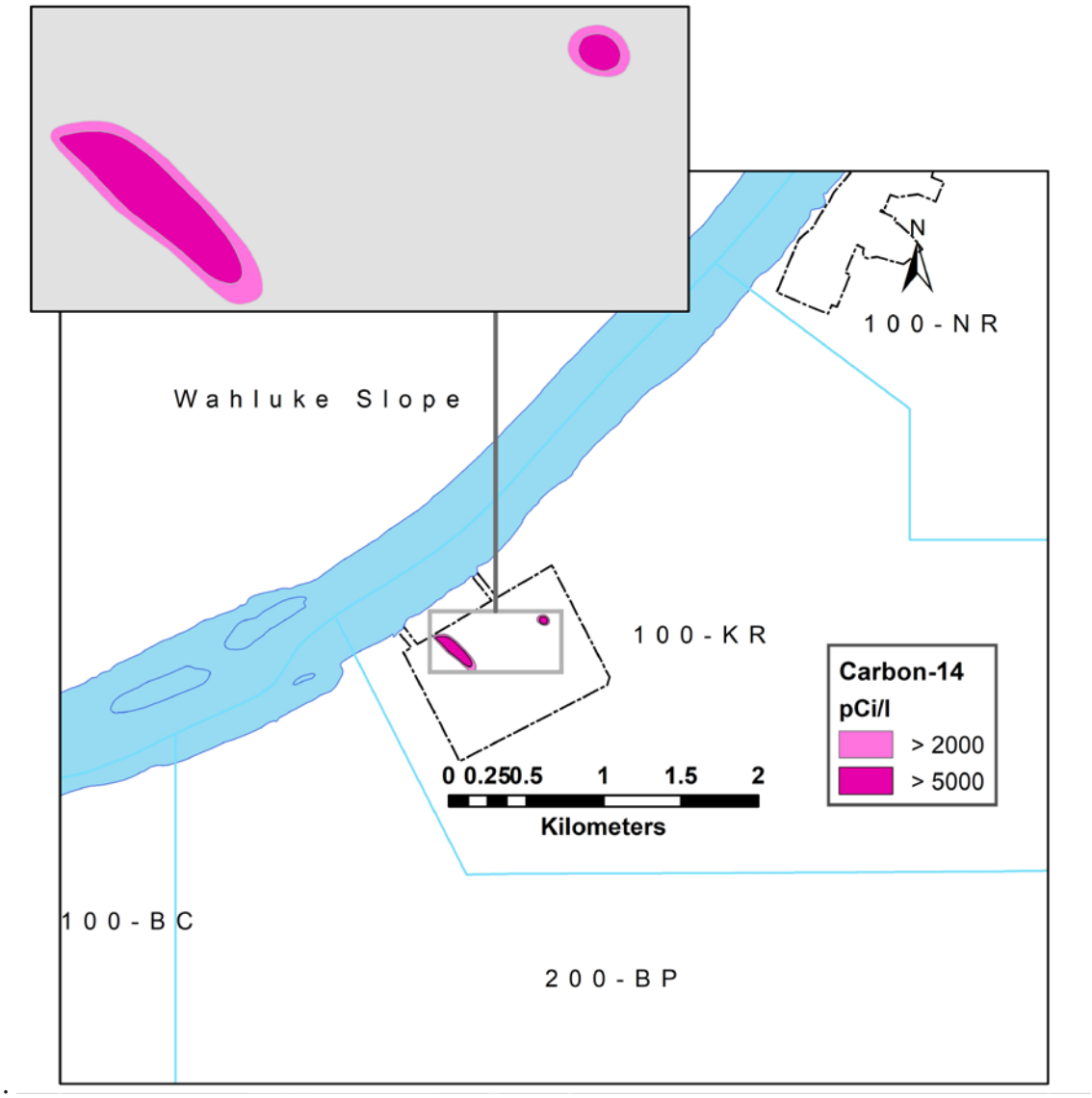

Figure 2.5. Estimated Extent of Carbon-14 Groundwater Plumes on Hanford in 2018. (Inset maps show small plumes. Contaminant plume data received from CHPRC as used in the Hanford Site Groundwater Monitoring Report for 2018, DOE-RL-2018-66.)

2.1.5 Chlorine-36 in Hanford Groundwater

Chlorine-36 at the Hanford Site exists primarily as a contaminant in decommissioned plutonium production reactors, where traces of natural chlorine left from purification of the graphite during its manufacture were transformed through neutron activation to chlorine-36 in the graphite, according to the equation $^{35}Cl + n \rightarrow {}^{36}Cl$ (Gray and Morgan 1988). Chlorine-36 has been found at detectable levels in only two wells within the 100-KR GWIA, once in 2016 (3.7 pCi/L in well 199-K-203) and once in 2018 (31 pCi/L in well 199-K-189). Both samples were well below the DWS for chlorine-36. Based on the decommissioning process for the plutonium production reactors, chlorine-36 could become a future groundwater contaminant of concern.

2.2 Remediation Approaches and Protectiveness for Low-Energy Beta Radioisotopes

The low-energy beta radioisotopes technetium-99, iodine-129, carbon-14, and tritium are identified as contaminants of concern or contaminants of potential concern in multiple groundwater OUs at the Hanford Site, as described in Section 2.1. They are also present in some waste-site OUs (e.g., 200-DV-1, 200-WA-1, and 200-EA-1) as current or potential future sources of groundwater contamination. The contaminant properties affect the types of remediation alternatives that are practicable for these contaminants at the Hanford Site.

Cleanup levels specified in current Hanford Site Records of Decision (RODs) and interim RODs are consistent with regulatory requirements and policy objectives in both the RCRA and CERCLA programs, where:

> "EPA expects to return usable ground waters to their beneficial uses wherever practicable, within a time frame that is reasonable given the particular circumstances of the site. When restoration of groundwater to beneficial uses is not practicable, EPA expects to prevent further migration of the plume, prevent exposure to the contaminated ground water and evaluate further risk reduction." – 40 CFR 300.430(a)(1)(iii)(F)

Protectiveness and risk during remediation, and where return to beneficial use is impracticable (e.g., plume management as part of a Technical Impracticability waiver) is related to the use of institutional controls and risk-based approaches and decision-making (Harclerode et al. 2016). Use of risk-informed prioritization and actions, as described by the GAO (2019), requires an evaluation of risk based on contaminant exposure and the effects of exposure. As context for plume remediation of low-energy beta emitters, summaries of remediation technology status for technetium-99, iodine-129, carbon-14, and tritium are provided below.

2.2.1 Iodine-129

There are several chemical species that contain iodine-129 in the Hanford Site subsurface (Truex et al. 2017; Qafoku et al. 2018; Neeway et al. 2019). Iodate is the dominant species and is moderately mobile in groundwater, with several interactions with sediments that can attenuate its transport (e.g., interaction with carbonate). Iodide and organic iodine are also present as iodine-129 species, though these chemical species account for a smaller fraction of the iodine mass in the subsurface compared to iodate. Iodide is highly mobile in groundwater. Organic iodide can also be a mobile species. There can be cycling between these and other iodine species, but current data show that iodate appears to be the dominant species and would be the primary remediation target. Radioactive decay is very slow, with a half-life of nearly 16 million years, and is therefore not a relevant process to include for natural attenuation.

Based on an evaluation of aboveground and in situ remediation technologies for the Hanford Site 200-UP-1 OU, there are no current practicable approaches for the 200-UP-1 OU plume (Truex et al. 2019). In situ source remediation methods for the Hanford Central Plateau are being evaluated as part of source-zone treatability testing to sequester iodine-129 in place so that it does not contaminate groundwater (DOE 2019b,c). This evaluation was initiated through a thorough evaluation of potential source-zone remediation technologies in the *Technology Evaluation and Treatability Studies Assessment for the Hanford Central Plateau Deep Vadose Zone* (DOE 2019c). This evaluation identified technology options for contaminants relevant to the Central Plateau (including iodine-129) and selected those most promising for subsequent treatability testing. Planned treatability testing for mitigating source zones is described in a treatability test plan (DOE 2019c) With respect to in situ source-zone treatment, geochemical reduction

does not decrease iodine-129 mobility, so other types of sequestration approaches were identified for treatability testing evaluated. The technology evaluation identified that surface barriers and desiccation, which are technologies that mitigate the water flux through vadose-zone contamination, could be appropriate to address iodine-129 vadose zone sources and these technologies are mature and ready for evaluation in future feasibility studies (DOE 2019c; Truex et al. 2018).

In summary, remediation of the 200-UP-1 OU iodine-129 groundwater plume is not practicable. Source-zone treatment by infiltration control is mature, but maturation of the limited number of potential in situ remediation approaches is still needed. On a mass-basis, the current iodine-129 clean up objective in RODs/interim RODs of 1 pCi/L is very low (~6 ng/L).

2.2.2 Technetium-99

The dominant chemical species of technetium-99 in the Hanford Site subsurface is pertechnetate (Pearce et al. 2020a,b). Pertechnetate is highly mobile with effectively no sorption or reactions with sediments to retard its transport in the oxidized Hanford Site subsurface. Radioactive decay is very slow, with a half-life greater than 200,000 years, and is therefore not a relevant process to include for natural attenuation.

For P&T remediation, the pertechnetate concentration can be effectively decreased by treatment of extracted groundwater with commercially available ion-exchange resin to remove technetium-99 mass from the groundwater (DOE 2019b). In situ remediation methods are being evaluated as part of source-zone treatability testing to sequester technetium-99 in place so that it does not contaminant groundwater (DOE 2019c.d). These in situ remediation methods have been considered for potential technetium-99 source zone treatment in the future for sources that could produce a plume of concern, pending evaluation in feasibility studies. Pertechnetate can be biogeochemically reduced, and the reduced species have low solubility. However, reduced species can readily re-oxidize because oxidative conditions exist within the vadose zone and groundwater at Hanford. Thus, immobilization by geochemical reduction alone has not been considered as an effective approach in technology evaluations to date (DOE 2019c,d). Other in situ remediation approaches have been evaluated and are based on processes that can immobilize technetium-99 using a sequential, 2-step reduction – sequestration process, whereby a low-solubility precipitate binds or coats technetium-99 in a way that prevents remobilization under oxidative subsurface conditions. These approaches are currently part of treatability testing for potential use as a source-zone treatment at the Hanford Site and are not commercially available at this time (DOE 2019c). As described above for I-129, surface barriers and desiccation to mitigate water flux have been evaluated for addressing technetium-99 vadose-zone sources and these technologies are mature and ready for evaluation in future feasibility studies (DOE 2019c; Truex et al. 2018).

In summary, groundwater treatment for technetium-99 is mature and is currently being applied at the Hanford Site. Source-zone treatment in the vadose zone by mitigating water flux is mature, but maturation of in situ remediation approaches is still underway. On a mass-basis, the current technetium-99 clean up objective in RODs/interim RODs of 900 pCi/L is very low (~53 ng/L).

2.2.3 Tritium

Tritium is mobile and moves directly with groundwater. Radioactive decay is rapid (half-life of ~12.5 years). Hence, tritium can attenuate naturally within reasonable timeframes, making monitored natural attenuation an effective passive remedy.

2.2.4 Carbon-14

Subsurface transport of carbon-14 is primarily associated with the carbonate system (DOE 2019c). As such, transport is retarded substantially by natural processes. Radioactive decay is very slow, with a half-life of 5700 years, and is therefore not a relevant process to include for natural attenuation.

P&T is not effective for carbon-14 because of the low mobility and C-14 interactions with the natural carbonate system. Initial evaluation of in situ remediation methods has been conducted and there are limited options available (DOE 2019c). Each option needs additional maturation before consideration for a feasibility study.

In summary, groundwater treatment for carbon-14 is limited and may not be practicable. As described above for iodine-129, surface barriers and desiccation have been evaluated as treatments for addressing vadose zone sources by mitigating water flux and are considered mature (DOE 2019c; Truex et al. 2018). However, maturation of the limited potential for in situ remediation approaches is still needed. On a mass-basis, the current carbon-14 clean up objective in RODs/interim RODs of 2,000 pCi/L is very low (~0.4 ng/L).

