FINAL REPORT

A Risk-based Screening Analysis for Radionuclides Released to the Columbia River from Past Activities at the U.S. Department of Energy Nuclear Weapons Site in Hanford, Washington

Department of Health and Human Services
Centers for Disease Control and Prevention

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"Setting the standard in environmental health"
RAC
Risk Assessment Corporation
417 Till Road, Neeses, SC 29107
Phone 803.536.4883 Fax 803.534.1995

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Authors

Helen A. Grogan, Ph.D., Cascade Scientific, Inc.
Arthur S. Rood, K-Spar, Inc.
Jill Weber Aanenson, Scientific Consulting, Inc.
Edward B. Liebow, Ph.D., Environmental Health and Social Policy Center

Principal Investigator

John E. Till, Ph.D., *Risk Assessment Corporation*

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EXECUTIVE SUMMARY

The Hanford Environmental Dose Reconstruction (HEDR) Project reconstructed doses to offsite members of the public resulting from radionuclide releases since 1944 from operation of U.S. Government facilities at the Hanford Nuclear Site, in Washington State. This report focuses on radionuclide releases into the Columbia River. Initially, the HEDR Project considered all radionuclides released into the Columbia River between 1944 and 1972. Following a series of scoping calculations, doses were calculated for five radionuclides: sodium-24, phosphorus-32, zinc-65, arsenic-76, and neptunium-239. The radionuclide exposure pathways were also selected on the basis of screening calculations.

In a review of the HEDR dose estimates for the Agency for Toxic Substances and Disease Registry (Hoffman et al. 1998), it was suggested that ^{131}I, ^{60}Co, and ^{90}Sr should have been included in the HEDR dose calculations for the Columbia River. The objective of this report was to develop and apply a risk-based screening methodology that could be used to evaluate this recommendation. The screening methodology was applied to 23 radionuclides to ensure a more comprehensive evaluation, rather than limiting it to the 5 HEDR radionuclides with dose estimates and the 3 radionuclides identified in the ATSDR review.

A two-stage screening process was developed. The initial screening was based on conservative assumptions with regard to the exposure location, duration of exposure, and exposure pathway characteristics. Because of these conservative assumptions the screening values are generally overestimates of risk to the most exposed individuals and are expected to overestimate the risks to all real individuals. The availability of extensive historical monitoring data for the Columbia River allowed us to make realistic estimates of radionuclide concentrations in the Columbia River water and sediment.

A 2-dimensional advection-dispersion river transport model was developed to calculate radionuclide concentrations in river water and sediment from the downstream Hanford Site boundary to the McNary Dam below the confluence of the Snake River. Transport of radionuclides in both the dissolved and sorbed phase was considered, and was coupled to conservative assumptions for the exposure pathway scenarios to estimate screening risk values. The river transport model was calibrated to measured river water and sediment concentrations. In some cases, adjustments to the source term were made to provide better agreement between model predictions and measured data.

The exposure pathways considered were:

- Direct ingestion of river water
- Ingestion of fish
- Immersion in river water
- Ingestion of river water during swimming
- Ingestion of waterfowl
- External exposure to sediments
- Exposure to sediments through dermal contact
- Ingestion of sediments
- Inhalation of aerosols
- External exposure while boating
- Ingestion of produce irrigated with river water
- Ingestion of meat from cattle drinking river water and consuming feed that was irrigated with river water

- Ingestion of milk from cows drinking river water and consuming feed that was irrigated with river water

These pathways account for the different types of river users, activities, and practices that may have resulted in exposure to radionuclides released to the Columbia River. Explicit consideration was given to Native American tribes potentially impacted by releases from the Hanford Site because they lived in close proximity to the river and their lifestyle activities were intimately linked with the river. Screening values were calculated at two locations immediately downstream of the Hanford nuclear facility, Ringold and Richland. The highest screening values were calculated for Richland, and were therefore used for the analysis. When a risk-based screening criterion of 10^{-4} was applied[a], nine radionuclides (^{45}Ca, ^{51}Cr, ^{56}Mn, ^{64}Cu, ^{69,69m}Zn, ^{89}Sr, ^{93}Y, ^{122}Sb, and ^{133}I) were identified with screening values less than 10^{-4}. The uncertainty associated with the screening values for these nine radionuclides was assessed, and resulted in two (^{89}Sr and ^{133}I) remaining in the analysis. As a consequence, seven radionuclides were eliminated in the initial screening.

In the second-step of the screening process, three exposure scenarios were defined to represent the differing habits and activities of the most exposed river users: Native American, local resident, and migrant worker. The parameter values for the three exposure scenarios were selected to represent an average individual in the group rather than the most exposed individual. The focus was on assigning the parameter values consistently to allow the relative significance of the 15 radionuclides and the most important exposure pathways to be identified. The resulting risk-based screening values were expected to overestimate actual risks because the exposures were assumed to have occurred throughout the entire period of releases from the Hanford nuclear site (1944–1972) with the representative individual located at Richland.

The Native American scenario had the highest calculated screening values and the local resident scenario the lowest. For all three scenarios, four radionuclides accounted for more than 80% of the total risk. These were ^{76}As, ^{239}Np, ^{32}P and ^{65}Zn. This supported the HEDR Project conclusions where dose calculations were made for these four radionuclides. Unlike the HEDR Project, ^{76}As was shown to be the most important radionuclide for exposures at Richland and Pasco. The HEDR Project identified ^{32}P and ^{65}Zn as the dominant radionuclides. This difference occurred because the decrease in radioactivity in fish from the time they were caught to the time they were consumed was treated differently between the studies. The HEDR Project calculated doses not cancer incidence risks, and the dietary intake risk coefficient for ^{76}As is proportionally higher than those for ^{65}Zn and ^{32}P. Finally, a higher bioconcentration factor for ^{76}As was used in this study than in the HEDR Project.

The HEDR Project also made dose calculations for ^{24}Na, where it was shown to account for approximately 7% of the total effective dose equivalent for a maximum representative individual at Richland from 1944 to 1971. Our analysis supported this conclusion and suggested that ^{95}Zr in particular, and possibly ^{60}Co and ^{137}Cs represented comparable risks and may have warranted additional analysis. It appeared that ^{95}Zr was inadvertantly eliminated from the HEDR Project study at the screening stage because there were no release estimates available for the year the screening calculations were performed. Cobalt-60 consistently accounted for 1 to 2% of the total risk in the three scenarios. The source terms for ^{60}Co and ^{137}Cs are poorly understood and additional work outside the scope of this project would be required to develop more accurate

[a] Use of this value does not represent endorsement by the Centers for Disease Control and Prevention.

release estimates. Fallout from atmospheric weapons testing may have exaggerated the significance of ^{137}Cs in this study. However, the current screening is unlikely to underestimate the risks associated with these radionuclides and we believe this should be considered before any further work is undertaken in this area.

The screening results did not support the suggestion that the HEDR Project should have made dose calculations for ^{131}I and ^{90}Sr. Although they were not eliminated in the initial screening, they were identified as low priority in all three exposure scenarios (ranked lower than 10 out of 15). We accounted for the consumption of whole fish including the bones by Native Americans; however, our research indicated it was unrealistic to assume whole fish were consumed year round in large quantities. For this reason the dose and risk for ^{90}Sr (and ^{89}Sr) was not increased significantly. Iodine-131 screening values were ranked consistently low for the three representative scenarios. On an absolute level, ^{131}I risk for the local resident scenario at Richland was about a factor of 20 less than the estimated risk from atmospheric releases of ^{131}I at Ringold. Therefore, ^{131}I did not appear to warrant further investigation. If further evaluation of risks from radionuclides released to the Columbia River is undertaken, the following four radionuclides are considered most important for the analysis: ^{76}As, ^{239}Np, ^{32}P and ^{65}Zn; the following four of moderate priority: ^{24}Na, ^{95}Zr, ^{60}Co and ^{137}Cs, and that ^{131}I, ^{133}I, ^{90}Sr, ^{89}Sr, ^{72}Ga, ^{46}Sc, and ^{90}Y were of low priority and probably could be dismissed.

The screening results support the HEDR Project conclusion that fish ingestion was the dominant exposure pathway for releases to the Columbia River. Most of the exposure was incurred over the years 1952 to 1964. These years correspond to the years of highest release from the Hanford reactors. The significance of fish ingestion for Native American users of the river was greater than that for non-Native American users by a factor of ten because fish consumption rates reported for Native Americans tended to be higher than the value assumed for the maximum representative individual in the HEDR Project and for the migrant worker and local resident scenarios.

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ACRONYMS

API	American Petroleum Institute
ATSDR	Agency for Toxic Substances and Disease Registry
BCF	bioconcentration factor
CDC	Center for Disease Control and Prevention
EDE	effective dose equivalent
EPA	U.S. Environmental Protection Agency
FB	fractional bias
HEDR	Hanford Environmental Dose Reconstruction (Project)
ICRP	International Commission on Radiological Protection
IDA	individual dose assessment
K_d	sorption coefficient ($m^3\ g^{-1}$)
NCRP	National Council on Radiation Protection and Measurements
NESHAPs	National Emissions Standards for Hazardous Air Pollutants
NID	negligible individual dose
NMSE	normalized mean square error
NRC	U.S. Nuclear Regulatory Commission
P/O	predicted-to-observed
RM	River Mile
STRRM	Source Term River Release Model
TSP	Technical Steering Panel
UF	uncertainty factor
USGS	U.S. Geological Survey

A RISK-BASED SCREENING ANALYSIS FOR RADIONUCLIDES RELEASED TO THE COLUMBIA RIVER FROM PAST ACTIVITIES AT THE U.S. DEPARTMENT OF ENERGY NUCLEAR WEAPONS SITE IN HANFORD, WASHINGTON

1. OBJECTIVE

The primary purpose of the Hanford Environmental Dose Reconstruction (HEDR) Project was to reconstruct doses to offsite members of the public resulting from radionuclide releases since 1944 from operation of U.S. Government facilities at the Hanford Nuclear Site, in Washington State. The Columbia River Dosimetry Code (Farris et al. 1994a) was developed as part of the HEDR Project to calculate radiation doses for hypothetical individual users of the Columbia River at various locations on the river. Initially, the HEDR Project considered all radionuclides released from the Hanford Nuclear Site between 1944 and 1972. Ultimately, doses were calculated for five radionuclides: ^{24}Na, ^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np. The water concentrations for these radionuclides were estimated by the CHARIMA computer code (Walters et al. 1994).

The Technical Steering Panel of the HEDR Project selected the five radionuclides on the basis of a series of screening calculations (Napier 1993). The radionuclide exposure pathways considered in the dose calculations were also selected on the basis of these screening calculations. In a review of the HEDR dose estimates for the Agency for Toxic Substances and Disease Registry (ATSDR), Hoffman et al. (1998) suggested that ^{131}I, ^{60}Co, and ^{90}Sr should also have been included in the HEDR dose calculations and in the Hanford individual dose assessment (IDA)[b] process for the Columbia River.

This report developed and applied a screening methodology to the radionuclide releases to the Columbia River (see Appendix A for the original statement of work). To ensure a more comprehensive evaluation, the screening methodology was applied to a total of 23 radionuclides rather than just the five radionuclides with dose estimates in the HEDR Project, as well as the 3 radionuclides suggested by Hoffman et al. (1998).

A risk-based decision criterion for the screening was recommended and applied to determine if any radionuclides could be eliminated from further consideration using conservative assumptions about exposure to Columbia River water. Following the initial screening, three scenarios were used to represent the river users most at risk and to prioritize the radionuclides and exposure pathways. This report compared these results with the original HEDR analysis and the recommendations of Hoffman et al. (1998).

1.1. Screening Methodologies

Screening refers to the process that identifies potentially important radionuclides and/or exposure pathways by eliminating those of probably lesser significance. Typically, screening is designed to be a relatively rapid process that is conducted early in a study to identify where effort and resources should be allocated. Two general approaches can be used for screening: one is based on comparison to an absolute cirterion and the other on a prioritization (relative ranking).