3.0 Radiation Guidelines and Acceptable Risks

Multiple guidelines and standards are used by federal agencies such as EPA, DOE, and the Nuclear Regulatory Commission (NRC), and other national and international organizations to limit radionuclide exposure and regulate cleanup of radionuclides to limit risks to exposed individuals and populations. The standards are based primarily on determinations of potential dose or calculated human health risks that assure worker and public radiation protection from radionuclides in the environment and provide the technical bases to evaluate remediation actions.

Comparisons of the recommendations, guidelines, and regulatory standards developed by the different federal, national, and international organizations reveal that radiological dose limits, levels of acceptable risk to human health, and the parameters for calculating risk are not consistent across these organizations. Differences in guidelines and standards for dose limits and assessing risk contribute to the complexity and difficulty in applying and understanding the regulations governing the cleanup of radioactively contaminated sites. Examples of the differences in national and international standards and guidance for low-energy beta emitters in drinking water are presented in Table 3.1, along with calculated derived concentrations based on the most recent science-based recommendations for determining dose. The derived concentration standard used by DOE (DOE-STD-1196-2011) is the concentration of a specific radionuclide in water that could be continuously consumed at average annual rates and not exceed an effective dose equivalent of 100 mrem/y—an annual dose limit used by DOE. The last column of Table 3.1 uses recently recommended dosimetry to calculate the 4 mrem/y effective dose for each of the five low-energy beta emitting radioisotopes considered here.

Table 3.1. United States Drinking Water Standards, International Drinking Water Guidelines, and Dose-Derived Concentration Standards

Radionuclide	DWS[(a)] Based on EPA 4 mrem/y Dose (pCi/L)	WHO Drinking Water Guidelines (pCi/L)[(b)]	100 mrem/y Derived Concentration Standard[(c)] (pCi/L)	4 mrem/y Effective Dose[(d)] (pCi/L)
Carbon-14	2000	2700	62,000	2,500
Chlorine-36	700	2700	32,000	1280
Iodine-129	1	27	330	13
Technetium-99	900	2700	44,000	1,800
Tritium	20,000	270,000	1,900,000	76,000

(a) Primary DWS from 40 CFR 141, Subpart G, "National Primary Drinking Water Regulations," "Maximum Contaminant Levels and Maximum Residual Disinfectant Levels." The DWS for radionuclides were derived by EPA based on a 4 mrem/y dose standard using maximum permissible concentrations in water specified in NBS Handbook 69, *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (NBS 1963).

(b) World Health Organization (WHO) guidance level for each radionuclide represents the concentration that, if present in the drinking-water consumed throughout the year, would result in an individual dose of 0.1 mSv/y.

(c) DOE-STD-1196-2011, *Derived Concentration Technical Standard*. establishes derived concentration standards on a radionuclide- and pathway-specific basis, reflecting the current state of knowledge and practice in radiation protection. These derived concentration standards are used to calculate doses from exposure to groundwater and represent the activity concentration of a given radionuclide in groundwater that results in a member of the public receiving a 100 mrem total effective dose from drinking groundwater for one year. Concentration of a specific radionuclide in water that could be continuously consumed at average annual rates and not exceed an effective dose equivalent of 100 mrem/yr.

(d) Concentration of a specific radionuclide in water that would produce an effective dose equivalent of 4 mrem/y if consumed at average annual rates. The 4 mrem/y effective dose equivalent standard listed in this table was calculated using a more recent dosimetry system than that applied by EPA to calculate DWS. More recent dosimetry was adopted by DOE (see note b) to calculate the effective dose equivalent based on ICRP Publication 60 (ICRP 1991).

The differences in standards and guidance regarding dose limits and acceptable human health risks from these contaminants in groundwater used as drinking water reflect the differences in applicable laws, technical bases and assumptions, and regulatory approaches enacted at different times to minimize risks to workers and the public from radiation. Within this section, we present information on the background and underlying technical basis to aid in understanding the development and application of current regulatory standards used in the United State and abroad.

Organizations involved in providing the technical bases and guidance regarding radiation protection, both within the United States and internationally, include the following:

- The Health Physics Society—a nonprofit scientific organization chartered in the United States that develops position statements and recommendations on radiation protection.
- The National Council on Radiation Protection and Measurements (NCRP) —a national nonprofit corporation chartered by Congress in 1964 in part to "collect, analyze, develop, and disseminate in the public interest information and recommendations about (a) protection against radiation…and (b) radiation measurements, quantities and units, particularly those concerned with radiation protection." (Public Law 88-376)
- The International Commission on Radiological Protection (ICRP) —the principal international organization concerned with radiation protection; sometimes referred to herein as 'the Commission'. The ICRP is an independent, non-government, not-for-profit organization established to advance the science of radiological protection for the public benefit by providing recommendations and guidance on all aspects of protection against ionizing radiation.
- International organizations such as the International Atomic Energy Agency (IAEA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)—a committee established by the United Nations General Assembly in 1955 to provide unbiased international consensus on the risks of radiation exposure.

The following sections discuss how different agencies and organizations use the recommendations for radiation protection to develop regulations, directives, and guidelines.

3.1 Radiation Protection in the United States

The principal federal agencies with responsibilities for radiation protection of the United States public are the EPA, the NRC, and DOE. Regulations governing the cleanup of radioactively contaminated sites are complex and may be confusing because multiple agencies with overlapping authorities are involved in regulating multiple categories of radioactive materials. In addition, the regulatory structure in the United States for radiation protection based on dose is complex. Dose limits for each agency are calculated using different radiation protection guidance. Some EPA and NRC regulations require use of the ICRP Publication 2 methodology (ICRP 1960), but for the most part their dose-based regulations follow ICRP Publication 26 (ICRP 1977) and ICRP Publication 30 (ICRP 1979a,b). The Occupational Safety and Health Administration (OSHA) radiation protection regulations continue to be based on ICRP Publication 2 (ICRP 1960). DOE has adopted the approach outlined in ICRP Publication 60 (ICRP 1991) for calculating the doses to its workers. Because the different agencies rely on different technical bases and different (sometimes outdated) guidance, readily understanding the limits for regulatory compliance and cleanup can be difficult. The following paragraphs discuss the differences in how EPA, NRC, and DOE approach the cleanup of groundwater contaminated by beta radiation.

As previously indicated, the National Primary Drinking Water Regulations (EPA 2000; 40 CFR Parts 9, 141, and 142) specify maximum concentration levels (MCLs) for radionuclides that may be the ARARs for determining cleanup levels for radionuclides in groundwater at most CERCLA sites under authority of

the EPA. For anthropogenic beta particles and photon radioactivity (e.g., gamma radiation), EPA considers an annual cumulative dose equivalent of less than 4 mrem to the total body or any internal organ to be protective of human health. This is used to calculate estimated concentrations (Table 2.1) for selected radionuclides that would yield a 4 mrem/y dose for 2 L per day water intake (EPA 1976, 2000). It is important to note that the dose conversion factors for ingested radioactivity (National Bureau of Standards Handbook 69; NBS 1963; ICRP 1960) used to calculate the equivalent derived activity concentrations (pCi/L) are considered obsolete (EPA 1988, 1991; NCRP 2004).

With respect to cleanup levels for radionuclides at CERCLA sites, EPA (1997) further directs that:

> "Cleanup should generally achieve a level of risk within the 10^{-4} to 10^{-6} carcinogenic risk range based on the reasonable maximum exposure for an individual. The cleanup levels to be specified include exposures from all potential pathways, and through all media (e.g., soil, ground water, surface water, sediment, air, structures, biota). As noted in previous policy, "the upper boundary of the risk range is not a discrete line at 1 x 10^{-4}, although EPA generally uses 1 x 10^{-4} in making risk management decisions. A specific risk estimate around 10^{-4} may be considered acceptable if justified based on site-specific conditions."[4,5]

The EPA originally intended to revise the National Interim Primary Drinking Water Regulations (EPA 1976) to assess the use of newer data to calculate MCLs (EPA 1991). Although it was proposed to base the regulatory limit on the committed effective dose equivalent (ede) (ICRP 1977), the proposed rule (EPA 1991) was never finalized, largely because of concerns of commenters and Congress over the most effective way to regulate radon (EPA 2000). EPA's final rule regarding the MCLs for beta emitters remains based on the dose factors recommended in ICRP Publication 2 (ICRP 1960) and methodology published in NBS Handbook 69 (NBS 1963), and the cancer risk coefficients published in Federal Guidance Report (FGR)-13 (Eckerman et al. 1999a; EPA 2002). It is important to note that the EPA decided to retain the current MCL based on older scientific models for several reasons:

- Applying FGR-13 (Eckerman et al. 1999) demonstrated that developing MCLs based on the proposed 4 mrem-ede/y could result in concentration limits that fell outside the 10^{-4} to 10^{-6} risk range.
- The current MCLs based on 4 mrem/y dose for beta and photon emitters resulted in concentration limits within the 10^{-4} to 10^{-6} risk range.
- There is no evidence of appreciable occurrences of anthropogenic beta emitters in drinking water.

The final rule indicated an intent by EPA to review the 4 mrem/y dose limit for beta and photon emitters within 2 to 3 years of publication to ensure that the MCL reflects the best available science, but review or changes to the standards have not been implemented to date.

In contrast, the NRC's Radiological Criteria for License Termination (NRC 1997) sets an allowable cleanup level of 25 mrem/y (equivalent to approximately 5 x 10^{-4} increased lifetime risk) as the primary standard for the decommissioning of lands and structures with exemptions allowing dose limits of up to 100 millirem per year (equivalent to approximately 2 x 10^{-3} increased lifetime risk). The NRC rule does not include a separate requirement for protecting groundwater that is a current or potential source of drinking water to the MCLs established under the Safe Drinking Water Act. However, EPA has clearly indicated that for compliance with standards, EPA would use ARARs (especially MCLs) in assessing attainment of CERCLA cleanup levels, and that compliance with the dose limits in the NRC rule

[4] OSWER No. 9200.4-18 Memorandum *Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination*

[5] OSWER No. 9285.6-20 Memorandum *Radiation Risk Assessment at CERCLA Sites: Q & A*

generally should not be used to determine if an NRC cleanup attains, or will attain, CERCLA cleanup levels (risks to human health in the 10^{-4} to 10^{-6}) (EPA 2000).

DOE publishes derived concentration standards for ingestion of water and inhalation that are based on the 100 mrem/y annual total effective dose limit set out in DOE Order 458.1 for use in design and conduct of radiological environmental protection programs at DOE facilities and sites. This standard establishes derived concentration standards on a radionuclide- and pathway-specific basis, reflecting the current state of knowledge and practice in radiation protection. These derived concentration standards are used to calculate doses from exposure to groundwater and represent the concentration of a given radionuclide in groundwater that results in a member of the public receiving a 100 mrem total effective dose from drinking groundwater for one year. The DOE standards are based on calculations of the annual total effective dose using updated dose factors and risk coefficients in ICRP Publication 60 (ICRP 1991). The DOE standards are not comparable to the national primary DWS and should not be considered ARARs for remediation, but rather are used to assess radiation protection of workers and the public.

3.2 International Standards for Radiation Protection

Outside the United States, many countries regulate radiation exposure and radioactive materials based on recommendations of the International Atomic Energy Agency (IAEA). The IAEA recommendations are founded on risk estimates developed by UNSCEAR and recommendations from the ICRP. The UNSCEAR risk estimates are used by the ICRP to establish internationally accepted concepts and principles of radiation protection: i.e., justification, optimization, and limitation of radiation exposures. The ICRP uses this information to establish recommended dose limits for workers and members of the public [ICRP Publications 103 (ICRP 2008), 60 (ICRP 1991), 26 (ICRP 1977)]. Europe, along with most other countries with radiation protection programs, adopted ICRP 60. It is expected that these countries will now begin the process of adopting ICRP 103.