[b] The Hanford IDA Project is designed to allow individuals exposed to Hanford radiation releases historically to estimate their individual radiation doses.

Using the absolute screening approach, screening values for radionuclides and/or pathways are compared to an absolute screening criterion. Radionuclides with screening values less than the criterion are not considered any further. The screening value is typically a conservative estimate of effective dose equivalent, carcinogenic risk, or some other relevant endpoint. In this study, incremental lifetime cancer incidence risk was used as the screening value. Only those radionuclides and/or pathways with screening values above the predefined screening criterion are considered further in the analysis. For this approach to be effective, it is essential that no potentially significant radionuclide or exposure pathway is removed from the analysis. To ensure this is the case, conservative assumptions are made to characterize the exposure pathways and the radionuclide parameter values.

Using the prioritization approach, radionuclides and pathways are evaluated and ranked in order of significance. To allow a relative ranking it is important that the parameter values used to characterize the exposure pathways and the radionuclides are selected in a consistent manner to avoid biasing the results. Assigning realistic parameter values is preferred because it is difficult to define parameter values with the same degree of conservatism consistently. Furthermore, the relative importance of exposure pathways may depend on the concentration of the radionuclide in the environment.

Both approaches have advantages and disadvantages. Using the absolute screening approach radionuclides and pathways of no potential significance are removed from the analysis. However, the conservatism associated with the absolute screening may result in few radionuclides and/or exposure pathways being eliminated. Also, the absolute screening approach provides little information about the relative importance of specific exposure pathways or radionuclides. On the other hand, prioritization may require excessive effort to achieve a defensible relative ranking.

1.1.1. Screening Approach for Radionuclide Releases to the Columbia River

The screening analysis used for this work was unusual because it took place after completion of the HEDR Project, and detailed release estimates existed for many of the radionuclides of concern. However, this did not alter the general methodology that was applied. To screen the radionuclides released to the Columbia River, we began by defining a risk-based screening value against which the calculated screening values were compared. This was our risk-based screening criterion. All radionuclides that resulted in a screening value above the screening criterion, when the screening values for each radionuclide were summed across all pathways, remained in the analysis (Figure 1-1). The availability of extensive historical monitoring data allowed us to make realistic estimates of radionuclide concentrations in the Columbia River water and sediment within the model domain. We made conservative assumptions with regard to the exposure location and exposure pathway characteristics because the objective of the initial screening was not to underestimate the potential risk to any individual for a given radionuclide or a given exposure pathway.

In the second-step, a number of exposure scenarios were defined to represent the most exposed river users. More than one exposure scenario was required to cover the range of river users because of the differing habits and activities of the various groups. For the Columbia River three exposure scenarios were defined. The resulting risk-based screening values were expected to overestimate actual risks because the exposures were assumed to have occurred throughout the

entire period of releases from the Hanford Site (1944-1972) with the representative individual located at the point where the maximum offsite concentrations occur (Figure 1-1).

A number of inputs were required to apply the screening methodology. These included the radionuclide release estimates to the Columbia River from 1944–1971, an environmental transport model, the exposure pathways of potential significance with regard to health-risk, and a risk-based decision criterion. Each is discussed briefly below and in detail in later chapters of this report.

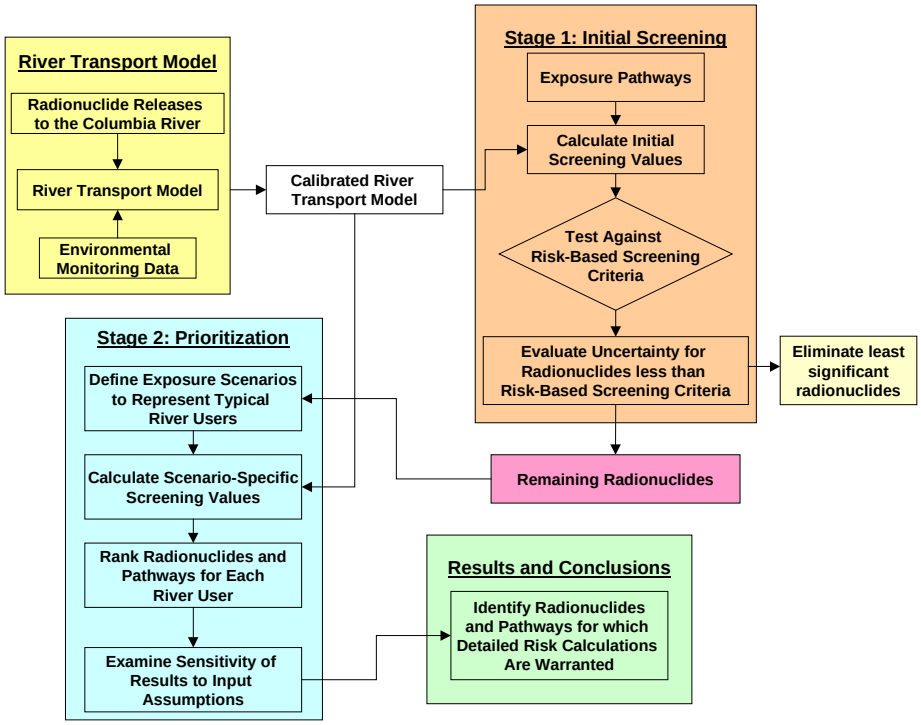

Figure 1-1. Overview of the screening methodology.

Estimates of the quantities of radionuclides released to the Columbia River throughout the operation of the Hanford Site provided the source term for any exposure and risk calculations. A summary of reactor operations and estimates of radionuclide releases to the Columbia River is provided in Chapter 2.

An environmental transport model was required in the screening methodology to account for the transport of radionuclides downstream from the Hanford Site in the water and sediment, radioactivity accumulation in sediment, and transfer into other environmental media or food products. Historical measurements of radionuclide concentrations in the various media were important for calibrating and testing the environmental transport model. Because this was a screening methodology, a detailed river model that estimates radionuclide concentrations at numerous locations downstream as far as the Pacific Ocean was not required. It was sufficient to predict the location where the highest radionuclide concentrations occured in river water and river sediment, and to assume that the exposure pathways existed at these locations. In this way the potential exposure consequences were not underestimated. For the river water, this was a short

distance downstream of the reactor outfall locations. For sediment, this may have been somewhat further downstream, in a location of sediment accumulation. For the current analysis, two exposure locations were considered for the initial screening: Ringold, and Richland. Ringold was the closest offsite location on the far bank (eastern shoreline) that is downstream of the Hanford Site. Richland was located a short distance downstream of the Hanford site boundary on the near bank (western shoreline) of the Columbia River (Table 1-1, Figures 2-1a,b). The screening values were reported and evaluated for the location with the highest calculated risk values.

Table 1-1. Location of Key Features along the Columbia River.

Feature	River mile (RM) [a]	Comment
Reactor 100-B	RM 384	Operated Sept. 1944 to 1968*
Reactor 100-C	RM 383.6	Operated Nov. 1952 to April 1969*
Reactor 100-KW	RM 381.8	Operated Jan. 1955 to Feb. 1970*
Reactor 100-KE	RM 381.4	Operated April 1955 to Jan. 1971*
Reactor 100-D	RM 377.6	Operated Dec. 1944 to June 1967*
Reactor 100-DR	RM 377.6	Operated Oct. 1950 to Dec. 1964
Reactor 100-H	RM 372.5	Operated Nov. 1949 to mid-1965
Reactor 100-F	RM 369	Operated Feb. 1945 to mid-1965
Ringold	RM 354	Located on far shore of Columbia River
300-Area	RM 345	Located on near shore approx. one mile north of Hanford Site Boundary
Richland	RM 340	
Yakima River confluence	RM 335	Enters from the west
Pasco	RM 329	
Snake River confluence	RM 325	Enters from the east
Walla Walla River confluence	RM 315	Enters from the east
McNary Dam	RM 292	Completed in 1953 creating Lake Wallula

[a] Distance in river miles above the mouth of Columbia River

* Labor strike on July 8, 1966 caused reactors to be down temporarily during July and August, 1966

The different groups of people who made use of the river and their different activities were considered to ensure that no important exposure pathway was omitted from the analysis or that the parameters used to quantify the exposure pathway were not underestimated. For example, fish consumption rates for Native American tribes that fished the river tended to be significantly higher than other residents along the Columbia River. For the initial screening, each exposure pathway was considered in isolation with regard to the potential for exposure, and parameter values that represented the most exposed individuals were selected. Following the initial screening, scenarios were defined to represent specific river users, with consistent exposure pathways and parameter values.

Another input to the screening methodology was a risk-based decision criterion. In this case, a risk-based decision criterion for screening was defined to identify those radionuclides that were below some minimum level of concern. If the initial screening values for a radionuclide for all exposure pathways that conservatively characterized the most exposed groups of individuals were below the predefined risk-based criterion, that radionuclide was eliminated from further analysis.

1.2. Risk-based Decision Criteria

Many radionuclides were discharged into the Columbia River as a result of operations at the Hanford nuclear facility. However, not all the radionuclides pose a significant exposure risk. For example, radionuclides with short half-lives decay rapidly resulting in no or minimal potential exposure. A screening methodology was used to identify and focus resources on the most important radionuclides and pathways. A risk-based decision criterion was applied in the methodology as an initial screening tool to identify those radionuclides and exposure pathways that were below a minimum level of concern.

This section reviews risk-based decision criteria that have been used at other locations for similar projects and by other agencies, and it concludes by recommending a risk-based screening value for this study.

The National Research Council (1995) suggested a decision criterion of 0.07 Sv for a whole-body lifetime dose for identifying sites where a dose reconstruction may be warranted. This value was based on the Federal Registry 10 CFR 20 maximum annual dose limit of 0.001 Sv to any individual at a nuclear site boundary, multiplied by 70 years to give a whole-body lifetime dose of 0.07 Sv. In terms of risk, this is roughly equivalent to a lifetime excess cancer incidence risk of 4×10^{-3}.

The Oak Ridge Health Agreement Steering Panel, of the Oak Ridge Dose Reconstruction study, established a decision criterion of 10^{-4} lifetime excess cancer incidence risk for the study as a whole (Thiessen et al. 1996). For screening releases of radionuclides to the aquatic pathways (Clinch River), a lifetime excess cancer incidence risk criterion of 10^{-5}, which is a factor of 10 lower, was applied (Apostoaei et al. 1999). The lower value was used because each radionuclide was compared to the decision guide independently for each exposure pathway rather than combining the exposure risk from all pathways. The calculated screening index was a conservatively biased estimate of excess lifetime risk to the most at-risk individual and was, therefore, expected to overestimate the risk to most or all real individuals (Apostoaei et al. 1999, page 3-1).

In the HEDR Project, one of the criteria used to define the physical area to be included in the study calculations (study domain) was a thyroid dose of 1 rad (0.01 Gy) to a child or infant (Shleien 1992). This dose represents an increased lifetime risk for radiation-induced thyroid cancer in the order of 2×10^{-4}.

For continuous exposures to ionizing radiation, the National Council on Radiation Protection and Measurements (NCRP) recommends an annual limit for members of the public of 1 mSv effective dose (NCRP 1993). This is the same as the value recommended by the International Commission on Radiological Protection (ICRP) (ICRP 1991). This dose limit corresponds to a lifetime risk of about 4×10^{-3}, assuming the risk per sievert from fatal and nonfatal cancers is 6×10^{-2} (ICRP 1991, Table 3) and a 70-year lifetime exposure. The NCRP also defines an annual negligible individual dose[c] (NID), which establishes a boundary below which the dose can be dismissed from consideration and sets the NID at 0.01 mSv effective dose. This corresponds to a lifetime risk of about 4×10^{-5} using the same assumptions as above.

The U.S. Environmental Protection Agency (EPA) has specified an upper bound individual lifetime cancer risk "target range" for carcinogens of 10^{-4} to 10^{-6}, within which EPA strives to

[c] Per source or practice.

manage risks as a part of a Superfund cleanup. The risk estimates are determined using reasonable maximum exposure assumptions for either current or future land use (EPA 1991).

Once a decision has been made to cleanup, EPA has expressed a preference for cleanups achieving the more protective end of the range (i.e., 10^{-6}). However, the upper boundary of the risk range (10^{-4}) is somewhat flexible, although EPA generally uses 10^{-4} in making risk management decisions. The EPA has stated that a specific risk estimate around 10^{-4} may be considered acceptable if justified based on site-specific conditions (EPA 1991). For example, in a Clean Air Act rulemaking establishing National Emissions Standards for Hazardous Air Pollutants (NESHAPs) for U.S. Nuclear Regulatory Commission (NRC) licensees, U.S. Department of Energy facilities, and many other kinds of sites, EPA concluded that a risk level of 3×10^{-4} is essentially equivalent to 1×10^{-4}. EPA explicitly rejected a risk level of 5.7×10^{-4} in the case of elemental phosphorus plants in this rulemaking. EPA has consistently concluded that levels of 15 mrem y^{-1} effective dose equivalent (EDE) (which EPA equates to approximately a 3×10^{-4} increased lifetime cancer risk) or less is protective and achievable (EPA 1997). EPA has explicitly rejected levels above 15 mrem y^{-1} EDE as being not sufficiently protective. For example, the EPA has found the NRC dose limit of 25 mrem y^{-1} (equivalent to approximately 5.7×10^{-4} increased lifetime risk) specified in NRC's Radiological Criteria for License Termination (decommissioning rule) to be beyond the upper bound of the risk range generally considered protective under the Comprehensive Environmental Response, Compensation and Liability Act (EPA 1997).

The EPA approach has been adapted to identify and prioritize potential remediation sites at the Idaho National Engineering and Environmental Laboratory using a target risk level of 10^{-6}. The scenarios evaluated are based on current residential or occupational exposure conditions with exposure durations of 30 and 25 years, respectively. The pathways evaluated are ingestion of drinking water, inhalation of contaminated particulates, ingestion of contaminated soil, and external exposure to soils. Each pathway is evaluated independently (Fromm 1996).

1.2.1. Recommendation

For the initial screening a risk-based screening value of 10^{-4} was recommended for use as a decision criterion to identify those radionuclides for further analysis. The screening values were conservatively biased estimates of risk and were expected to overestimate the risks to all real individuals. We applied this screening value to demonstrate its application, and its use does not represent endorsement by the CDC.

2. RADIONUCLIDE RELEASES TO THE COLUMBIA RIVER

Radionuclides were released into the Columbia River primarily in the cooling-water effluent from eight[d] once-through-cooled reactors at the Hanford Site (Figure 2-1a). Radionuclides also entered the river along the shoreline as a result of retention basin leakage and by leaks transmitted through the groundwater to the river (Walters et al. 1992). Releases to the shoreline also occurred during high flow conditions where the head drop between the cooling basins and the river was insufficient for gravity-fed flow through the outflow lines. This chapter provides a brief overview of reactor operations, which is summarized from two reports produced as part of the HEDR Project (Heeb and Bates 1994; Walters et al. 1992), and discusses the existing radionuclide release estimates and source terms for the current screening methodology.

2.1. History of Reactor Operations

Releases of radioactivity to the Columbia River began in September 1944 when the 100-B reactor, located farthest upstream at River Mile (RM) 384 above the mouth of the Columbia River, came online. The 100-D reactor (RM 377.6) began operating in December of the same year, and the 100-F reactor (RM 369) came online in February 1945. The 100-H reactor (RM 372.5) was the fourth reactor to come online in November 1949. In October 1950, 100-DR (RM 377.6) came online, followed by 100-C (RM 383.6) in November 1952. The last of the once-through-cooled reactors, 100-KW (RM 381.8) and 100-KE (RM 381.4), came online in January and April 1955, respectively.

`Between 1964 and January 1971, all eight reactors were taken offline permanently, starting with 100-DR in December 1964. The 100-H and 100-F reactors were closed in mid-1965. A labor strike caused all the remaining reactors to be closed down temporarily during July and August 1966. In June 1967, 100-D was taken offline, followed by 100-B in 1968, 100-C in April 1969, and 100-KW in February 1970. In January 1971, the last of the once-through-cooled reactors, 100-KE, was shut down permanently.

All eight reactors used raw river water drawn from the Columbia River to cool the reactor fuel elements during operation. Water from the Columbia River was pumped into the water treatment plant. Chemicals were added to adjust the pH, decrease turbidity, and inhibit corrosion of the supply piping and reactor process tubes. The processed river water was filtered, held in clear wells, and pumped into large holding tanks. From the tanks it was pumped through the reactor. The water took 1 to 2 seconds to pass through the reactor core region, during which time it was heated to over 100ºC (212ºF) in the highest power tubes. The hot effluent water was discharged from the reactor into external retention basins located near the Columbia River, where it was stored temporarily to allow thermal cooling and the shortest-lived radionuclides to decay. The water was discharged to the river via a spillway system to outfall lines.

[d] A ninth reactor (100-N or N-reactor) did not discharge directly into the Columbia River because it had a different design.

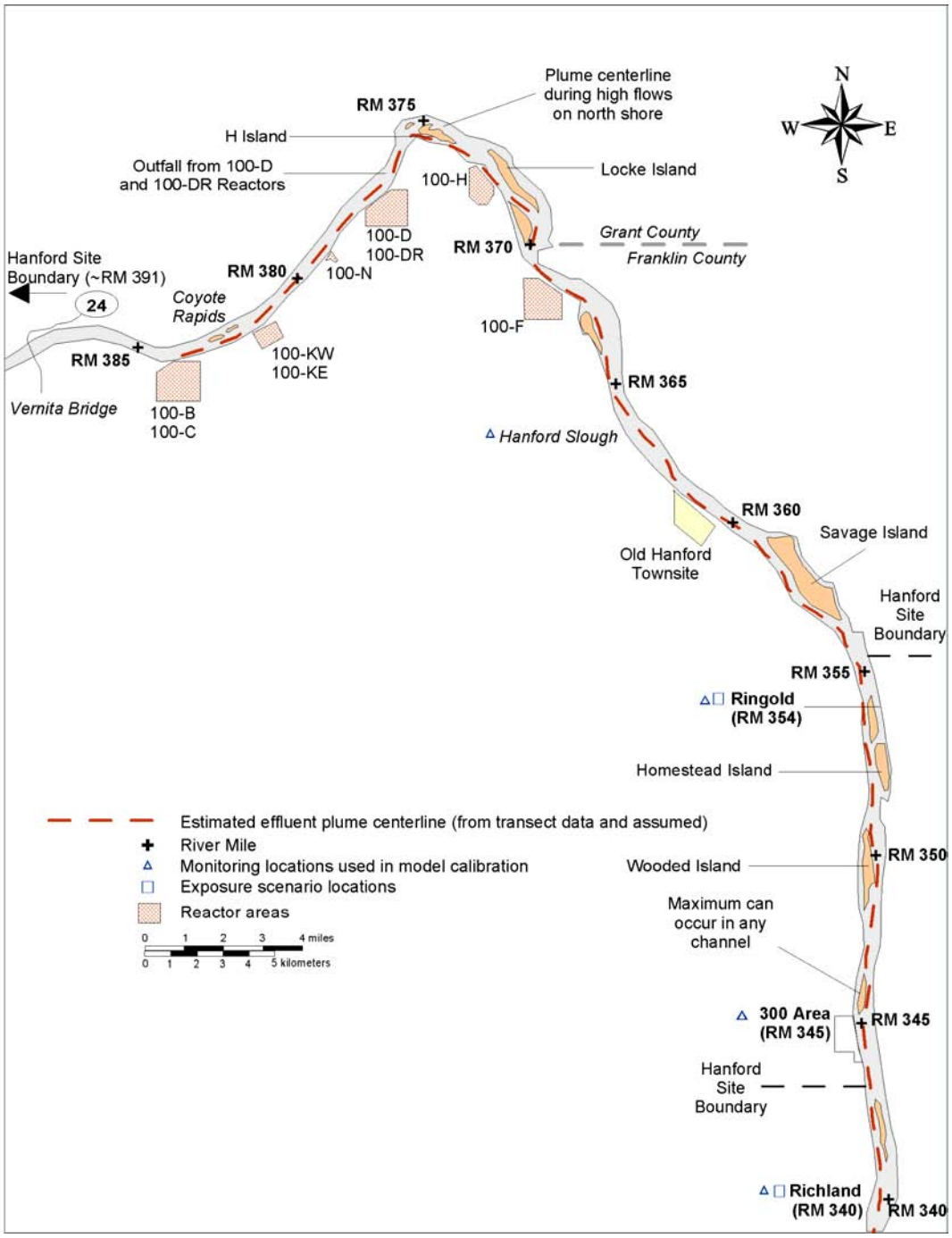

Figure 2-1a. The Columbia River reach from Vernita Bridge to Richland (Redrawn from Plate 2 in Walters et al. 1992).

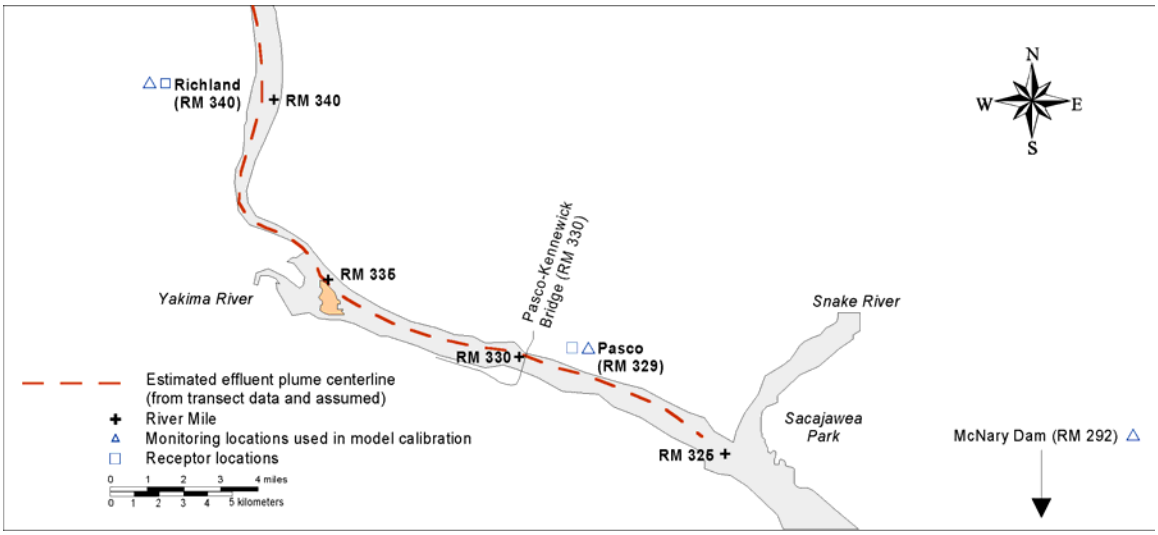

Figure 2-1b. The Columbia River reach from Richland to its confluence with the Snake River (Redrawn from Plate 2 in Walters et al. 1992).

Radioactive materials were produced primarily by fission of uranium in the reactors, activation of non-radioactive materials, and by fission and activation of naturally occurring uranium by neutron capture in reactor coolant water during reactor operations. Radionuclides were created when neutrons in the reactor core activated native elements present in the inlet cooling water from the Columbia River, as well as elements added to the water as part of the water treatment processes. Reactor neutrons also produced radionuclides by activating materials held in the films deposited on the tube and jacket surfaces. Uranium fuel-element failures caused additional radionuclide releases. A fuel-element failure occurred when the aluminum cladding was breached, allowing coolant water direct access to the irradiated uranium. The result was a release of fission products and activation products to the effluent water.