IAEA relies on the UNSCEAR and ICRP recommendations as the basis for setting international radiation safety standards and publishes these as Basic Safety Standards (BSS). The BSS are based on total effective radiation dose from all sources and all radionuclides. Individual radionuclides are not separately regulated or limited beyond their contribution to the total dose. Based on ICRP guidance (ICRP 2007), WHO has issued guidelines for radionuclides in drinking water (WHO 2017). The current drinking water guidelines are based on the ICRP recommended approach for situations of prolonged radiation exposure of the public. According to the ICRP, in planned exposure situations, it is prudent to restrict the prolonged component of the individual dose to 10 mrem (0.1 mSv) in any given year (ICRP 2000).

In a similar fashion, the Council of the European Union[6] (CEU) also uses an “indicative dose” (ID) of no more than 10 mrem/y (0.1 mSv) for radioactive contaminants in drinking water. The ID is the committed effective dose for 1 year of ingestion resulting from all the radionuclides whose presence has been detected in a supply of water intended for human consumption, of natural and artificial origin, but excluding tritium, potassium-40, radon, and short-lived radon decay products. The Council’s directive provides for calculation of derived concentrations corresponding to the 10 mrem/y dose to develop parametric values for each radionuclide that “above which Member States shall assess whether the presence of radioactive substances in water intended for human consumption poses a risk to human health which requires action and, where necessary, shall take remedial action to improve the quality of water to a level which complies with the requirements for the protection of human health from a radiation protection point of view.” The CEU further recommends a screening level for gross beta activity of 1.0 Bq/l (27 pCi/L)—if the gross beta activity exceeds 1.0 Bq/l, analysis for specific radionuclides is required.

[6] Council Directive 2013/51/Euratom of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption

3.3 Comparing Radiation Protection Guidelines

A number of factors should be considered when comparing different guidelines and regulations (National Research Council 1999):

- Differences in the primary bases of guidelines, especially judgments about acceptable risk versus judgments about risks that are reasonably achievable.
- Differences in statutory and judicial mandates for guidelines, especially the fundamental difference between a regulatory limit, as embodied in some guidelines, and a regulatory goal that can be relaxed on the basis of other considerations as embodied in other guidelines.
- Differences in the applicability of guidelines, especially guidelines that apply to all sources of exposure combined versus guidelines that apply only to specific sources or practices, or to particular environmental media and comparisons of guidelines that apply to quite different sources or practices.
- Differences in the population groups of primary concern, especially individuals who receive the highest exposures versus whole populations.
- Differences in the considerations of natural background.

Note that the methodologies that form the primary bases for regulatory limits on radioisotopes in drinking water in the United States differ from those applied to develop current guidance and directives in other countries. The CERCLA guidance for cleanup of contaminated groundwater to be used as a drinking water source clearly indicates that the National Primary DWS MCLs should be the first ARARs applied, with the caveat that cleanup should generally achieve a level of risk within the 10^{-4} to 10^{-6} carcinogenic risk range based on the reasonable maximum exposure for an individual. As previously noted, the National Primary DWS for beta-emitting radionuclides is based on the initial methods and parameters developed to support radiation protection guidance first issued in 1959 (NBS 1963; ICRP 1960) and derived concentrations for the DWS are based on a dose limit of 4 mrem/y. International guidance for radioactive contaminants in drinking water is based on calculations that apply more recent dosimetric methods, parameters, and guidance (ICRP 2008; IAEA 2014) to calculate the dose and risk associated with low-beta emitting contaminants. Outside the U.S., the derived concentrations for radionuclides in drinking water are based on limiting exposure to a dose equal to or less than 0.1 mSv, which is equivalent to 10 mrem. Differences in how the dose is calculated and how acceptable risks are viewed result in guidance that allows greater MCL values for these contaminants outside the U.S. than those promulgated in the U.S. DWS (Table 3.1).

4.0 Dose and Risks Associated with Low-Energy Beta Radioisotopes in Groundwater

Calculated doses and human health risks are evaluated to determine attainment of remediation goals for cleanup of radioactive contamination at a particular waste site or groundwater OU. The dose and risk values depend on the residual concentration of each radionuclide after remediation, the set of assumptions about conditions of future exposures, and the methodology and parameters used in the assessment. As previously noted, radiation protection science has advanced significantly over the past 60 years, resulting in improved methodologies and changes in recommendations for the parameters used to calculate these values.

Section 4.1 presents a chronology and description of methods and parameters recommended for estimating dose and risk over the past 60 years. The different methodologies and recommended parameter sets are applied in a Resident Tap Water scenario,[7] described in Section 4.2. This scenario was selected because it includes the primary pathways for human exposure to contaminated groundwater. The low-energy beta groundwater plumes occur at depths well below the soil-rooting zone, and do not intersect surface waters, except in limited areas where tritium plumes occur adjacent to the Columbia River (DOE/RL-2018-66). Tritium concentrations in the Hanford Townsite seep on the Columbia River were 22,700 pCi/L in 2018, slightly above the DWS of 20,000 pCi/L, and concentrations downstream of the Hanford Site are approximately 60 pCi/L. The other four low-energy beta radionuclides in groundwater generally are not accessible to ecological receptors, and the ecological risk of groundwater entering the surface water environment in the distant future is not addressed here. Section 4.3 compares how the advancements and updates to dosimetry models and parameters change the calculated dose and risk estimates on a unit basis for each of the five beta-emitting contaminants. These comparisons are intended to aid in understanding the factors that influence how human health risks are currently assessed and provide insight into the relative risks associated with the concentrations of beta-emitting radioisotopes concentrations in Hanford groundwater.

4.1 Evolution of Dosimetric Science

The science and philosophy of radiation protection has advanced over the years through research and analysis. The United States has issued regulations for radiation protection over a number of years, which are based on different methodologies and recommendations developed at different times for estimating the dose from ingested radionuclides. These approaches are all based on methods published by the ICRP, which initially worked in parallel with the U.S. National Committee on Radiation Protection and Measurements. The U.S. group was later chartered by Congress as the National Council on Radiation Protection and Measurements (NCRP). This section presents the history and evolution of science-based methods for understanding dose and risk from exposures, from the original recommendations of the ICRP and National Bureau of Standards (NBS 1953) in 1959 to the most recent recommended approaches and information as of 2019.

[7] The Risk Assessment Information System, RAIS Radionuclide Risk Calculator Users Guide, https://rais.ornl.gov/tools/rais_rad_risk_guide.html

4.1.1 ICRP-2/NBS-69

The commencement of industrial production of radioactive sources as part of the Manhattan Project in World War II was the impetus for development of concepts and standards related to ingestion or inhalation of radioactive materials. The U.S. National Bureau of Standards (NBS) supported the publication of the National Committee's report, *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water*, in 1953 [NBS Handbook 52 (NBS 1953)]. This was subsequently updated in 1959 by ICRP Publication 2, *Report of Committee II on Permissible Dose for Internal Radiation* (ICRP 1960), which was summarized and published by NBS as *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure*, NBS Handbook 69 (NBS 1963). All of these documents focused on the concepts of body burden and maximum permissible concentration, but also introduced the concept of radiation dose as the basis for these other end points.

In ICRP-2/NBS-69, radiation dose is estimated simply as the energy absorbed per unit mass. The energy absorbed is estimated as that fraction absorbed from the radionuclides as if they were a point source in the center of a spherical organ or body. These methods were used because they allowed conservative analytical solutions to the basic problem of how much energy was deposited in an organ from a radioactive disintegration.

Using the ICRP-2/NBS-69 terminology, the dose rate (*DR*) per unit activity (*Q*) maintained in the organ or total body is given by Soldat (1976) as:

$$DR/Q = 18.7\ (\varepsilon/m) \tag{4.1}$$

where

18.7 = units conversion constant (mrem g/MeV pCi)
ε = effective energy absorbed per disintegration, MeV
m = mass of the organ, g

The ICRP-2/NBS-69 methods were not based on risk of cancer; the primary focus was on minimizing immediate effects and attempting to avoid hereditary effects. For workers, the limitations were defined in terms of annual dose, rather than committed dose.

4.1.2 ICRP 26/30

The first comprehensive system of dosimetry to be founded on the concept of "detriment" or risk was published by the ICRP in 1977 in Publication 26 (ICRP 1977). In this system, the detriment (a combination of long-term cancer risks and other adverse effects represented as a mathematical expectation of harm) was a function of the "dose equivalent." This was based on the principle that the risk should be equal whether the whole body is irradiated uniformly or there is non-uniform irradiation. This condition was met if

$$\sum_T w_T H_T \ \leq \ H_{wb,L} \tag{4.2}$$

where w_T is a weighting factor representing the fraction of the risk resulting from tissue T to the total risk when the whole body is irradiated uniformly, H_T is the total dose equivalent of the annual dose equivalent in tissue T, and $H_{wb,L}$ is the annual dose-equivalent limit for uniform irradiation of the whole body. The Commission named this new weighted dose equivalent quantity "effective dose equivalent" (ICRP 1978). In the definition and calculation of effective dose the recommended radiation weighting factors, w_R, allow

for the differences in the effect of various radiations in causing stochastic effects while tissue weighting factors, w_T, allow for the variations in radiation sensitivity of different organs and tissues to the induction of stochastic effects.

The organ dose equivalents H_T in this system are committed doses over a 50-year period. These were calculated using sophisticated Monte Carlo calculations of energy absorbed in a target organ from disintegrations that occurred in a source organ in which the radioactive material was uniformly distributed. The weights were developed on the basis of radiation effects as they were understood at the time. The organ-specific weights are included in Table 4.1.

Table 4.1. Organ-Specific Weights for Use in Calculation of Organ Dose Equivalents Over a 50-Year Period

Tissue or Organ	w_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30

The relatively high weighting for gonads reflects the early concern about hereditary effects. The values of dose per unit intake were published over several years in multiple volumes of ICRP Publication 30 (ICRP 1979a,b; 1980; 1981a,b; 1982a,b). This is the system currently in use by the NRC in 10 CFR Part 20.

4.1.3 ICRP-60/72

As the understanding of radionuclide biokinetics and radiation effects has developed, the dosimetry has also advanced. In addition to various refinements in biokinetic models, the definition of detriment has also changed, resulting in refinements for the tissue weighting factors w_T. In 1990, ICRP Publication 60 updated the weighting factors (Table 4.2). In addition, considering that biological effects are not solely governed by the linear energy transfer, the Commission decided to use “radiation weighting factors,” which were selected based on the relative biological effectiveness in inducing stochastic effects at low doses, instead of the quality factors used in calculation of the dose equivalent of the ICRP 1977 Recommendations in Publication 26. To distinguish the resulting quantity from the “dose equivalent,” the Commission named the new quantity “equivalent dose.” Accordingly, the effective dose equivalent was renamed “effective dose.”

Table 4.2. Updated Weighting Factors Based on ICRP Publication 60 (ICRP 1991)

Tissue or Organ	w_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

The factors for radiation dose per unit intake using this system are summarized in ICRP Publication 72 (ICRP 1996).

Some parts of DOE now allow the application of this system of dosimetry in environmental and risk assessments. As noted in DOE Order 458.14e(7), “DOE-approved dose coefficients must be used to evaluate doses resulting from DOE radiological activities. Use of alternative dose coefficients must be approved by the Chief Health, Safety and Security Officer or by a Cognizant Secretarial Officer in consultation with the Chief Health, Safety and Security Officer.”

One DOE application using the ICRP Publication 60 methods that has been approved is the Derived Concentration Standards (DCS) (DOE-STD-1196-2011), which are based not only on Publication 60 but also on age-specific effective dose coefficients, revised gender-specific physiological parameters for the Reference Man (ICRP 2002), and the latest information on the energies and intensities of radiations emitted by radionuclides in ICRP Publication 107 (ICRP 2008). The DCS represent the concentration of a given radionuclide in either water or air that results in a member of the public receiving 1 mSv (100 mrem) effective dose following continuous exposure for 1 year for each of the following pathways: ingestion of water, submersion in air, and inhalation.