The radionuclide composition and activity level of cooling water discharged to the Columbia River varied considerably as a result of several factors, including:

- The number of reactors operating and their power levels
- Seasonal changes in the chemical composition of the raw river water
- Chemicals used in water treatment
- Corrosion rates of reactor piping and fuel element cladding
- Purging of radioactive film from reactor components
- Fuel element failures (ruptures)
- The length of time effluent was retained in basins before discharge to the river.

Radionuclide concentrations and distribution in the Columbia River were also determined by seasonal fluctuations in the hydrologic characteristics, and were greatly impacted by the construction of dams across the Columbia River. For example, McNary Dam (RM 292) did not exist when the first reactors came online during the 1940s. Figure 2-2 (taken from Walters et al. 1992) shows the river profile as it was in 1944 and the sequence of dam construction from 1953 to 1967.

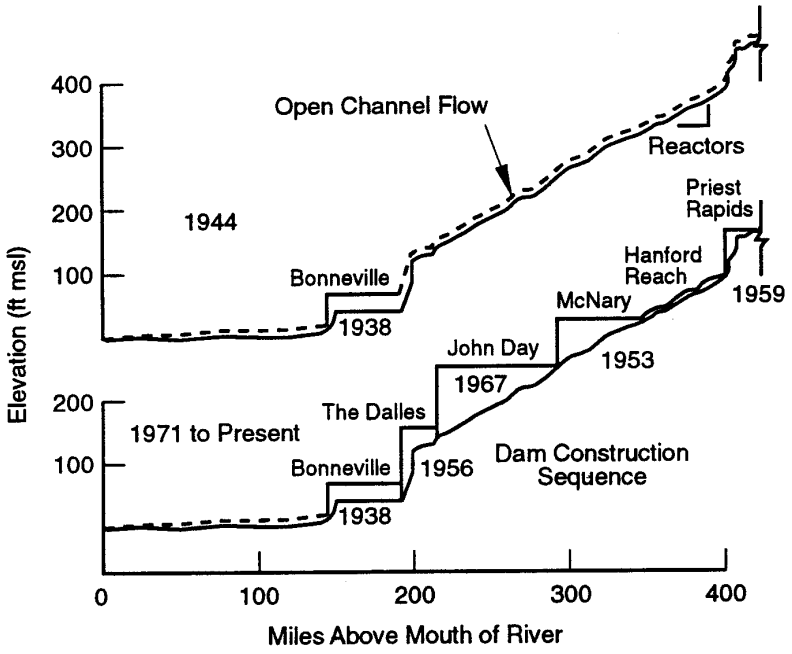

Figure 2-2. Profile of the Columbia River showing conditions in 1944 as compared to 1971 to present. Sequence of dam and reservoir construction is indicated (taken from Walters et al. 1992, Figure 3.1).

2.2. Existing Radionuclide Release Estimates for the Columbia River

Although a large number of different radionuclides were discharged into the Columbia River, the inventories of most were small and/or their half-lives were short (Heeb and Bates 1994). Napier (1993) screened 19 of these radionuclides, and based on the results, the Technical Steering Panel (TSP) of the HEDR Project identified 11 radionuclides (^{24}Na, ^{32}P, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{65}Zn, ^{72}Ga, ^{76}As, ^{90}Y, ^{131}I, and ^{239}Np) and gross nonvolatile beta activity for further study. Heeb and Bates (1994) went on to estimate distributions of total annual and monthly releases to the Columbia River from the eight single-pass Hanford production reactors for these 11 radionuclides and gross nonvolatile beta activity for the years 1944 through 1971. The release estimate distributions were based on 100 Monte Carlo simulations for each radionuclide, and the minimum, median, and maximum values were reported. These were the final source term estimates for the HEDR Project and were reconstructed using the Source Term River Release Model (STRRM), where reactor operating history and measurements of radionuclide concentrations (if available) provided the necessary input. (The original output files from STRRM were never provided by Battelle). Missing data were reconstructed using a statistical analysis of existing data coupled with Monte Carlo modeling techniques. Of the 11 radionuclides for which detailed source term estimates were made, the TSP directed that downriver water and biota concentrations and associated doses be estimated for the five most significant radionuclides (^{24}Na, ^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np) (Napier 1993). Farris et al. (1994a) presented the HEDR methodology and dose calculations.

The initial screening of the 19 radionuclides was based on interim monthly release estimates generated by Dr. Maurice Robkin for 1944–1971 (Napier 1993). No attempt was made to adjust for missing data; therefore, gaps existed in the data, especially for the early years. Few data were available before mid-1958. Appendix B provides a summary of HEDR scoping study reports and other reports directly related to this issue.

2.2.1. Starting Point for Screening Methodology

To ensure that the current screening methodology was comprehensive, 23 radionuclides were included in the analysis. This list included

- The 19 radionuclides screened by Napier (1993) in the HEDR Project (^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, ^{69}Zn, ^{69m}Zn, ^{72}Ga, ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr and ^{239}Np) where 1961 was identified as the year of maximum releases and, therefore, doses. This provided the basis for screening decisions. However, no release estimates were available for ^{60}Co and ^{95}Zr for that year and as a result these two radionuclides appear to have been forgotten in the HEDR Project calculations and dropped from the analysis.
- The 3 radionuclides identified by Hoffman et al. (1998) (^{60}Co, ^{90}Sr, ^{131}I),
- Three additional radionuclides identified by Hoffman (1999) in a subsequent report in support of a legal case related to the Hanford Site (^{122}Sb, ^{133}I, and ^{137}Cs),
- One radionuclide identified in early scoping studies (Napier 1991; PNL 1991) for the HEDR Project but not in Napier (1993) (^{64}Cu).

Because the same radionuclide may have been identified by more than one reference, these numbers did not add up to 23.

The final HEDR Project release estimates that existed for 11 of the 23 radionuclides were used as the source term input for the current screening methodology. Unfortunately, there was no detailed source term information for the remaining 12 radionuclides, furthermore it was outside the scope of this work to develop new and detailed source term estimates. Therefore we reviewed the method used by Hoffman (1999) and the available data to address this issue.

Hoffman (1999) adopted a simple scaling approach that was based on the monthly median source term estimates provided by Heeb and Bates (1994) and the relative concentration of the radionuclide in reactor effluent water reported by Soldat in 1969 (Napier 1991, Appendix E) to estimate releases of ^{60}Co, ^{64}Cu, ^{90}Sr, ^{122}Sb, ^{133}I, and ^{137}Cs to the Columbia River. According to Hoffman (1999), the source terms for radionuclides that are activation products (^{60}Co, ^{64}Cu, ^{122}Sb) were estimated as a function of the Heeb and Bates (1994) monthly median source term estimate for ^{32}P, also an activation product. The activation product ^{32}P was selected because its source term appeared least affected by changes in process (e.g., treatment of effluent water). Source terms for the fission products (^{90}Sr, ^{137}Cs) were estimated as a function of the Heeb and Bates (1994) monthly median source term estimate for the fission product ^{90}Y. This allowed for both fission products from fuel element failures and from fission of natural uranium in river water. The source term for ^{133}I was estimated as a function of the source term for ^{131}I because both would have been subject to the same changes in effluent treatment.

There were many difficulties associated with the use of the data in Soldat (1969) that were included in Appendix E of Napier (1991). Soldat (1969) was a draft document. The data were single measurements of the concentration of about 70 radionuclides in reactor effluent water

entering the Columbia River in 1968, 1964 and 1956. The 1964 and 1968 data were corrected for radioactive decay back to the time of sample collection, whereas the 1958 data were reported as of 4 hours after sample time. In particular, the measured ratios of ^{89}Sr, ^{90}Sr, ^{93}Y, ^{95}Zr and ^{137}Cs to ^{90}Y determined from the 1968 concentration measurements appeared to be suspect, in many cases yielding very different ratios from the 1964 and 1956 data.

Concern about the quality of the Soldat (1969) data led us to examine a series of spreadsheets from the HEDR Project that Battelle provided to us early in this work. The spreadsheets contained information compiled on radionuclide releases to the Columbia River from each of the eight Hanford plutonium production reactors that was used in Napier (1993) to determine the key radionuclides related to dose from the Columbia River pathway. Dr. Maurice Robkin of the HEDR Technical Steering Panel prepared the spreadsheets.

For each radionuclide of interest, the ratio of the release estimate compiled in the HEDR spreadsheets to the relevant median source term estimate reported by Heeb and Bates (1994) for the same month was compiled in a Microsoft Excel© Workbook (filename: release_ratios.xls). The distributions of the ratios are summarized in Table 2-1, where N represents the number of monthly data pairs used to generate the statistics. In all cases the distributions were best represented by a lognormal distribution.

Table 2-1. Radionuclide Release Ratios Calculated from the HEDR Spreadsheets.

Radionuclide release ratio	N	Max/Min	Mean	Standard deviation	GM	GSD	Computed mean[a]
^{90}Sr to ^{90}Y	284[b]	1960	0.0052	0.014	0.0015	3.9	0.0038
^{89}Sr to ^{90}Y	285	2080	0.030	0.081	0.010	3.7	0.024
^{93}Y to ^{90}Y	348	443	3.4	2.1	2.9	1.9	3.5
^{133}I to ^{131}I	155	158	18	20	9.9	3.2	20
^{69m}Zn to ^{65}Zn	208	91	1.6	1.3	1.1	2.5	1.7
^{45}Ca to ^{32}P	266[c]	954	0.063	0.059	0.047	2.3	0.066
^{64}Cu to ^{32}P	643	1480	63	51	47	2.4	69
^{60}Co to ^{32}P	229[d]	700	0.059	0.095	0.031	2.8	0.054
^{95}Zr to ^{239}Np	109	3660	0.082	0.24	0.022	4.8	0.076

[a] Mean value was computed from the GM and GSD.
[b] Two values that exceeded 0.5 were excluded from the calculations.
[c] Twelve values that exceeded 4 were excluded from the calculations.
[d] Two values that exceeded 3.5 were excluded from the calculations.

The GM ratios summarized in Table 2-1 were used to define the missing source terms for the screening analysis in preference to the ratios estimated from Soldat (1969) because they were based on many more data points. The screening calculations were deterministic, so a single release quantity was assumed each month, rather than a distribution of releases. Uncertainty in the source term was not considered unless the calculated screening risk value was close to 10^{-4} *and* there were no river water data to compare the model predictions against. For the deterministic screening calculations, the GM ratio value was multiplied by the relevant median release estimate, Q_X, where $_X$ represents the median radionuclide release estimate reported by Heeb and Bates (1994), such that Q_Y represents ^{90}Y, Q_P represents ^{32}P, Q_{Zn} represents ^{65}Zn, Q_{Np} represents

^{239}Np, and Q_I represents ^{131}I. There are four exceptions to this procedure, ^{64}Cu, ^{60}Co, ^{69m}Zn and ^{90}Sr, where the ratios were adjusted based on comparison of predicted and observed river water measurements. Except for ^{60}Co, the ratios that were used (Table 2-2) were well within the distribution of ratios reported in Table 2-1. Cobalt-60 was particularly troublesome with regard to model calibration and calibration was performed for two alternate source terms.

The spreadsheets did not contain data for ^{126}Sb or ^{137}Cs. Therefore the ratio of ^{126}Sb to ^{32}P that was derived from Soldat (1969) was used in the absence of any other data. For ^{137}Cs, a ratio of $0.01 \times Q_Y$, where Q_Y is the release rate for ^{90}Y, was estimated based on the data in Soldat (1969). A summary of the source term estimates for the screening is provided in Table 2-2. Evaluation of uncertainty in the radionuclide release estimates was limited to those nuclides where the initial screening risk estimate was close to 10^{-4} (the screening decision criterion), and no river or sediment data exist (See Model Calibration section of Chapter 4).