4.1.4 Federal Guidance Report 13

EPA has published cancer risk coefficients for environmental exposures to radionuclides as FGR-13 (Eckerman et al. 1999a,b; EPA 2002). This EPA document is built around the concepts of ICRP Publication 60 (ICRP 1991), with minor revisions. A companion database includes dose coefficients that are very similar to the ICPR-60 values. FGR-13 extends the dose coefficients found in ICRP publications to include different age groups and allow application for exposure scenarios other than occupational exposure.

EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population (EPA 2011), also known as the Blue Book, is a revision of the EPA methodology for estimating cancer risks from radiation exposure. These updates are based on the 2006 National Research Council report, *Biological Effects of Ionizing Radiation (BEIR VII),* as well as on other updated science. The document takes into account recommendations from the EPA Science Advisory Board (SAB), which completed its review in January

2010. The SAB relied on advice from its Radiation Advisory Committee panel of non-EPA scientists chosen for their objectivity, integrity, and expertise in radiation science and protection. EPA will use the scientific information on radiation risks provided in the Blue Book, together with information from other sources, when considering potential modifications and updates to radiation protection rules and guidance. One of the documents that will be updated based on the new science in the Blue Book is FGR-13. This update is still in progress.

4.1.5 ICRP-103/IAEA

The *Revised Recommendations for a System of Radiological Protection* formally replaced the Commission's previous 1990 Recommendations in 2007 (ICRP 2007). These recommendations update, consolidate, and develop additional guidance on the control of exposure from radiation sources issued since 1990. The ICRP 103 recommendations (ICRP 2007) update the radiation and tissue weighting factors used in the quantities equivalent dose and effective dose, and update the radiation detriment based on the latest available scientific information of the biology and physics of radiation exposure. The tissue weighting factors recommended in ICRP Publication 103 are shown in Table 4.3.

Note that the weight for gonads has been significantly reduced from the 1977 recommendations; this follows from the accumulated lack of hereditary effects found in human cohorts following irradiation. This allows other weights to be scaled up so that the total is 1. The ICRP Publication 103 recommendations are the basis of the most recent BSS issued by the IAEA (IAEA 2014).

Table 4.3. Weighting Factors Based on ICRP Publication 103 Recommendations

Tissue or Organ	w_T
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breast	0.12
Remainder	0.12
Gonads	0.08
Esophagus	0.05
Bladder	0.05
Thyroid	0.05
Liver	0.05
Skin	0.01
Bone surface	0.01
Brain	0.01
Salivary glands	0.01

These recommendations are used in a new series of ICRP Publications, the Occupational Intakes of Radionuclides (OIR), which will replace the ICRP-30 and ICRP-54, 68, and 78 series. OIR Part 1 (ICRP 2015) describes the assessment of internal exposure, biokinetic and dosimetric models, etc. OIR Part 2 (ICRP 2016), OIR Part 3 (ICRP 2017), OIR Part 4 (ICRP 2019), and OIR Part 5 (in preparation) provide updated information on chemical forms, decay parameters, biokinetics, and tables of committed effective dose for inhalation and ingestion. The tables provide only effective dose; the organ equivalent doses are

not yet available. The results are only provided for adult workers; age-dependent dose coefficients have not yet been prepared.

4.1.6 DOE Standard 1196-2011

DOE Standard 1196-2011 presents Derived Concentration Standards, or DCS, which are radiological quantities used as reference values to control effluent releases from DOE facilities. The DCS of this standard are based on age-specific effective dose coefficients computed in the manner of ICRP Publication 72 (ICRP 1996) and FGR-13 (EPA 1999), using revised gender-specific physiological parameters for members of the public set forth in ICRP Publication 89 (ICRP 2002), and the nuclear decay data of ICRP Publication 107 (ICRP 2008). The standard's values are derived using age-specific effective dose coefficients for reference persons of the public and age- and gender- dependent intake rates for ingestion of water and inhalation of air. The members of the public are represented by six age subgroups. The analysis weights the effective dose coefficients for each subgroup by their fractional representation in the U.S. population and their intake of the radionuclide through inhalation, ingestion, or air submersion. The result is a single, effective dose coefficient for each pathway.

4.1.7 External Dose Coefficients

Older sources of external dose coefficients were less organized and robust than those for internal coefficients. For example, the dose coefficients used by GENII Version 1.485 (Napier et al 1988), which were calculated for idealized receptors as a single value, were particularly variable for beta emitters; some sources ignored the beta contribution, others accounted for beta bremsstrahlung and applied it as a uniform photon field. All organs/tissues were assumed to have essentially the same exposures.

The first guidance document to apply the ICRP weighting of organ doses for external exposures was published as FGR-12 (EPA 1993). This source provided equivalent and effective dose coefficients for external exposures to contaminated air, water, and soil. These remained essentially state-of-the-art until the recent release of FGR-15 (Bellamy et al. 2019). FGR-15 updates and expands the 1993 FGR-12. Compared to FGR-12, FGR-15 incorporates six different age groups (whereas FGR-12 had one), updated tissue weighting factors (as recommended in ICRP Publication 103) and radionuclide decay data (as provided in ICRP Publication 107), and improved computing power to provide more precise calculations. Dose coefficients are listed in Appendix A of this report. Note that the OIR and DOE STD-1196-2011 guidance do not provide external dose or risk coefficients.

4.1.8 Risk Coefficients

Risk estimates initially were based on dose-to-risk conversion factors. Early values were on the order of 10^{-4} per rem; later values based on BEIR-3 were in the range of 10^{-3}-to-10^{-4} per rem. The generally accepted value currently used for simple dose to risk conversion is approximately $5x10^{-4}$ per rem (5% per Sv).

Risk factors have evolved over time as the risk assessment methods, assumptions, and calculations changed. To assist risk estimation for RCRA and Superfund analyses, EPA generated the Health Effects Assessment Summary Tables (HEAST; e.g., EPA 1995). HEAST Table 4 included slope factors (risk per unit exposure factors) for different pathways: inhalation, ingestion, and external exposure to soil contamination (but not air submersion or water immersion). FGR-13 (Eckerman et al. 1999; EPA 2002) supplanted the HEAST in 2001. As noted in Section 4.1.4, FGR-13 is also in the process of being updated. Risk coefficients are listed in Appendix A of this report. All the risk factors, excluding the simple dose-to-risk conversions, are based on ICRP-style dosimetry calculations coupled with U.S.

population survival data and vital statistics where recommendations regarding risk are associated with uniform, whole-body irradiation.

4.1.9 Summary of Changes in Recommendations

Soon after the introduction of large-scale use of radionuclides in industry following the Manhattan Project, the knowledge that large doses of radiation could result in physical hazards led to a radiation-protection philosophy of maintaining radiation doses below a "threshold" for which it was assumed that workers would be protected; the public dose was set to a fraction of the worker dose limit because of the potential for enhanced effects in children or old people. The EPA, in setting the DWS (in part because it did not have statutory authority to regulate the entire exposure), chose to apportion the dose limit separately to the pathway that it could regulate – setting a limit to dose to adults of 4 mrem/y to any organ from ingestion of drinking water. This limit was derived originally as an extension of the "critical organ" approach, wherein dose was regulated based on the organ receiving the highest dose. In this simplified approach – suitable for hand-calculations – the radionuclide in the body was treated as a point source inside of a spherical organ or body (ICRP 1960; NBS 1963).

Since the adoption of the final rule on DWS, updates and revised approaches for calculating dose from exposure to radionuclides have been developed and recommended for use in radiation protection (Pacquet et al. 2016). These approaches are all based on methods published by the ICRP, which initially worked in parallel with the U.S. National Committee on Radiation Protection and Measurements. The U.S. group was later chartered by Congress as the National Council on Radiation Protection and Measurements (NCRP).

As the knowledge base concerning radiation effects grew, it became evident that different organs had different sensitivities to radiation. This knowledge eventually was used by the ICRP to develop the concept of the "effective dose"[8] – the weighted accumulation of internal doses that are "effectively" the same as an equivalent whole-body irradiation (ICRP 1977, 1991). Effective dose is implemented using more sophisticated biokinetic models of the retention and distribution of radionuclides in the body following ingestion or inhalation, by the consideration of "crossfire" – the irradiation of neighboring organs by deposition of radionuclides in individual organs, and by inclusion of organ-specific risks through organ/tissue weighting factors that reflected the "detriment" to the organ or function from the exposure. Recent updates to this basic philosophy consider enhanced knowledge of radionuclide biokinetics, refined understanding of the "crossfire" terms, and developments in radiation epidemiology through revisions to the organ/tissue weighting factors.

The development of the effective dose equivalent (ICRP 1977) represented a significant advancement in assessing radiation exposure and provides a meaningful method for adding internal and external radiation exposures. The purpose of the effective dose is to provide a dose relevant for the entire body. Effective dose is intended for use as a protection quantity and is based on risk factors for an average human (no distinction for age, sex, or ethnic factors). The ICRP (2007) specifically states, "The main uses of effective dose are the prospective dose assessment for planning and optimization in radiological protection, and demonstration of compliance with dose limits for regulatory purposes."

As discussed in Section 3.0, the regulations controlling radiation exposure are complex because the U.S. regulatory process is fragmented between agencies with different statutory responsibilities that have adopted differing sets of radiation protection recommendations as bases for regulation. At the federal

[8] Wolfgang Jacobi introduced the concept of effective dose in 1975 and it was included in Publication 26 by the ICRP (1977) as "effective dose equivalent." In 1991, ICRP publication 60 shortened the name to "effective dose." This quantity is sometimes incorrectly referred to as the "dose equivalent" and that misnomer in turn causes confusion with equivalent dose.

level, NRC, EPA, OSHA, and DOE oversee exposure standards for the public and for workers. The transportation of radionuclides is regulated by the U.S. Department of Transportation. The NRC and the U.S. Food and Drug Administration exercise primary regulatory authority over the use of ionizing radiation in medicine. In some cases, regulatory standards are established at the federal level but are administered by the states. Where federal oversight is absent, some states regulate independently in their roles as protectors of the public health and safety, but state laws and regulations often differ. This has resulted in a patchwork of differing regulations for worker and public exposure limits and different technical bases for regulatory approaches. In addition, public concerns about "liberalizing" dose limits reduces agency support for changing protection philosophies without demonstrably large benefits. Thus, some older rules still use the critical organ approach (e.g., the U.S. DWS), others use effective doses, and other regulatory limits are based entirely on risk evaluations – bypassing dose entirely.

4.2 RAIS Resident Tap Water Scenario and Exposure Pathways

For the purposes of calculating and comparing dose and risk in this evaluation, the exposure pathways for humans to contaminated groundwater are defined using the Resident Tap Water Scenario as described in the Risk Assessment Information System (RAIS).[9] This scenario was selected not only to calculate the risks of drinking water ingestion, but to also to provide the range of doses that would be incurred by a resident who also used the groundwater for bathing and watering a vegetable garden. This scenario does not consider all the pathways included in a resident farmer scenario.

The RAIS Residential Tap Water Scenario uses a standard simple set of assumptions and exposure parameters that are intended to relate an initial, constant well-water concentration to long-term radiation dose and risk. The initiating condition is entered as a concentration of radioactive contaminant(s) in groundwater extracted for domestic use from a well. Doses and risks are based on default exposure parameters and factors that represent Reasonable Maximum Exposure conditions for long-term/chronic exposures and are based in part on the methods outlined in EPA's *Risk Assessment Guidance for Superfund, Part B Manual* (EPA 1991).

[9] RAIS Radionuclide Risk Calculator User's Guide, https://rais.ornl.gov/tools/rais_rad_risk_guide.html
The RAIS online tools are jointly managed by the University of Tennessee and Oak Ridge National Laboratory with support from DOE.

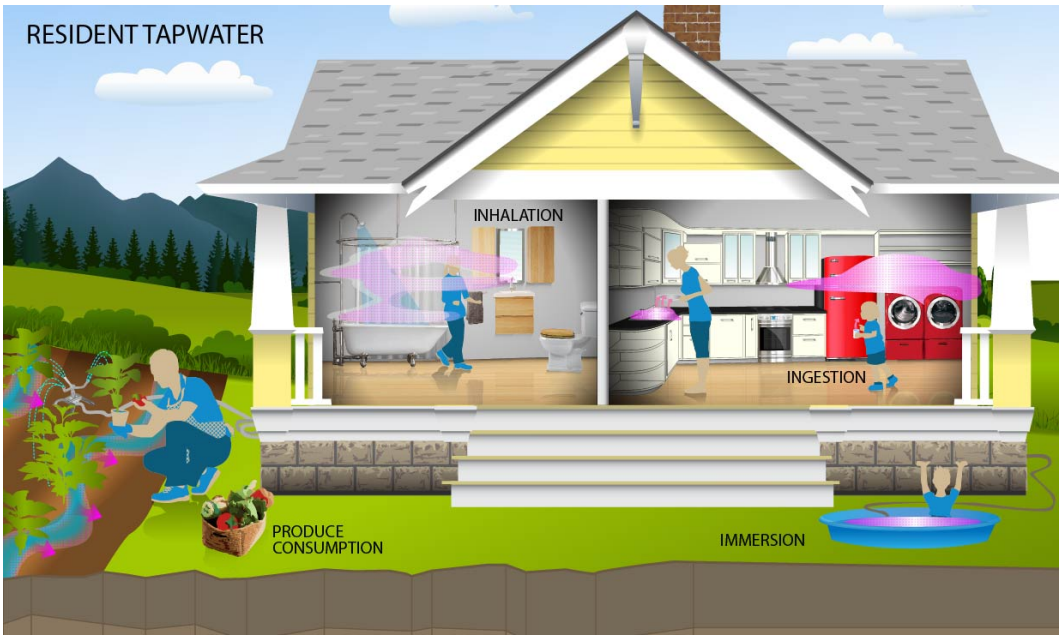

Figure 4.1. Exposure Pathways in the RAIS Resident Tap Water Scenario (as published online RAIS https://rais.ornl.gov/tools/rais_rad_risk_guide.html)

In this scenario, the well water is used without additional processing or purification. The water is used in the home for drinking and other domestic purposes, including laundering, cooking, garden irrigation, and immersion (bathing/swimming). The in-house use releases volatile components to the air within the home, leading to a subsequent inhalation pathway. The water is assumed to be used over a period of many years: An initial period of irrigation for 30 years leads to an accumulation of contaminants in the garden soil.

Calculation of intake of contaminants via direct consumption of contaminated drinking water uses only the average drinking rate and the exposure time. Calculation of inhaled materials is based on the assumption that the quantity of contaminant in indoor air can be expressed as an equivalent mass of water in air (which is essentially humidity for tritiated water); this volatilization factor is based on results of Andelman (1990) for organic chemicals and is assigned a value of 0.5 L/m^3 of water in air.

Garden crops that are ingested are grown on-site and the following assumptions are used to calculate uptake of contaminants:

- Crops are irrigated with well water at a constant rate for a portion of the year, with contaminants accumulating slowly in the soil.
- Radionuclides are removed from the soil by radioactive decay and/or by leaching to deeper soil layers, where they become effectively removed from accessibility.
- The leaching rate is approximately 1% per year
- The soil rooting zone has an “areal density” of 240 kg/m^2 – this is roughly the equivalent of a rooting depth of 15 cm and a soil density of 1.6
- Contaminated sprayed irrigation water deposits materials on the plant surfaces—42% of the material in water irrigated onto the crop deposits on the leaves, and of that 100% remains available (translocate) in edible parts of the crop

- Material deposited by irrigation weathers from the plant surface, with a depletion half-time of 14 days, over a 60-day above-ground growing period
- Fruits and vegetables have a vegetative yield of 2 kg/m^2.
- Root uptake of contaminants from soil is estimated using a soil-to-plant concentration ratio that is contaminant-dependent.
- Plants retain a small amount of soil on their surfaces, which is consumed with the plant; the RAIS calculator uses a constant value of 0.0135 g soil per gram of plant, but the EPA version uses a separate (and usually smaller) value for different types of fruits and vegetables.

Residents are assumed to spend 6 years as children and 20 years as adults at the same residence, for a total exposure of 26 years.[10] Inhalation and consumption rates are based on US national averages as published in the Exposure Factors Handbook. Average rates for children and adults used in the Tap Water Scenario are given in Table 4.4. In this scenario, 25% of foods are locally produced. Annual residence time is 350 d/y to allow some time away. For this analysis, the irrigation rate was assumed to be 600 mm/year, which is considered to be reasonable for irrigation of crops in the Columbia Basin (NRCS 1997).

Table 4.4 Tap Water Scenario Individual Exposure Factors

Exposure Factors	Child	Adult
Drinking water consumption, L/d	0.78	2.5
Inhalation rate, m^3/d	10	20
Vegetable consumption, g/d	41.7	128.9
Fruit consumption, g/d	68.1	188.5
Bathing time, h/d	0.54	0.71

Note: The garden crop consumption rates are totals; they must be prorated for the “contaminated fraction” of produce, which is 25%.

4.3 Dose and Risk Calculated for the Resident Tap Water Exposure Pathways

The methods and parameters recommended over the past 60 years for calculating dose and risk (Section 4.1) were applied using the assumptions and pathways defined for the Resident Tap Water Scenario to allow comparisons of values calculated using older dose and risk models with values developed using scientific approaches currently recommended. Section 4.3.1 provides the calculated annual dose for each of the pathways considered in the Resident Tap Water Scenario. Section 4.3.2 outlines the calculated annual and lifetime risk associated with each pathway except the immersion pathway. The dose and risk coefficients for each of the exposure pathways associated with each set of recommendations used in these calculations are provided in Appendix A.

Both dose and risk are presented here to provide evaluation and basis of comparison with current regulatory guidelines for each of the five low-energy beta radionuclides. Calculations showing the annual dose using the early and current methodologies recommended by the ICRP allow comparison of the contributed dose from each pathway and total dose with the regulatory limit of 4 mrem/y dose for beta-

[10] Although EPA guidance for assessing risks for residential exposures assumes a 30-year lifetime exposure, this evaluation uses the RAIS Resident Tap Water default exposure period of 26 years.

emitting radionuclides. Calculation and presentation of the annual and lifetime risks for each pathway and the total risk allow evaluation with respect to EPA guidance regarding CERCLA, which states that cleanup should generally achieve a level of risk within the 10^{-4} to 10^{-6} carcinogenic risk range based on the reasonable maximum exposure for an individual.

The Resident Tap Water Scenario, as described in Section 4.2, involves calculation of the dose/risk contributions from each pathway: direct consumption of drinking water from a groundwater well (2.5 L/day); ingestion of garden crops irrigated with that water; indirect inhalation of volatilized radionuclides from the water; and immersion (swimming/bathing) in the water. Note that the National Primary DWS is based on the calculated dose from only ingestion of drinking water at a rate of 2 L/day and does not include dose from ingestion of irrigated crops, inhalation, or immersion in well water. Thus, the dose calculated for the Resident Tap Water Scenario represents a more conservative and comprehensive evaluation of the potential exposure to these contaminants in groundwater.

4.3.1 Dose Estimates for the Resident Tap Water Scenario

The evolution of the science of radiation dosimetry, as detailed in Section 4.1, has resulted in essentially five different recommended methodologies and sets of coefficients/values for calculating dose, which are evaluated here as applied in the Resident Tap Water Scenario:

1. The original methodology, the basis of the National Drinking Water Standards, as described in ICRP Publication 2 and National Bureau of Standards Handbook 69 (ICRP-2/NBS Handbook 69) (ICRP 1960; NBS 1963).
2. The first major revision, now used by the NRC, incorporates the methods of ICRP Publication 26 with the dosimetry of the multiple volumes of ICRP Publication 30 (ICRP-26/30).
3. The EPA worked with ICRP during development of ICRP Publications 60 through 72, to release FGR-13 (ICRP-60/72/FGR13).
4. DOE combined several of the ideas of FGR-13 age-dependencies into a single regulatory tool with DOE Standard-1196.
5. The most recent ICRP recommendations in Publication 103 are in the process of being developed in the OIR series.

All doses presented here are for a unit concentration (1 pCi/L) of each of the radionuclides of interest. Doses are estimated using the methodology and parameters as recommended and implemented in ICRP Publication 2/NBS Handbook 69, ICRP-26/ICRP-30, FGR-13/ICRP-72, OIR, and DOE Std-1196 for drinking water ingestion, inhalation, and crop ingestion. For those recommended systems that include the appropriate coefficients and assumptions, the dose to critical organs for either a child or an adult is presented.

It is important to note that the original ICRP-2/NBS Handbook 69 directive using the dose to the “critical organ” as the basis for the maximum permissible body burden was supplanted by the ICRP-26/30 use of “effective dose.” In the development of the concept of “effective dose,” it was recognized that for a few radionuclides that concentrated in specific organs of the body, the doses to the individual organs could exceed 5 rem/y (the limit for dose to an organ) while the effective dose was still below acceptable limits. Thus, it was recommended that the “Allowable Limits of Intake” should be based on either the organ or effective dose, whichever proved limiting. However, in the context of dose or risk limitation for the Drinking Water or Resident Tap Water Scenarios, the doses to all organs are sufficiently small (do not approach the 5 rem/y limit) that the effective dose is considered the appropriate measure of exposure.

In considering the dose from the inhalation pathway, two issues are important to note in the Resident Tap Water Scenario. First, the inhalation pathway is only relevant and estimated for volatile radionuclides: tritium and carbon-14—the other three low-energy beta radioisotopes are considered to be non-volatile.[11] Thus, the data presented here for chlorine-36, iodine-129, and technetium-99 do not include an estimated inhalation dose.

Second, the inhalation exposure estimate uses an approximation for the amount of radioactivity in the air based on the initial concentration in water; this value is the quantity of radionuclides in 0.5 L of water in every 1 m^3 of household air. The value of 0.5 L/m^3 is based on research on volatile chemicals in water released into a room from activities such as showering, cooking, or laundering (Andelman 1990). However, because most radionuclides are non-volatile, this value is used in the EPA modeling for only the radionuclides tritium (as water vapor) and carbon-14 (carbonates in water convert to calcium carbonate deposits releasing CO_2 gas). Still, problems remain with use of this value. The amount of water vapor any mass of air can contain depends on the temperature of that air: the warmer the air is, the more water it can hold. A low relative humidity means that the air is dry and could hold a lot more moisture at that temperature. For example, at 20°C (68°F), a cubic meter of air can hold a maximum of 18 g of water (i.e., 0.018 L). At 25°C (77°F), it can hold 22 g of water (0.022 L). Thus, the use of 0.5 L/m^3 is an on overestimate of at least a factor of 50 because it is assumed that the indoor air is at the over-saturated condition 100% of the time. Similarly, the amount of carbonate in water necessary to produce the assumed concentration is highly unlikely to occur in natural conditions. Therefore, either the indoor inhalation pathway for radionuclides should not be included in the assessment conclusions, or the over estimation of dose should be recognized as being highly conservative and not representative of actual exposures. It is included in this review for tritium and carbon-14 comparisons but noted to be an overly conservative estimate. The calculation of risks is also affected by the same issues and problems associated with the assumptions discussed in this paragraph and so it also noted to be an overly conservative estimate of risks associated with the inhalation pathway.