Table 2-2. Radionuclide Source Terms for Columbia River Releases

Nuclide (half-life)	Deterministic Value	Uncertainty[a]	Basis for Source Term
^{24}Na (15 h)	HEDR minimum	HEDR distribution[b]	Heeb and Bates (1994) and comparison to monitoring data
^{32}P (14.3 d)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{45}Ca (163 d)	$0.0047 \times Q_P$	GSD = 2.3	HEDR spreadsheets ratio
^{46}Sc (83.8 d)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{51}Cr (27.7 d)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{56}Mn (2.6 d)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{60}Co (5.3 y)	$0.0868 \times Q_P$[c,d] 0.388[c] $\times Q_P$[c,d]	GSD = 2.8	Monitoring data supported by HEDR spreadsheets ratio[c]
^{64}Cu (12.7 h)	$54 \times Q_P$	GSD = 2.4	Monitoring data supported by HEDR spreadsheets ratio
^{65}Zn (244 d)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{69}Zn[d] (57 m)	Equal to ^{69m}Zn	Not applicable	Short-lived progeny of ^{69m}Zn.
^{69m}Zn (13.8 h)	$2.75 \times Q_{Zn}$	GSD = 2.5	Monitoring data supported by HEDR spreadsheets ratio
^{72}Ga (14.1 h)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{76}As (26.3 h)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{89}Sr (50.5 d)	$0.01 \times Q_Y$	GSD = 3.7	HEDR spreadsheets ratio
^{90}Sr (29.1 y)	$0.0044 \times Q_Y$	GSD = 3.9	Monitoring data supported by HEDR spreadsheets ratio
^{90}Y (64 h)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)
^{93}Y (10.1 h)	$2.9 \times Q_Y$	GSD = 1.9	HEDR spreadsheets ratio
^{95}Zr (64 d)	$0.022 \times Q_{Np}$	GSD = 4.8	HEDR spreadsheets ratio
^{122}Sb (2.7 d)	$0.5 \times Q_P$		Soldat (1969)
^{131}I (8 d)	HEDR minimum	HEDR distribution[b]	Heeb and Bates (1994) and monitoring data
^{133}I (20.8 h)	$9.9 \times Q_I$	GSD = 3.2	HEDR spreadsheets ratio
^{137}Cs (30 y)	$0.01 \times Q_Y$[e]		Soldat (1969)
^{239}Np (2.4 d)	HEDR median	HEDR distribution[b]	Heeb and Bates (1994)

[a] Uncertainty in the source term was **only** evaluated for those nuclides that lacked river water measurements and had screening risk values close to the 10^{-4} screening decision criterion.

[b] Based on 100 Monte Carlo simulations (Heeb and Bates 1994).

[c] A ratio of $0.02 \times Q_P$ is estimated from Soldat (1969) and a ratio of $0.03 \times Q_P$ is estimated from the HEDR spreadsheets (see Table 2-1). However, it was necessary to increase this ratio so that predicted river water and sediment concentrations agreed with corresponding measured values during calibration. Two alternate source terms are presented based on different calibrations. See text for more detail.

[d] Short-lived daughter would have grown to equilibrium activity by the time the water left the holding pond.

[e] A ratio of $0.01 \times Q_Y$ is estimated from Soldat (1969).

3. ENVIRONMENTAL MONITORING DATA

During the HEDR Project, environmental data were reviewed and compiled for use in the HEDR study. Although environmental data existed for a range of time periods, a few critical years were used in the HEDR Project to calculate preliminary estimates of dose and provide screening estimates for maximally and typically exposed individuals. It was primarily these data that made up the information contained in the HEDR files that were obtained at the outset of this project. Because these data were compiled only in report form, we compiled a descriptive spreadsheet containing the data. This spreadsheet was used to calibrate the river transport model developed for this screening analysis (see Chapter 4). The spreadsheet and data are described in this chapter. We compiled environmental monitoring data relevant for assessing radionuclide releases to the Columbia River electronically in a Microsoft Excel© Workbook (filename: hanford data.xls). This workbook contained four important types of historical radionuclide measurements: annual average radionuclide concentrations in river water, monthly radionuclide concentrations in river water grab samples, weekly cumulative concentrations in river water, and radionuclide concentrations in sediment. Each dataset was important for different reasons. The measured annual average concentrations in river water allowed the river transport model to be calibrated on a macro-scale temporally and showed the concentrations of long-lived radionuclides averaged over the course of a year. For the early years, radionuclide-specific measurement techniques were not available to discern the different radionuclides within a river sample. The data for these early years showed total beta activity concentrations. The weekly cumulative data revealed another level of detail, and they provided insight into the fluctuations in river water radionuclide concentrations throughout the year. The impact of seasonal variations in the volume and velocity of the river water on radionuclide concentrations were examined. Because some of the radionuclides released from the reactors had very short half-lives, the monthly grab samples were useful for estimating the transport of these nuclides. Finally, sediment data were important for revealing some information about how the radionuclides in the river sorb onto the sediments. Unfortunately, few sediment data were collected during the period of interest for the study because the Site geared much of the environmental monitoring toward estimating annual doses to potential receptors. Sediment measurements did not contribute directly to dose estimates; instead, pocket ionization chambers were placed outside to measure the external dose (Walters et al. 1992). This information had limited usefulness in terms of assessing the radionuclide sediment load.

The river upstream of McNary Dam, probably at the location of Ringold, had the highest radionuclide concentrations in river water. McNary Dam was completed in 1953 and was logically the location of highest radioactivity in sediments because it was the first dam downstream of the Hanford reactors. Environmental data gathered in the river stretch from the last Hanford reactor to McNary Dam were the focus of the environmental data compiled in the workbook.

The first worksheet (name: annual averages) in the Microsoft Excel workbook included the annual average radionuclide concentration data for river water at different locations downstream of the Hanford reactors. Annual average beta activity concentration measurements at Pasco were included for the years 1945–1971. Radionuclide concentrations were documented for different years at different locations. Annual average concentrations in river water were compiled in this worksheet for locations at the Richland Pumping Station (1963–1989), the Pasco Pumping Station (1959–1965), and the McNary Dam (1964–1969).

Grab sample measurements of radionuclide concentrations in river water were also compiled in the Microsoft Excel© Workbook (filename: hanford data.xls) in the second worksheet (name: grab samples) for the years 1964–1966 at various locations. Grab samples were collected and analyzed for ^{24}Na, ^{32}P, ^{51}Cr, ^{64}Cu, ^{65}Zn, ^{76}As, ^{90}Sr, ^{131}I, ^{72}Ga, ^{56}Mn, ^{69m}Zn, and ^{239}Np. Locations of interest where the data were available included Richland and Ringold.

Cumulative data were collected over a 1-week period during which the sample chamber collected continuously from the river water, and they were compiled in the Microsoft Excel© Workbook (filename: hanford data.xls) in the third worksheet (name: cumulative data). These data represented concentrations of longer lived radionuclides at various locations. Radionuclides collected and analyzed in this manner included ^{32}P, ^{51}Cr, ^{54}Mn, ^{60}Co, ^{65}Zn, ^{90}Sr, and ^{131}I. For some of the radionuclides, only limited data existed. The time period spanned by the compiled data was 1964–1966. Locations between Hanford and McNary Dam where continuous data were collected were the 300 Area, Richland, Pasco, and the upstream side of McNary Dam.

The sediment data were primarily compiled from special studies conducted by other agencies. A number of studies and their results were outlined in the fourth worksheet (name: sediment data). One study was conducted after the reactors were shut down and radionuclide concentrations in surface sediments in April 1971 and August 1976 were measured. Surface sediment concentrations decreased dramatically over this time period, and it was estimated that sediments uncontaminated with radionuclides released from the Hanford site were being deposited behind the McNary Dam on top of the contaminated sediments at a rate of 38 to 76 cm per year (15 to 30 in. y^{-1}).

During the early 1960s, the U.S. Geological Survey (USGS) conducted a number of sediment studies to examine the role of sediments in the uptake and transport of radionuclides in the Columbia River. The first study, documented in Nielsen and Perkins (1957), attempted to assess the magnitude of radionuclide uptake by sediments between the reactors and McNary Dam. This study showed the percent loss of different radionuclides between the reactors and Pasco and between Pasco and Vancouver. It also reported a few radionuclide concentrations behind McNary Dam.

In the second USGS sediment study documented here (Nelson et al. 1964), water, suspended sediment, and surficial streambed samples were collected several times per week at different locations. Transport rates calculated for the radionuclides showed that only 30% of ^{51}Cr was lost to sediment, but that ^{65}Zn was almost entirely sorbed by sediment and was resuspended during periods of high river flow. This study documented the radionuclides associated with aqueous phase and sediments, as well as concluding that 75% of the depletion of radionuclides by sediments occurred behind McNary Dam. Total inventories of radioactive material in sediments were estimated.

3.1. Concentrations of Radionuclides in Fish

Consumption of fish was identified as the dominant exposure pathway in the HEDR assessment of doses from radionuclide releases to the Columbia River (Farris et al. 1994a). Measured concentrations of radionuclides in fish were compiled from Thiede and Duncan (1994, Appendix B) in the Microsoft Excel© Workbook (filename: fish.xls) for the years 1960–1967, at two locations: Ringold and Richland. The majority of the data related to resident fish, however there were limited data for anadromous fish (salmon and steelhead trout), which were compiled in

the same workbook (worksheet name: anadromous). The data were used for model testing as described in the Model Calibration section of Chapter 4.

4. ENVIRONMENTAL TRANSPORT MODEL

This chapter describes the reach of the Columbia River that was modeled for the screening calculations. This is referred to as the model domain. The equations used to calculate concentrations of radionuclides in river water and sediment are also presented. First, a conceptual model for the environmental transport of radionuclides along the Columbia River was developed. The conceptual model was then translated into the mathematical model. Key assumptions, processes, and parameter values are discussed.

4.1. Description of the Columbia River within the Domain of Study

The model domain for the screening calculations extended from the upstream boundary of the Hanford Reservation near the Vernita Bridge at River Mile (RM) 385, to its confluence with the Snake River near RM 325 (Figures 2-1a, 2-1b). Within this stretch, the river was free flowing before the construction of the McNary Dam (RM 292), which was completed in December 1953 and created Lake Wallula. After construction of the McNary Dam, Columbia River flows were shown to be backed up to its confluence with the Snake River, based on the width of the river channel illustrated in Plate 2 of Walters et al. (1992). However, Walters et al. (1992) stated that the influence of the dam on water flow extended about 62 miles upstream, near the southern boundary of the Hanford Reservation at Ringold (RM 354). One stretch of rapids was reported in the model domain (Coyote Rapids) between the 100-B and 100-C reactors and 100-KW and 100-KE reactors.

Walters et al. (1992) reported the mean annual discharge of the Columbia River at Hanford to be 121,512 cfs (3440.837 $m^3 s^{-1}$). Based on monthly-averaged discharge data measured below the Priest River Dam (~RM 400) by the U.S. Geological Survey, the average monthly flow rate between the years 1944 and 1972 was 127,034.523 cfs (3597.217 $m^3 s^{-1}$). Two tributaries join the Columbia River within the model domain. The confluence with the Yakima River is at RM 335 and the confluence with the Snake River is at RM 325. The Yakima River has a mean annual discharge of 3661 cfs (103.68 $m^3 s^{-1}$) and the Snake River has a mean annual discharge of 53,948 cfs (1527.807 $m^3 s^{-1}$). Both tributaries, but especially the Snake, dilute effluent concentrations and contribute a significant volume of sediment to the Columbia River (Walters et al. 1992).

The U.S. Geological Survey (USGS) monitors suspended sediment loads in rivers at numerous locations around the country and posts these data on their Web page (http://webserver.cr.usgs.gov/sediment/). Two stations monitor suspended sediment in the Columbia River, one at the McNary Dam and the other at Vancouver, Washington, which is many miles downstream from Richland and below the Bonneville Dam. The average daily sediment load at McNary Dam from May 1965 to September 1966 (the only data set available) was 13.8 mg L^{-1}. At Vancouver, Washington, the average daily load between October 1, 1963 and September 30, 1969 was 34 mg L^{-1}. Sediment loads in the Yakima River were also available at a monitoring station located about 8 km (5 mi) west of Richland near Kiona, Washington. The average daily sediment load for the Yakima River from June 1977 to October 1980 was 60 mg L^{-1}. Most of the load (~90%) was comprised of fine sand and silt (0.062–0.0039 mm). Because the flows in the Yakima were substantially smaller than the Columbia, the overall impact on sediment loads on the Columbia River below its confluence with the Yakima was not expected to be significant. Unfortunately, no sediment data were found for the Snake River.

Within the region of the river where the reactors discharged (RM 369 to RM 384), the river was free flowing with an estimated channel width ranging from about 300 m to 600 m, based on Figures 2-1a and 2-1b [Plate 2 in Walters et al. (1992)]. In places, islands were present forming two separate channels. Within this region, river velocities may have been extremely variable. In pooled areas and along the inner bank of a meander where the flow velocity may have been low, fine sediment may have accumulated during low flow conditions, only to be remobilized during higher flow conditions. In some areas where velocities were relatively high, the channel bed may have been composed of only coarse sand or gravel. Farther downstream near Pasco and the confluence with the Snake River, and where flow was influenced by the McNary Dam, significant deposition of fine sediment may have occured as the flow velocity decreased.

As Walters et al. (1992) summarizes

> "Because of the location along the same shoreline and proximity of the reactor outfalls to each other, these [reactor] plumes tended to coalesce and hug the Richland side of the river. The various channel islands, the roughness of the channel bed (i.e., the presence of boulders), the location of pools and riffles, and curvature of the river's natural flow all affected the rate at which the plume spread and mixed with the river water. Under some flow conditions, the plume was not entirely mixed over the full river width until it approached Pasco."

4.2. Conceptual Model

The screening approach used in this analysis was designed to estimate radioactivity concentrations in the Columbia River and radioactivity sorbed onto river sediment within the model domain. Where feasible, radionuclide concentrations in river water and radioactivity sorbed to sediment were calibrated to historical monitoring data. Estimates of radionuclide water concentrations and radioactivity sorbed to sediment were then coupled with an exposure scenario for a hypothetical individual. The exposure scenario described intakes and exposure to environmental media (water, soil, and air) that were contaminated as a result of radionuclide discharges to the Columbia River from reactor operations. The exposure scenarios were designed to overestimate intakes of contaminated water, air, and soil, and the time spent on contaminated sediment. Therefore, the exposure scenario was termed *conservative*, in that exposure and intakes of contaminated media were overestimated. Intakes and exposures were then quantified in terms of a screening level defined by the incremental lifetime cancer incidence risk. Screening levels were calculated by applying a risk coefficient that relates intake or exposure to a radionuclide to a cancer incidence risk.

In general, estimates of radionuclide concentrations in river water and radioactivity sorbed to sediment were limited to the stretch of river from Ringold (RM 354) to Pasco (RM 329) where historical monitoring data exists and where persons were likely to have been exposed.

The conceptual model for radionuclide transport in the river assumed a straight-line channel of constant width and depth (Figure 4-1). Radionuclides were introduced to the river at a point (xs,ys) and were advected downstream at a mean flow velocity, u. During advection, radionuclides dispersed in the longitudinal (x) and transverse (y) direction. Transverse dispersion was limited by the width of the river channel. Uniform and steady-state water flow was assumed

and effluent discharged to the river was assumed to mix rapidly in the vertical direction within the river channel. Partitioning between dissolved aqueous phase and the sorbed phase was described by the equilibrium partition coefficient. This coefficient was the ratio of the sorbed radioactivity per unit mass of sediment to the dissolved-phase radioactivity concentration in water at equilibrium. Suspended sediment was assumed to be transported downstream at a rate equal to the river velocity (u). Radionuclides also sorbed onto immobile sediment in the channel bed (the fixed bed sediments). Therefore, the net downstream velocity of radionuclides may have been retarded to some extent depending on the sorptive properties of the radionuclide and the amount of bed sediment that interacted with dissolved radionuclides in the water column. Sediment that was considered immobile was, in reality, continuously scoured, deposited, and remobilized. These effects were not treated explicitly in the model. The fixed bed sediment that interacted with radionuclides in the water column was thought of as an "effective" mass of sediment in the channel bed that radionuclides sorbed onto, and that remained immobile relative to the radionuclides traveling in the dissolved phase and also radionuclides that were sorbed onto suspended sediment. The thickness of the bed sediment that interacted with river water was assumed to be both temporally and spatially constant throughout the model domain.

In parts of the river channel such as shoreline sloughs and behind McNary Dam, sediment could have accumulated. Radionuclides sorbed to suspended sediment deposited from the water column as the velocity of the water decreased. These sorbed radionuclides were considered fixed and did not repartition back into the water, forming a sink of radionuclides in sediment. In reality, some redistribution occured, but repartitioning was mainly a function of the aqueous phase concentration in the sediment pore water and not the river water concentration. The loss of radionuclides through sediment deposition from the water column was ignored.

In the Hanford Environmental Dose Reconstruction (HEDR) project, the CHARIMA model (modified by PNNL to include radioactive decay) was used. CHARIMA is a one-dimensional, finite difference model that simulated unsteady flow (flood wave) hydrodynamics and nonuniform sediment transport in an open channel. In its application (Walters et al. 1994), only dissolved phase transport was considered. Presumably, the dissolved phase was simulated as fine suspended particles. Effects of sorption and desorption on sediment were not considered, and inclusion of such processes may have required additional modifications to the code. The model was applied to a domain considerably larger (extending all the way to the Pacific Ocean). Use of CHARIMA in this exercise was considered, but later dismissed because a) exposure to sediment pathways was to be considered and CHARIMA may have required modification to include this pathway, b) within the domain of this study, radionuclide plumes were not fully mixed across the channel (CHARIMA is one dimensional), c) the complexity of the hydrodynamics incorporated in CHARIMA was not warranted for a screening exercise. Additionally, the CHARIMA model assumed all releases occurred from a single point. In reality, reactors were spread over a distance of about 26 km and it was unclear whether this simplifying assumption would make a significant difference in the model estimates. Finally, using a different model from that used in the HEDR Project provided an independent calculation. For these reasons, we chose to use a different model.

The model for transport of radionuclides in the Columbia River from the furthest upstream reactor (RM 384) to its confluence with the Yakima River was described by a 2-dimensional advection-dispersion model. The same model was used for receptors downstream of the Yakima River confluence; however, concentrations were modified by a dilution factor that accounted for the additional dilution from the inflow of the Snake and Yakima Rivers. Behind McNary Dam

and at other points in the model domain, a first order kinetic model was used to estimate radionuclides in deposited sediments.

The river transport model (Figure 4-1) assumed a constant river channel width (*W*) and depth (*D*). A Cartesian coordinate system was defined having its origin at RM 385 on the near shoreline (southern shoreline) of the river. The near shore represented the southern shoreline upstream of RM 375 and the western shoreline downstream of RM 375. Releases were described by a vertically averaged point source at a point defined by the coordinates, *xs* and *ys*.

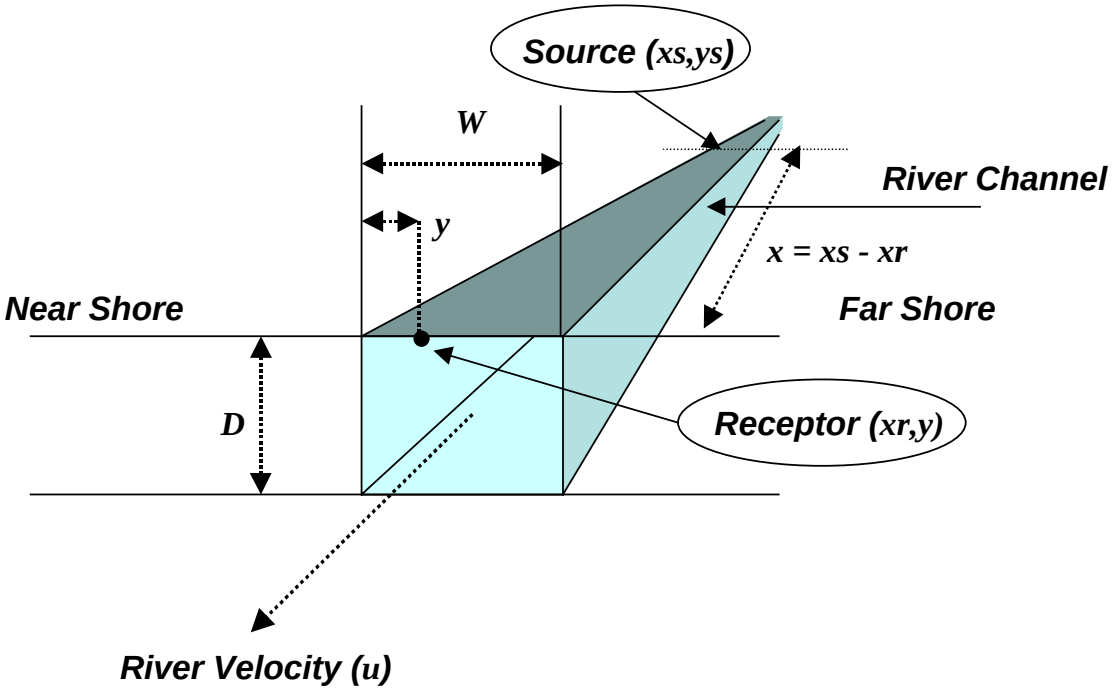

Figure 4-1. Conceptual representation of the river transport model for screening radionuclides released to the Columbia River from the Hanford Site. The terms *xs* and *ys*, describe the position of the source relative to RM 385. The term, *xr*, is the position of the receptor relative to RM 385. Other terms are defined in the text.

4.3. Mathematical Model

The mathematical model was based on the work of Codell et al. (1982) and Jirka et al. (1983), who developed semi-analytical solutions for the advection-dispersion equation in river channels. The model was modified to include retardation, and therefore is similar in form to the groundwater transport equations in a porous media (Codell et al. 1982; Codell and Duguid 1983). The mass-balance equation for a vertically-averaged radionuclide concentration in a uniform flow field with retardation was written as

$$R_d \frac{\partial C}{\partial t} = E_x \frac{\partial^2 C}{\partial x^2} + E_y \frac{\partial^2 C}{\partial y^2} - u \frac{\partial C}{\partial x} - R_d \lambda C \qquad (4\text{-}1)$$

where

C = aqueous phase radionuclide concentration in the river water (Ci m^{-3})

E_x = longitudinal turbulent dispersion coefficient ($m^2\ s^{-1}$)
E_y = transverse turbulent dispersion coefficient ($m^2\ s^{-1}$)
u = river flow velocity ($m\ s^{-1}$)
λ = decay rate constant (s^{-1})
x = the downstream distance from the source (m)
y = the transverse distance from the near shoreline (m)
R_d = the retardation factor (unitless).

The initial and boundary conditions are given by

- $C = 0$, at $t = 0$ for all values of x and y.
- $\partial C/\partial y = 0$, at $y = 0$, $y = W$ (width of river channel).

Additionally, the retardation factor was assumed to be spatially and temporally constant. Assuming a straight rectangular channel of width W, depth D, and a uniform and steady velocity u, the solution to Equation (4-1) for the concentration at a point x,y downstream resulting from an instantaneous unit release at $t = 0$ at the point, (xs, ys) was given by

$$C(x,y,t) = \frac{1}{\sqrt{4\pi E_x t/R_d}\,DW\,R_d} \exp\left[-\frac{(x-ut/R_d)^2}{4E_x t/R_d} - \lambda t\right] \left[1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2 E_y t/R_d}{W^2}\right) \cos\left(n\pi\frac{ys}{W}\right) \cos\left(n\pi\frac{y}{W}\right)\right] \quad (4\text{-}2)$$

where
D = effective river depth (m)
W = effective river width (m)
x = downstream distance from source (m)
y = transverse distance of the receptor from the near shoreline (m)
ys = transverse distance of source from the near shoreline (m)
t = time (s).