The dose by radionuclide for the ingestion of drinking water by children and adults is shown in Table 4.5 based on the scenario parameters for ingestion of 0.78 L/day and 2.5 L/day of water for children and adults, respectively. The estimated dose for the inhalation pathway for children and adults is shown in Table 4.6. Table 4.7 presents the dose by radionuclide for the garden crop ingestion pathway for children and adults. Dose factors for immersion were not published in the same sets of recommendations used for the other three pathways. Doses for immersion of children and adults by radionuclide were estimated using ICRP-2 (as exemplified by Napier et al. 1988), FGR-12, and the new FGR-15 methods are presented in Table 4.8.

[11] Section 4.1.4 in the RAIS Radionuclide Risk Calculator User's Guide, https://rais.ornl.gov/tools/rais_rad_risk_guide.html Note that although the RAIS user guide states that "The inhalation exposure route is only calculated for C-14, H-3, Rn-220, and Rn-222 which volatilize," use of the calculator appeared to indicate that all five radioisotopes considered here were assumed to be volatile and inhalation doses were estimated for each of the five. This report presents only the inhalation dose estimated for the two radioisotopes, carbon-14 and tritium, known to be volatile.

Table 4.5. Calculated Annual Dose to Organs and/or Total Body Resulting from the Drinking Water Ingestion Pathway for the Resident Tap Water Scenario (mrem per pCi/L)

	ICRP-2 (NUREG-0172)				ICRP-30		ICRP 72/FGR-13				OIR	STD-1196
Radionuclide	Child Organ Dose	Adult Organ Dose	Child Total Body Dose	Adult Total Body Dose	Adult Organ Dose	Adult Effective Dose	Child Organ Dose	Adult Organ Dose	Child Effective Dose	Adult Effective Dose	Adult Effective Dose	Reference Person Effective Dose
C-14	3.30E-03	2.35E-03	6.61E-04	4.97E-04	1.83E-03	1.83E-03	1.17E-03	2.04E-03	1.00E-03	1.88E-03	5.18E-04	1.72E-03
Cl-36	NP	NP	NP	NP	3.59E-03	2.65E-03	5.19E-03	6.78E-03	3.19E-03	3.01E-03	-- NP	3.38E-03
H-3	5.54E-05	9.19E-05	5.54E-05	9.19E-05	5.60E-05	5.60E-05	5.27E-05	7.96E-05	3.41E-05	6.21E-05	6.13E-05	5.74E-05
I-129	1.52E+00	6.33E+00	2.08E-03	8.06E-03	8.03E+00	2.42E-01	3.47E+00	6.83E+00	1.74E-01	3.42E-01	3.04E-01	2.56E-01
Tc-99	1.92E-03	5.32E-03	5.84E-05	4.39E-05	1.10E-02	1.28E-03	1.46E-02	1.28E-02	2.33E-03	2.07E-03	8.74E-04	2.45E-03

NP = No dose factors provided for chlorine-36 for ICRP 2 or OIR

Table 4.6. Calculated Annual Dose to Organs and/or Total Body Resulting from the Inhalation Pathway for the Resident Tap Water Scenario (mrem per pCi/L)

	ICRP-2 (NUREG-0172)				ICRP-30		ICRP 72/FGR-13				OIR	STD-1196
Radionuclide	Child Organ Dose	Adult Organ Dose	Child Total Body Dose	Adult Total Body Dose	Adult Organ Dose	Adult Effective Dose	Child Organ Dose	Adult Organ Dose	Child Effective Dose	Adult Effective Dose	Adult Effective Dose	Reference Person Effective Dose
C-14	1.70E-02	1.49E-03	3.19E-03	1.49E-03	8.18E-05	8.18E-05	7.39E-05	8.05E-05	7.39E-05	8.05E-05	1.68E-04	7.74E-05
Cl-36	NC	NC--	NC	NC	NC	NC	NC	NC	NC	NC	NA	NC
H-3	5.32E-04	5.53E-04	5.32E-04	5.53E-04	2.24E-04	2.24E-04	2.00E-04	2.38E-04	2.00E-04	2.38E-04	2.59E-04	2.20E-04
I-129	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Tc-99	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC

NC = Not calculated—not volatile radioisotopes

1.

Table 4.7. Calculated Annual Dose to Organs and/or Total Body Resulting from the Garden Crop Ingestion Pathway for the Resident Tap Water Scenario (mrem per pCi/L)

	ICRP-2 (NUREG-0172)				ICRP-30		ICRP 72/FGR-13				OIR	STD-1196
Radionuclide	Child Organ Dose	Adult Organ Dose	Child Total Body Dose	Adult Total Body Dose	Adult Organ Dose	Adult Effective Dose	Child Organ Dose	Adult Organ Dose	Child Effective Dose	Adult Effective Dose	Adult Effective Dose	Reference Person Effective Dose
C-14	1.62E-03	1.04E-04	3.25E-04	2.20E-04	8.10E-04	8.10E-04	5.73E-04	9.04E-04	4.94E-04	8.34E-04	2.30E-04	7.72E-04
Cl-36	NP	NP	NP	NP	2.67E-01	1.97E-01	4.28E-01	5.05E-01	2.64E-01	2.24E-01	NP	2.54E-01
H-3	3.19E-04	4.77E-04	3.19E-04	4.77E-04	2.91E-04	2.91E-04	3.03E-04	4.14E-04	1.97E-04	3.23E-04	3.18E-04	3.01E-04
I-129	4.04E-01	1.51E+00	5.52E-04	1.93E-03	1.92E+00	5.78E-02	9.19E-01	1.63E+00	4.62E-02	8.18E-02	7.28E-02	7.95E-02
Tc-99	6.20E-03	1.55E-02	1.89E-04	1.28E-04	3.20E-02	3.20E-03	4.73E-02	3.73E-02	7.52E-03	6.05E-03	2.55E-03	7.22E-03

NP = No dose factors provided for chlorine-36 for ICRP 2 or OIR

Table 4.8. Calculated Annual Dose to Organs and/or Total Body Resulting from the Immersion Pathway in the Resident Tap Water Scenario (mrem per pCi/L)

	ICRP-2 (GENII V.1.485)	FGR-12 (1993)		FGR-15 (2019 revision)			
Radionuclide	Adult Effective	Adult Organ	Adult Effective	Child (5yr) Organ	Child (5yr) Effective	Adult Organ	Adult Effective
C-14	2.12E-09	4.53E-09	1.45E-09	2.24E-09	6.97E-09	2.26E-09	9.33E-09
Cl-36	1.10E-07	3.71E-07	1.48E-07	1.92E-07	4.66E-07	2.13E-07	6.26E-07
H-3	3.00E-14	0.00E+00	0.00E+00	3.52E-13	5.68E-14	7.45E-14	2.04E-14
I-129	2.36E-07	8.47E-06	2.95E-06	3.19E-06	1.80E-06	4.24E-06	1.70E-06
Tc-99	9.81E-09	3.31E-08	1.04E-08	1.70E-08	7.51E-08	1.77E-08	1.02E-07

Note that the dose resulting from immersion is extremely small for all five of the radionuclides considered, ranging from 2.04E-14 to 6.09E-06, and so is considered to contribute only negligible amounts to the total dose per pCi/L.

The estimated doses for different pathway/radionuclide combinations vary depending on the dose factors for each radionuclide and radionuclide-specific parameters such as solubility and soil to plant transfer factors. Thus, the relative proportion of total body or effective dose contributed by each exposure pathway for the five radionuclides evaluated also vary:

- carbon-14 dose — Drinking Water > Crop Ingestion > Inhalation *(except for ICRP 2 estimates where dose from the Inhalation pathway > Drinking Water and Crop Ingestion pathway)*
- chlorine-36 dose — Crop Ingestion > Drinking Water
- tritium dose — Crop Ingestion > Inhalation > Drinking Water *(except for ICRP 2 estimates where dose from Inhalation > Crop Ingestion > Drinking Water)*
- iodine-129 dose — Drinking Water > Crop Ingestion
- technetium-99 dose — Crop Ingestion > Drinking Water

4.3.2 Risk Estimates for the Resident Tap Water Scenario

Annual and lifetime risk associated with each exposure pathway also were estimated for a unit concentration (1 pCi/L) for the low-energy beta emitting radionuclides considered in this report. Risks were calculated using the risk coefficients from EPA's HEAST tables and risk coefficients from FGR-13 (EPA 2002) for three of the four pathways in the Resident Tap Water Scenario. No risk coefficients were available for calculating the immersion pathway risks, and the risks from immersion are assumed to be so small as to be negligible. Note that HEAST does not provide risk coefficients for calculating the risk to a child.

Table 4.9 through Table 4.11 present the risk estimate per pCi/L for each of the five low-energy beta radionuclides for three exposure pathways of the Resident Tap Water Scenario: drinking water ingestion, inhalation, and irrigated crop ingestion.

Table 4.9 Risk per pCi/L for the Drinking Water Ingestion Pathway in the Resident Tap Water Scenario

		FGR-13		
Radionuclide	HEAST Adult Annual Risk	Child Annual Risk	Adult Annual Risk	Lifetime[(a)] Risk
C-14	9.01E-10	2.35E-09	8.42E-10	2.97E-08
Cl-36	1.95E-09	8.41E-09	1.45E-09	6.32E-08
H-3-	6.26E-11	7.92E-11	2.74E-11	9.70E-10
I-129	1.61E-07	2.19E-07	6.86E-08	2.83E-06
Tc-99	1.23E-09	9.36E-09	6.67E-10	5.26E-08

(a) Lifetime risk is calculated for 26 years of exposure—6 y as child, 20 y as adult.

Table 4.10. Risk per pCi/L for the Inhalation Pathway in the Resident Tap Water Scenario

Radionuclide	HEAST Adult Annual	FGR-13 Child Annual	FGR-13 Adult Annual	FGR-13 Lifetime[(a)]
C-14	2.45E-11	1.82E-10	3.92E-11	1.60E-09
Cl-36	NC	NC	NC	NC
H-3	3.36E-10	4.71E-10	1.16E-10	4.52E-09
I-129	NC	NC	NC	NC
Tc-99	NC	NC	NC	NC

(a) Lifetime risk is calculated for 26 years of exposure—6 y as child, 20 y as adult
NC = Not calculated—not volatile radioisotopes

Table 4.11. Risk per pCi/L for the Irrigated Crop Ingestion Pathway in the Resident Tap Water Scenario

Radionuclide	HEAST Adult Annual	FGR-13 Child Annual	FGR-13 Adult Annual	FGR-13 Lifetime[(a)]
C-14	4.00E-10	1.17E-09	4.07E-10	1.71E-08
Cl-36	1.45E-07	6.96E-07	1.17E-07	6.38E-06
H-3	3.25E-10	4.56E-10	1.56E-10	6.53E-09
I-129	3.85E-08	5.84E-08	1.78E-08	8.91E-07
Tc-99	3.57E-09	3.05E-08	2.22E-09	2.25E-07

(a) Lifetime risk is calculated for 26 years of exposure—6 y as child, 20 y as adult

Comparing lifetime risks (risk/pCi/L) calculated for each of the five radionuclides shows that drinking water ingestion presents the greatest risk per pCi/L for carbon-14 and iodine-129, whereas crop ingestion presents the greatest risk per pCi/L for tritium, chlorine-36, and technetium-99, and the inhalation pathway presents lesser risks (but still a significant contribution for tritium and C-14):

- carbon-14 Drinking Water > Crop Ingestion > Inhalation
  2.97E-08 1.71E-08 1.60E-09
- chlorine-36 Crop Ingestion > Drinking Water
  6.38E-06 6.32E-08
- tritium Crop Ingestion > Inhalation > Drinking Water
  6.53E-09 4.52E-09 9.70E-10
- iodine-129 Drinking Water > Crop Ingestion
  2.83E-06 8.91E-7
- technetium-99 Crop Ingestion >Drinking Water
  2.25E-7 5.26E-08

4.3.3 Evaluation of Dose and Risk for Low-Energy Beta Radionuclides

The total dose and total risk summed for the pathways evaluated in the Resident Tap Water Scenario are presented in this section. Note that the total dose summed for non-volatile radioisotopes (chlorine-36, iodine-129, and technetium-99) does not include a dose from the inhalation pathway. Comparisons of dose focus on the summed effective dose based on the recent recommendations of the ICRP (Table 4.12). The effective dose currently is recommended as a standard for use in evaluating radiation protection because effective dose considers the equivalent doses to all organs, each adjusted to account for the

sensitivity of the organ to radiation. Effective dose takes three factors into account: the absorbed dose to all organs of the body, the relative harm level of the radiation, and the sensitivities of each organ to radiation.