The distance, x is given by

$$x = xs - xr \quad (4\text{-}3)$$

where
xr = the distance downstream from the origin (RM 385) to the receptor (m)
xs = the distance downstream from the origin (RM 385) to the source (m).

For example, the distance, x, from the 100-F reactor (RM 369) to Richland (RM 340) was 29 miles or 46,671 m.

Equation (4-2) gave the concentration for an instantaneous release at $t = 0$. The more generalized solution for an arbitrary release occurring over time was given by the convolution integral.

$$Ca(x,y,t) = \int_0^t C(x,y,t-\tau)\, q(\tau)\ d\tau \qquad (4\text{-}4)$$

where

Ca = concentration for an arbitrary release described by $q(\tau)$ (Ci m^{-3})
$C(t-\tau)$ = instantaneous concentration at time $(t-\tau)$ for a release at time $(t-\tau) = 0$ (Ci m^{-3})
$q(\tau)$ = source release rate (Ci s^{-1}).

Releases to the Columbia River occurred not from a single point, but eight reactors spread over an interval of approximately 26 km (16 mi). Concentrations at points downstream were then a function of the sum of the contributions from each individual reactor, and were solved using methods of superposition, given in Equation (4-5).

$$C_t(x,y,t) = \sum_{i=1}^{n} \int_0^t C_i(x_i,y,t-\tau)\, q_i(\tau)\ d\tau \qquad (4\text{-}5)$$

where

C_t = concentration from all reactor sources (Ci m^{-3})
C_i = instantaneous concentration at time $(t-\tau)$ for a release at time $(t-\tau) = 0$ from the i^{th} reactor source (Ci m^{-3})
n = number of reactors
x_i = distance downstream from the i^{th} reactor source to the receptor, or $xs_i - xr$ (m)
xs_i = the distance downstream from the origin (RM 385) to the i^{th} reactor (m)
$q_i(\tau)$ = source release rate for the i^{th} reactor (Ci s^{-1}).

Although not explicitly stated, $C_t(x_i,y,t-\tau)$ was also a function of ys_i, the transverse distance from the near shore of the i^{th} reactor source. The starting time of the simulation was January 1, 1944. The first reported releases from the reactors to the Columbia River were in October of 1944; therefore, all initial values of t preceded the startup of reactor operations.

Equations 4-1–4-5 were formulated for an arbitrary release of any time duration. During initial model development, it was anticipated that releases to the Columbia River would consist of both monthly-average releases, and short-term releases on the order of 1 or 2 days (representing presumably fuel-element failures for specific reactors). In the first case (monthly-averaged release rates), steady-state conditions were achieved rapidly in the model domain during the month, and Equation 4-4 and 4-5 could be integrated analytically. For a short-term arbitrary release, steady-state conditions were not achieved, and a numerical approximation was used to integrate Equations 4-4 and 4-5. Numerical integration was also used to integrate Equations 4-4 and 4-5 for the steady-state release condition. Equations 4-4 and 4-5 were numerically integrated using software developed specifically for this project because this method could handle both the monthly and short-term release events. As it turned out, only monthly-average release rates were provided and numerical integration was not necessary. However, we retained the numerical approximation of Equations 4-4 and 4-5 in the software developed for this project in the event such releases may be provided in the future.

4.3.1. Treatment of Nonsteady Flow and Changing River Dimensions

The mathematical model presented in Equations (4-1–4-5) assumed the river flow was at steady state. However, water flow in the Columbia River varied seasonally (Figure 4-2), changing the extent of radionuclide dilution and downstream travel times. Figure 4-2 was based on data from the USGS's Priest Rapids Dam gauging station (which was located upstream of the Hanford Reservation) and represented average monthly flow rates.

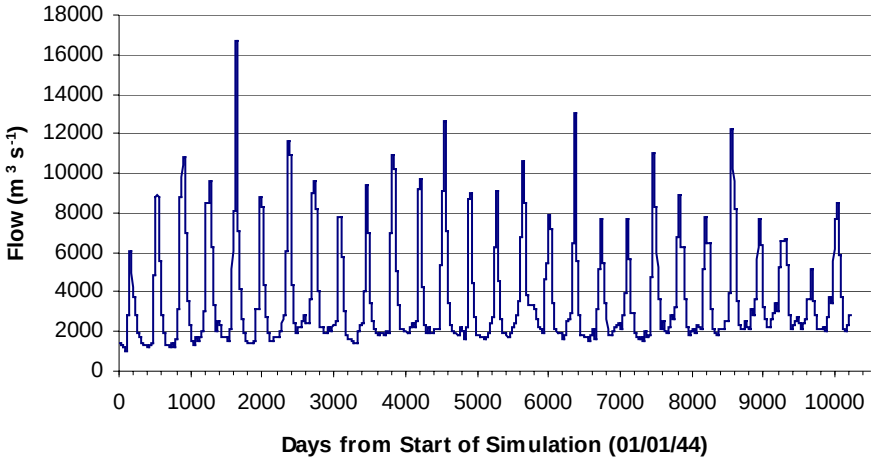

Figure 4-2. Monthly average flow rate in the Columbia River as measured by the U.S. Geological Survey below the Priest Rapids Dam (Gauging Station 12472800).

Travel times of peak concentrations from the 100-D Reactor (RM 377.6) to the Pasco-Kennewick bridge (RM 330) as a function of river discharge were estimated by Walters et al. (1992). These travel times represented the mean river flow velocity at the reported discharge. Travel times ranged from 0.43–1 day (Table 4-1). Because the travel times were relatively short compared to changes in the river flow and effluent release history (1 month), monthly fluctuations in the flow rate were incorporated into the model much the same way as variable wind vectors are incorporated into the Gaussian Plume air dispersion model.

Table 4-1. Flow Rate and Travel Times between 100-D Reactor and Pasco Pumping Station[a]

Flow rate ($m^3\ s^{-1}$)[b]	Travel time (days)	u ($m\ s^{-1}$)[c]
1840.59525	1	0.886629
4898.81505	0.67	1.32332
8749.90665	0.48	1.84714
12232.8792	0.43	2.06193

[a] Data from Walters et al. (1992) are reported to be estimated from Soldat (1962).
[b] Units have been changed from cubic feet per second to cubic meters per second.
[c] u = 76.60477 km (47.6 mi)/travel time.

For any given day of simulation, the monthly-average flow rate was used to calculate *u*, *W*, and *D*. The mean river velocity as a function of the river flow rate was fit to data in Walters et al. (1992) that is presented in Table 4-1. The mean velocity for different flow rates was determined by dividing the distance from the 100-D reactor to the Pasco pumping station (76.6 km [47.6 mi]) by the travel times reported in Walters et al. (1992) as shown in the third column of Table 4-1. These data were then fit to a power function of the form

$$u = bF^{m} \tag{4-6}$$

where F is the flow rate ($m^3\ s^{-1}$) and b and m are fitting parameters. Taking the natural logarithm of each side yielded an equation that was fit to a linear model using linear regression.

$$\ln(u) = \ln(b) + m\ln(F) \tag{4-7}$$

The parameters, b and m were estimated to be 0.02836464 and 0.45640746, respectively. The Pearson product moment correlation coefficient (r) was 0.994. The number of significant digits for the parameters, b and m, and the data in Table 4-1 were not justified by the accuracy of the relation but were retained for documentation purposes.

The width and depth of the river were calculated using an equation for depth as a function of flow rate developed by Leopold et al. (1964). Recall that the river width and depth were held spatially constant in the model domain but may have changed with monthly river flows. The river depth as a function of the flow rate was estimated by (Leopold et al. 1964):

$$D = 0.163\,F^{0.447} \tag{4-8}$$

Using the relationship $F = D \times W \times u$, the effective width was calculated for any flow rate using Equation (4-9).

$$W = \frac{F}{u\,D} \tag{4-9}$$

4.3.2. Dispersion Coefficients

Contaminant dispersion is a function of differential sheer flow and cross-sectional turbulent mixing. Longitudinal dispersion coefficients were calculated using equations developed by Fischer et al. (1979) as reported in Jirka et al. (1983).

$$E_x = \frac{0.011\,u^2W^2}{D\,u_*},\ E_y = \beta_y u_* D \tag{4-10}$$

where

u_* = shear velocity ($m\ s^{-1}$)

β_y = unitless coefficient having a value of 0.6 ± 0.3.

The shear velocity was estimated by

$$u_* = \sqrt{g\ D\ s} \tag{4-11}$$

where

g = gravitational acceleration (9.8 m s^{-2})
s = channel slope (m m^{-1}).

Channel width, depth, and velocity were calculated for every month of the simulation based on the monthly average flow rates in Figure 4-2 and Equations 4-6–4-9. The effective channel slope was estimated from plots of water surface height vs. downstream distance provided in Walters et al. (1992), and Walters et al. (1994) for different flow rates and times before and after construction of McNary Dam (Table 4-2). This calculation assumed the water depth is relatively constant at each of the measurement points. The average of four estimates (2.4×10^{-4} rounded to two significant digits) was used in the computations.

Table 4-2. Channel Slope Estimates in the Model Domain

River Mile	Water surface height (ft)[a]	Flow rate (cfs)	Channel slope[b]	Reference
330 390	328 411	341,000	2.61995×10^{-4}	Walters et al. (1994); Figure 9 (July 26, 1943)
330 390	327 396	93,900	2.17803×10^{-4}	Walters et al. (1994); Figure 10 (August 23, 1943)
320 390	273.3 366	N/A	2.50812×10^{-4}	Walters et al. (1992); Figure 3.1 (based on pre 1944 flows)
344.4 390	309.4 366	N/A	2.35081×10^{-4}	Walters et al. (1992); Figure 3.1 (1971–present)

[a] Feet above mean sea level. These values were interpolated from the figures in Walters et al. (1992) and Walters et al. (1994).

[b] The average of the four estimates, rounded to two significant figures, (2.4×10^{-4}) was used in the computations.

The value of β_y used in the computations was 0.9, which represents the upper-bound estimate for this parameter (β_y = 0.6 ± 0.3). The value of 0.9 was selected because only about 50% plume mixing was achieved at Pasco using a β_y value of 0.6. Walters et al. (1992) reported that the plume was fully mixed across the river channel at Pasco. Percent mixing was defined as

$$\%M(x) = \frac{C_{\min}(x)}{C_{\max}(x)} \times 100 \tag{4-12}$$

where

$\%M(x)$ = the percent mixing of the plume at a downstream distance, x
$C_{min}(x)$ = the minimum concentration across the river channel at a downstream distance, x
$C_{max}(x)$ = the maximum concentration across the river channel at a downstream distance, x.

Note that when $C_{min}(x) = C_{max}(x)$, then complete mixing was achieved. Using a β_y value of 0.9 resulted in ~75% mixing at the Pasco location. We did not adjust β_y further and recognized that complete mixing was not achieved at this location. Figure 4-3 shows the quantity $C_t(x,y)/C_{max}(x)$ as a function of y/W for two locations (Ringold and Pasco) and two flow rates. Concentrations were calculated for ^{65}Zn in December, 1956 for low flow conditions (64,590 cfs), and March 1956 for high flow conditions (447,500 cfs). Under high flow conditions, there appeared to be slightly less transverse dispersion relative to the width of the river.