The largest differences in doses calculated using the different sets of recommendations are between the effective dose compared to the doses estimated using recommendations in ICRP-2 and the estimated organ doses. The estimated effective dose is less than 1 mrem/pCi/L for all radionuclides considered regardless of which set of updated recommendations from ICRP is used in calculating dose. Although the calculated organ doses are up to several orders of magnitude greater than effective dose, they represent a targeted exposure of the most sensitive organ and are not representative of the dose that person would incur in the tap water scenario considered here.

As previously indicated, the National Primary DWS (EPA 2000; 40 CFR Parts 9, 141, and 142) specify MCLs for radionuclides that represent the ARARs for determining cleanup levels for radionuclides in groundwater at most CERCLA sites under authority of the EPA. For anthropogenic beta particles and photon radioactivity (e.g., gamma radiation), EPA considers an annual cumulative dose equivalent of less than 4 mrem to the total body or any internal organ to be protective of human health as determined using dosimetric methods and parameters outlined in NBS Handbook 69 (NBS 1963) and ICRP Publication 2 (ICRP 1960). This annual dose is the basis for the MCLs indicated in the DWS. As part of this evaluation, derived concentrations equivalent to a 4 mrem/y adult effective dose incurred from ingestion of drinking water were calculated for each of the five low-energy beta radioisotopes using updated recommendations for comparison with the current DWS (Table 4.13). In evaluating the data in Table 4.13, it is important to note that the concentrations derived based on the estimates of effective dose were calculated using a drinking water ingestion rate of 2.5 L/day for adults, whereas the DWS concentrations were derived assuming a 2 L/day ingestion rate for drinking water. Also note that because the estimated effective dose for children is based on drinking less water (0.78 L/d), the derived concentrations for adults represents a more conservative value than concentrations corresponding to a 4 mrem/y effective dose to children.

Table 4.12. Total Annual Dose for a Unit Concentration of 1 mrem/pCi/L Estimated as the Sum of Doses from All Pathways in the Resident Tap Water Scenario

Dose (mrem/ Ci/L)	ICRP-2 (NUREG-0172)				ICRP-30		ICRP-72/FGR-13				OIR / ICRP-103	STD-1196
Radionuclide	Child Organ Dose	Adult Organ Dose	Child Total Body Dose	Adult Total Body Dose	Adult Organ Dose	Adult Effective Dose	Child Organ Dose	Adult Organ Dose	Child Effective Dose	Adult Effective Dose	Adult Effective Dose	Reference Person Effective Dose
C-14	0.0219	0.0049	0.0042	0.0022	0.0027	0.0027	0.0018	0.0030	0.0016	0.0028	0.0009	0.0026
Cl-36	NP	NP	NP	NP	0.2711	0.1998	0.4332	0.5115	0.2668	0.2270	NP	0.2571
H-3	0.0009	0.0011	0.0009	0.0011	0.0006	0.0006	0.0006	0.0007	0.0004	0.0006	0.0006	0.0006
I-129	1.9272	7.8389	0.0026	0.0100	9.9488	0.2993	4.3863	8.4678	0.2204	0.4239	0.3771	0.4091
Tc-99	0.0081	0.0208	0.0002	0.0002	0.0430	0.0050	0.0620	0.0500	0.0098	0.0081	0.0034	0.0097

NC = Not proivded; no dose factors published for chlorine-36 in these recommendations

Table 4.13. Derived Concentrations Corresponding to a 4 mrem/y Effective Dose through Ingestion of Drinking Water for Carbon-14, Chlorine-36, Tritium, Iodine-129, and Technetium-99.

Radionuclide	DWS-equivalent derived activity concentrations (pCi/L)[(a)]	ICRP-30 (pCi/L)	ICRP-72/FGR-13 (pCi/L)	ICRP-103/OIR (pCi/L)	STD-1196/ICRP-60; ICRP-72 (pCi/L)
C-14	2000	2191	2126	7722	2320
Cl-36	200	1510	1329	N/A	1184
H-3	20,000	71417	64386	65306	69669
I-129	1	17	12	13	12
Tc-99	900	3128	1929	4576	1632

(a) The EPA DWS for radionuclides derived based on a 4 mrem/y dose standard using maximum permissible concentrations in water specified in NBS Handbook 69, *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure*. 40 CFR 141.16

N/A = not available

The total risk for the Resident Tap Water Scenario shown in Table 4.14 represents the sum of risks posed by the drinking water, inhalation, and crop ingestion pathways that are presented in Section 4.3.2. No risk coefficients are available to calculate risk for the immersion pathway, which is assumed to be negligible.

Table 4.14. Total Risk per Unit Concentration (pCi/L) for the Resident Tap Water Scenario

Radionuclide	HEAST Adult Annual	FGR-13 Child Annual	FGR-13 Adult Annual	FGR-13 Lifetime[(a)]
C-14	1.3E-09	3.7E-09	1.3E-09	4.8E-08
Cl-36	1.5E-07	7.0E-07	1.2E-07	6.4E-06
H-3	7.2E-10	1.0E-09	3.0E-10	1.2E-08
I-129	2.0E-07	2.8E-07	8.6E-08	3.7E-06
Tc-99	4.8E-09	4.0E-08	2.9E-09	2.8E-07

(a) Lifetime risk is calculated for 26 years of exposure—6 y as child, 20 y as adult.

To put the risk per pCi/L in perspective for these five radioisotopes, we can examine the range of concentrations that would result in a specific level of risk. For making risk management decisions, EPA generally uses a risk level of 1×10^{-4} as the upper value of acceptable risk. Table 4.15 presents the concentration that would result in an annual or lifetime (26 years) risk level of 10^{-4} based on the ingestion of drinking water (2.5 L/d) for each of the low-energy beta radionuclides found in groundwater at Hanford.

Table 4.15. Concentrations of Five Low-Energy Beta Radionuclides that Correspond to a 10^{-4} Risk Level from Ingestion of Drinking Water

Radionuclide	HEAST Adult All	FGR-13 Child Annual	FGR-13 Adult Annual	FGR-13 26-yr Lifetime
C-14	110957	42494	118800	3371
Cl-36	51249	11893	68847	1583
H-3	1598402	1263105	3651301	103061
I-129	621	456	1458	35
Tc-99	81633	10679	149981	1900

A more conservative approach to evaluating the potential risk associated with these five radionuclides in groundwater can be accomplished by examining the concentrations that correspond to a risk level of 10^{-4} for the sum of all pathways examined in the Resident Tap Water Scenario (ingestion of drinking water, ingestion of irrigated crops, and inhalation for volatile compounds). These values are shown in Table 4.16.

Table 4.16. Concentrations of Five Low-Energy Beta Radionuclides that Correspond to a 10^{-4} Risk Level from Exposure through the Pathways in the Resident Tap Water Scenario

	HEAST	FGR-13		
Radionuclide	Adult	Child	Adult	Lifetime
C-14	75446	27003	77613	2066
Cl-36	679	142	843	16
H-3	138281	99417	334701	8315
I-129	501	360	1157	27
Tc-99	20841	2511	34635	360

4.3.4 Spatial Visualization of Cumulative Risk

The risks calculated for the Resident Tap Water Scenario can be associated with the plume concentrations of radioisotopes found in Hanford groundwater. Prioritizing and designing risk management strategies can be aided with spatial displays of risk associated with plume concentrations, As an example, the lifetime risk levels determined using the Resident Tap Water Scenario that correspond to the 2018 plume concentration contours for iodine-129 and tritium are shown in Figure 4.2. Note that these “risk contours” take into account both drinking water and irrigated crop ingestion of iodine-129 and tritium as well as inhalation of volatilized tritium over a 26-year exposure period for an individual. The light yellow areas of the plume present a risk of $\leq 4.5 \times 10^{-5}$ associated with iodine-129 concentrations between 1 and 10 pCi/L. Areas delineated in orange (>10 pCi/L) represent risk greater than 4.5 x 10-5, but likely less than 1.0×10^{-4} based on the maximum iodine-129 concentrations (23 pCi/L; DOE-RL-2018-66) measured on the Central Plateau in 2018. For tritium, lifetime risks of 10^{-4} to 10^{-3} are associated with concentrations of 20,000 pCi/L to 200,000 pCi/L, shown in pale blue on the map. Note that where the plumes overlap, the risks are higher and are assumed to be additive. Also note that radioactive decay of tritium contributes to diminishing risk over time because of its short half-life of about 12.5 years.

Although these risk maps represent static illustrations of the current risk, they can play important roles in decision frameworks because areas of concern can be more easily identified. These concepts can be extended to visualize and model the results of adaptive management strategies and natural attenuation over time. Incorporating risk map information with groundwater simulation predictions would allow decision-makers to examine the resulting declines in exposure and risk as contaminant concentrations are reduced (especially with tritium) and examine management strategies for remedial options and institutional controls. Combining spatial risk maps with spatially explicit groundwater modeling of contaminant plume extent, volume, and mass can also aid in evaluating the technical and economic implications of different remediation strategies and land use decisions.

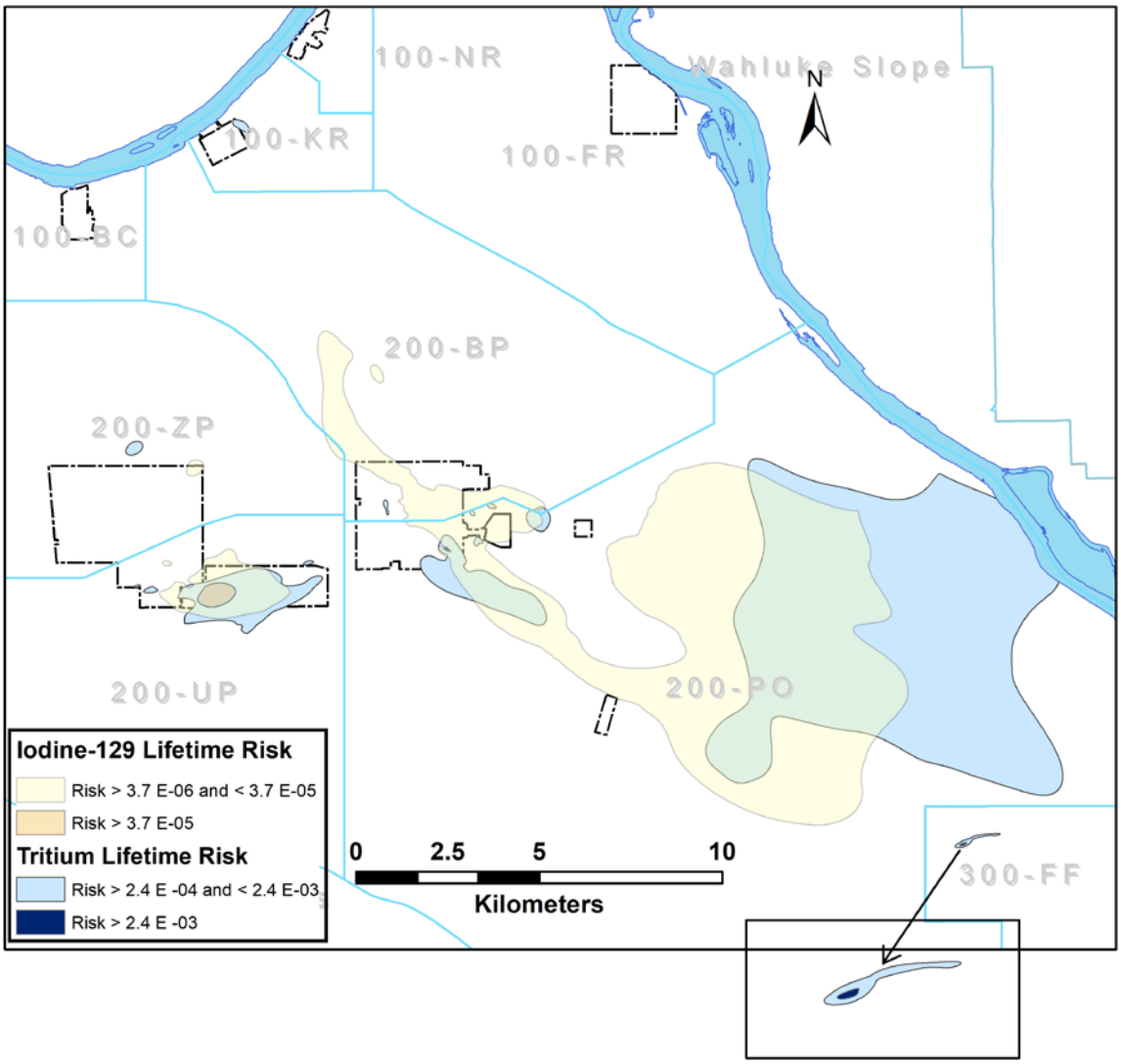

Figure 4.2. Estimated Risk Levels Corresponding to 2018 Iodine Groundwater Plume Concentrations

5.0 Summary and Conclusions

The current U.S. drinking water standards are based on radiation protection science from more than 50 years ago. The 4 mrem/y groundwater objective was assigned by EPA as the portion of the total dose incurred from the drinking water pathway. This value and the ICRP 2/Handbook 69 dose assumptions and coefficients formed the basis for developing the DWS adopted as part of the Safe Drinking Water Act. Although EPA originally intended to evaluate the technical basis for the DWS and consider updated recommendations for dosimetry and risk related to the DWS, the 1976 Interim DWS were finalized using the original technical basis. In comparison, international standards for the protection of drinking water rely on updated recommendations of the ICRP and the BSS—and concentration limits are significantly different than those used in the United States. Internationally, the WHO DWS are based on the assumption that prolonged exposures resulting in a dose of 10 mrem/y (0.1 mSv/y) or less would not be harmful.

In this report, information is provided on how the current scientific methodologies for determining dose and risk could be applied to determine derived concentrations that correspond to the 4 mrem/y dose limit for low-energy beta radioisotopes. For four of the five low-energy beta radioisotopes considered here, derived concentrations corresponding to 4 mrem/y limit for ingestion of drinking water based on the current scientific methodologies for calculating effective dose are 3 to 10 times greater than the derived concentrations used for the National Primary DWS, which are based on the older, original methodologies. Derived concentrations for a 4 mrem/y dose for carbon-14, although still greater than the DWS of 2000 pCi/L, are only significantly different for the occupational intake of radionuclides. Derived concentrations of the radionuclides that would correspond to 10^{-4} risk levels for ingestion of drinking water are also greater than the MCLs indicated in the National Primary DWS. EPA's policy decision to use the NCP's risk range (10^{-4} to 10^{-6}) in developing risk management strategies for cleanup of radionuclides at CERCLA remedial sites indicates that risk-based concentrations such as those shown in Table 4.15 and Table 4.16 for derived concentrations corresponding to a 10^{-4} risk level represent a starting point for developing risk-informed cleanup standards and prioritizing actions.

When evaluating risk management strategies, the current assumptions and science-based approaches for calculating dose and risk may be appropriate to consider. This type of approach and the calculation of risk-based cleanup levels is central to developing a decision-making approach that considers trade-offs among risks to human health and the environment, cost, and other factors as recommended by the GAO (2019). It also allows risk-informed prioritization of remediation, providing information needed to assess and rank risks within and among sites and thus allocate federal taxpayer monies to manage the highest-priority risks through the most cost-effective means (GAO 2019).

As described in this report, concentrations of low-beta radioisotopes that correspond to lifetime risk levels of 10^{-4} for drinking water ingestion range from 1.7 (carbon-14) to more than 10 (iodine-129) times the DWS MCLs. Using the current ICRP recommended approach for calculating effective dose and risk provides a technically defensible line of evidence that can be weighed and considered by decision-makers, regulators, and stakeholders in developing protective risk-based remediation approaches.

6.0 Quality Assurance

This work was performed in accordance with the Pacific Northwest National Laboratory (PNNL) Nuclear Quality Assurance Program (NQAP). The NQAP complies with the United States Department of Energy Order 414.1D, Quality Assurance. The NQAP uses NQA-1-2012, Quality Assurance Requirements for Nuclear Facility Application as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality.

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Appendix A – Dose and Risk Coefficients for Low-Energy Beta Emitters Based on ICRP Recommendations from 1959 through 2019

The recommendations issued by the International Commission on Radiological Protection (ICRP) and the U.S. Environmental Protection Agency (EPA) over the past 60 years result in changes to the coefficients used dose and risk coefficients used in calculation. This appendix presents the dose and risk coefficients for the three main pathways addressed. Ingestion dose coefficients (normalized to units of rem/Ci) for the radionuclides of interest in this report are presented in Table A.1 to allow evaluation of the changes in dose coefficients as dosimetry evolved over the past 50 years. Table A.2 and Table A.3 provide similar comparisons of the inhalation dose coefficients and immersion dose coefficients (normalized to rem/h per pCi/L). Comparison of the ingestion risk coefficients (normalized to units of Ci ingested) for the radionuclides of interest in this report are presented in Table A.4. Changes in inhalation risk coefficients are similarly compared in Table A.5.

Table A.1. Recommended Ingestion Dose Coefficients (rem/Ci)

	ICRP-2 (1960)		ICRP-30 (1979)		ICRP-72/FGR13 (1996/1999, 2002)		ICRP-103 (2007)/ OIR[(a)] (2015-2019)	STD-1196 (2011)
Radionuclide	Total Body	Critical Organ	Effective Dose	Highest Organ Equivalent Dose	Effective Dose	Highest Organ Equivalent Dose	Effective Dose	Reference Person Effective Dose
C-14	568	2680	2087	2087	2150	2330	592	2342
Cl-36	NP	NP	3027	4107	3440	7750		4588
H-3 H_2O	105	105	64	64	71	91	70	78
H-3 Organic	NP	NP	NP	NPA	155	176	189	169
Tc-99	50.2	6080	1461	12543	2370	14600	999	3330
I -129	9210	7230000	276020	917600	391000	7810000	347800	447700

(a) OIR organ doses not yet available.
NP = Not ProvidedAvailable

Table A.2. Recommended Inhalation Dose Coefficients (rem/Ci)

	ICRP-2 (1959)			ICRP-30			ICRP-72/FGR13 (1995/1999, 2002)			OIR (2015-2019)		STD-1196 (2011)
Radionuclide	Lung Clearance Class	Total Body	Critical Organ	Lung Clearance Class	Effective Dose Equivalent	Highest Organ Effective Dose	Lung Clearance Class	Effective Dose	Highest Organ Effective Dose	Lung Clearance Class	Effective Dose	Reference Person Effective Dose
C 14	NA	426	426	CO_2	24	24	CO_2	23	23	CO_2	48	25
	NP	NP	NP	Y	NP	NP	S	21200	174000	S	44400	22755
Cl-36	NA	NP	NP	D	2242	4912	F	1220	4710	F	NP	1524
	NP	NP	NP	W	20350	170200	M	27100	19100	M	NP	29785
	NP	NP	NP	Y	NP	NP	S	140000	1160000	S	NP	214
H 3	NA	158	158	Vapor	64	64	Vapor	67.9	67.9	Vapor	74	71
	NP	NP	NP	Organic	NP	NP	Organic	153	153	Organic	85.1	158
I-129	NA	6910	5540000	D	173530	5772000	F	133000	2650000	F	236800	150220
	NP	NP	NP	Vapor	NP	NP	Vapor	355000	7090000	Vapor	347800	403300
	NP	NP	NP	Organic	NP	NP	Organic	277000	5520000	Organic	244200	311170
Tc-99	NA	12.5	101000	W	8325	8214	M	14900	118000	M	4070	16354
	NP	NP	NP	Y	NP	NP	S	49400	407000	S	107300	52540

(a) OIR organ doses not yet available; STD-1196 organ doses not published
(b) ICRP-2 had only a single inhalation category
NA = Not Applicable
NP = Not Provided

Table A.3. Recommended Immersion (Swimming) Dose Coefficients (rem/hour per Ci/L)

	ICRP-2 (GENII V.1.485)	FGR-12 (1993)		FGR-15 (2019 revision)			
	Adult Effective Dose	Adult Organ Dose	Adult Effective Dose	Child Organ Dose	Child Effective Dose	Adult Organ Dose	Adult Effective Dose
Radionuclide	rem/h per Ci/L						
C-14	8.53E-03	1.82E-02	5.85E-03	1.26E-02	3.90E-02	9.11E-03	3.76E-02
Cl-36	4.43E-01	1.49E+00	5.97E-01	1.07E+00	2.61E+00	8.55E-01	2.52E+00
H-3	1.21E-07	0.00E+00	0.00E+00	1.97E-06	3.90E-07	3.00E-07	8.19E-08
I-129	9.50E-01	3.41E+01	1.19E+01	1.78E+01	1.01E+01	1.70E+01	6.85E+00
Tc-99	3.95E-02	1.33E-01	4.18E-02	9.55E-02	4.21E-01	7.13E-02	4.12E-01

Table A.4. Ingestion Risk Coefficients (per Ci)

	HEAST	FGR-13					
	Adult	Child		Adult		Lifetime	
Radionuclide	All	Water	Diet	Water	Diet	Water	Diet
C-14	1.03E+00	8.62E+00	8.70E+00	9.62E-01	1.05E+00	1.55E+00	2.00E+00
Cl-36	2.23E+00	3.08E+01	3.09E+01	1.66E+00	1.80E+00	3.30E+00	4.44E+00
H-3 H_2O	7.15E-02	2.90E-01	2.90E-01	3.13E-02	3.43E-02	5.07E-02	6.51E-02
H-3 Organic		6.25E-01	6.33E-01	6.92E-02	7.59E-02	1.12E-01	1.44E-01
I-129	1.84E+02	8.03E+02	8.07E+02	7.84E+01	8.51E+01	1.48E+02	1.93E+02
Tc-99	1.40E00	3.43E+01	3.45E+01	7.62E-01	8.70E-01	2.75E+00	4.00E+00

Table A.5. Inhalation Risk Coefficients (per Ci)

Radionuclide	Lung Clearance Class	HEAST Adult	FGR-13 Child	FGR-13 Adult	FGR-13 Lifetime
C 14	CO_2	6.99E-03	1.04E-01	1.12E-02	1.99E-02
	Y/S		1.02E+02	1.06E+01	1.69E+01
Cl-36	D/F	1.30E+00	1.17E+01	5.92E-01	1.32E+00
	W/M		1.47E+02	1.47E+01	2.50E+01
	Y/S		5.77E+02	6.85E+01	1.01E+02
H-3	Vapor	9.59E-02	2.69E-01	3.30E-02	5.62E-02
	Organic		6.22E-01	7.40E-02	1.28E-01
	Y/S		6.44E+00	4.96E-01	8.51E-01
I-129	D/F	1.22E+02	3.11E+02	2.89E+01	6.07E+01
	Vapor		7.47E+02	7.73E+01	1.60E+02
	Organic		5.81E+02	6.03E+01	1.24E+02
Tc-99	W/M	2.89E+00	8.18E+01	7.96E+00	1.41E+01
	Y/S		2.23E+02	2.45E+01	3.81E+01

Note: For FGR-13, Child 1-5, Adult 25-70, and Lifetime 0-110 years; Cancer Incidence (Morbidity)

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