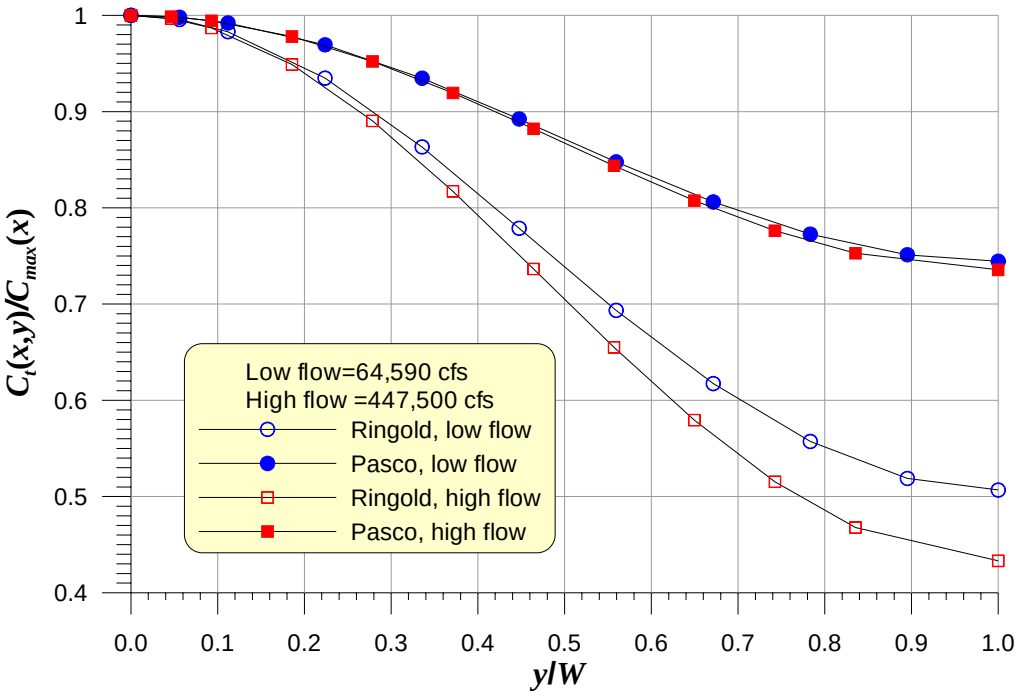

Figure 4-3. The ratio of $C_t(x,y)$ to $C_{max}(x)$ as a function of the distance from the near shore (y) divided by the width of the river (W) for two flow rates and using a β_y value of 0.9. Concentrations represent those of ^{65}Zn in March 1956 for high flow conditions and December 1956 for the low flow conditions.

Equations 4-10 and 4-11 produced E_x and E_y values on the order of 3400–7900 $m^2\ s^{-1}$ (36,597– 85,035 $ft^2\ s^{-1}$) and 0.44–1.6 $m^2\ s^{-1}$ (4.74–17.2 $ft^2\ s^{-1}$), respectively, for Columbia River flows given in Figure 4-2 and using a β value of 0.9. The HEDR model (Walters et al. 1994) used substantially smaller longitudinal dispersivity values, on the order of 46.5 $m^2\ s^{-1}$ (500 $ft^2\ s^{-1}$) to 232 $m^2\ S^{-1}$ (2500 $ft^2\ S^{-1}$), and concluded that the predicted river water concentrations were not very sensitive to this parameter. Except for short-lived isotopes such as ^{56}Mn (half-life = 0.107 d) average concentrations were insensitive to longitudinal dispersivity.

4.3.3. Retardation Factor and Sediment Effects

A criticism of the HEDR Project was the exclusion of contaminated sediments as a pathway of exposure (Hoffman et al. 1998). To address this concern, sediment effects were incorporated into our screening model. Partitioning of radionuclides in the aqueous and sorbed phases was

described by the equilibrium partition coefficient. The radioactivity inventories in sediment and water were a function of the suspended sediment load and the fixed sediment bed that interacted with radioactivity in the river water. Derivation of the concentration in each phase began with the mass balance equation for radionuclides in aqueous and sorbed phases.

$$C_T = C_w + C_w K_d Ss + C_w K_d \frac{T_b \rho}{D} \tag{4-13}$$

where

C_T = total radionuclide inventory in a unit volume of water including radioactivity in the fixed sediment bed (Ci m^{-3})
C_w = radionuclide concentration in aqueous phase only (Ci m^{-3})
K_d = partition coefficient (m^3 g^{-1})
Ss = suspended sediment load in river water (g m^{-3}).
ρ = bulk density of fixed sediment bed (assumed to be 1.2×10^6 g m^{-3})
T_b = thickness of fixed sediment bed that interacts with river water (m)
D = depth of river (m).

In this formulation, aqueous-phase radionuclides held in the pore spaces (assuming 100% saturation) of the fixed sediment bed were ignored. The fraction of radioactivity that sorbed to the fixed sediment bed, and was therefore retarded in movement was given by

$$\frac{C_w K_d T_b \rho / D}{C_T} = \frac{K_d T_b \rho / D}{1 + K_d Ss + K_d T_b \rho / D} = \frac{K_d T_b \rho}{D(1 + K_d Ss) + K_d T_b \rho} \tag{4-14}$$

The thickness of the fixed sediment bed that interacted with river water was estimated to be 5.99 cm (2.36 inches) by Onishi et al. (1982)[e] and was based on the modeling of sediment and radionuclide transport for two rivers in New York State using the SERATRA code. This value (5.99 cm) represented the thickness of the top layer of cohesive sediments. Marshall Richmond of PNNL suggested a value of several grain diameters of the fixed sediment bed[f]. Richmond also stated that typical suspended sediment loads for the Columbia River above its confluence with the Snake River were about 10 g m^{-3}. The fixed sediment bed thickness would be in the range of 1 to 4 mm assuming the sediment bed is comprised of coarse to very coarse sand (½ to 2 mm). The relative amount of radionuclide sorbed to suspended sediment and that sorbed to the fixed sediment bed was evaluated by taking the ratio of $T_b \rho/D$ to Ss. Using the minimum value for the thickness of the fixed sediment bed of 0.1 cm, a river depth of 6.3 m (based on Equation 4-8 and the mean discharge of 3597 m^3 S^{-1}), and a suspended sediment load of 10 g m^{-3} as provided by Richmond, gave a ratio of 19. Because the ratio of the two was relatively large (i.e., bed sediment mass is 19 times that of the suspended sediment mass), sorption of radionuclides onto suspended sediment was ignored in the calculation of the retardation factor. If suspended sediment loads

[e] The value of 5.99 cm was taken from the SERATRA output file on page C.3 in Onishi et al. (1982).

[f] Personal communication with Marshal C. Richmond, Pacific Northwest National Laboratories, August 24, 2000.

were considered in the retardation factor, then the solution below the confluence with the Snake River where sediment loads were higher would have to be matched with the solution upstream of the confluence. This violated the spatially constant retardation factor assumption in the solution to the transport equation given by Equation 4-2. The retardation factor was then derived from Equation 4-13, ignoring the suspended sediment load.

$$C_T = C_w + C_w K_d \frac{T_b \rho}{D}$$
$$C_w = \frac{C_T}{1 + K_d \frac{T_b \rho}{D}} = \frac{C_T}{R_d} \quad (4\text{-}15)$$

where $R_d = 1 + K_d\, T_b\, \rho/D$. The term, C_w was equivalent to C in Equation 4-1 and 4-2 and Ca and C_t in Equation 4-4 and 4-5 respectively, and represented both dissolved phase and sorbed suspended sediment radioactivity in river water. The radioactivity sorbed per unit mass of suspended sediment (C_s) was given by

$$C_s = C_w K_d \quad (4\text{-}16)$$

The aqueous phase concentration (C_A) that did not include radioactivity sorbed to suspended sediment was given by

$$C_A = \frac{C_w}{1 + K_d Ss} \quad (4\text{-}17)$$

Many other complex physical processes not included in this model occur during sorbed phase transport, including deposition and suspension of sediment, temporal and spatial fluctuation of both the quantity and characteristics of the sediment load, and changes in water chemistry that affect the sorption process. Models that incorporate such processes (Onishi et al. 1982) often require calibration to detailed site-specific sediment data that are not historically available for the Columbia River. Furthermore, models such as these are complex and beyond the scope of a screening exercise. Selection of a sediment bed thickness is discussed in the Model Calibration section.

The net effect of sorption on the fixed sediment bed was to retard the movement of radionuclides downstream. This effect was described in terms of the mean transit time (T_t) from source to receptor.

$$T_t = \frac{x\, R_d}{u} \quad (4\text{-}18)$$

For radionuclides with half-lives a factor of 5 or greater than T_t, retardation has virtually no effect on the steady-state concentration. For radionuclides with half-lives $\leq 5 \times T_t$, concentrations were reduced by additional decay during transit.

Aqueous phase concentrations as given by Equation 4-17 were compared to river water measurements and used in the risk calculations for the drinking water pathway. Aqueous and sorbed suspended sediment concentration as given by Equation 4-15 were used in risk

calculations for inadvertent ingestion of river water, fish ingestion, and aerosol inhalation. The sorbed radioactivity per unit mass of sediment as given by Equation 4-16 provided a source term for the sediment submodel described in the next section.

4.3.4. Sediment Submodel

The treatment of sediment effects discussed in previous sections did not account for radionuclides that were sorbed onto suspended sediments that were later deposited and were either covered by clean sediments or remained exposed. In either case, desorption from the sediments back into river water was restricted because sediment desorption was controlled by the sediment pore water and not the river water, which was typically more dilute compared to pore water. Therefore, radioactivity sorbed to the deposited sediments formed a sink. To address this potential pathway, a separate sediment submodel was developed. This submodel assumed that the radioactivity that was removed from the system through sediment deposition was minimal and was not subtracted from the total radioactivity in the river system. The submodel was an adaptation of the shoreline exposure models described in Soldat et al. (1974) and Strenge et al. (1986) and implemented in NCRP (1996). The model was described by a first-order compartment model where radioactivity sorbed to suspended sediments accumulated and radioactive decay was the only loss mechanism considered.

$$\frac{dQs}{dt} = v_d\, C_w\, K_d\, Ss - \lambda Qs \tag{4-19}$$

where

Qs = radionuclide inventory in deposited suspended sediment (Ci m^{-2})
v_d = deposition velocity in river water (m d^{-1}).

The solution to Equation 4-19 for the initial conditions, $Qs = Qs_o$ at $t = 0$, and a constant v_d, C_w, and Ss was

$$Qs(t) = \frac{v_d\, C_w\, K_d\, Ss}{\lambda}\left(1 - e^{-\lambda t}\right) + Qs_o\, e^{-\lambda t} \tag{4-20}$$

The term, C_w [which is equivalent to $C_t(x,y,t)$] was calculated at a location, (x, y) where exposure was assumed to occur. For these calculations, y was defined by

$$y = \frac{1}{2}W - y_{shore} \tag{4-21}$$

where y_{shore} was the distance from the center of the river channel to the near (or far shore) of the river. For computational purposes, y_{shore} was positive if it was measured in the direction of the near shore (from the center of the river channel) and negative if it was measured in the direction of the far shore. If $y<0$ or $y>W$, then the computation was not performed because no river water

covered the point of exposure. For risk calculations, y_{shore} was assigned a value of 225 m. This value represented one-half the 25th percentile of the distribution of estimated monthly-averaged river widths from January 1944 to December 1971. Therefore, for 25 percent of the time, the point of exposure on the shoreline was assumed to be exposed to the air and not accumulating radioactivity. River widths were estimated using Equation 4-9.

The deposition velocity was assigned a value of 0.07 m d^{-1} based on the work of Soldat et al. (1974) as reported in NCRP (1996), who used sediment and water concentrations in the Columbia River between Richland, Washington and Tillamook Bay, Oregon to estimate deposition of contaminated sediments. The quantity *Qs* was used to calculate the risk from external exposure to shoreline sediments, inadvertent ingestion of sediment, and dermal contact. Dividing *Qs* by the mass of sediment accumulated in time, Δt ($M_{sed} = Ss \times v_d \times \Delta t$) provided the radioactivity accumulated in sediments per unit mass. This value was compared with measured radioactivity levels in sediments.

4.3.5. Source Term

Details related to developing the radionuclide release estimates (also called the source term) were discussed in Chapter 2. This section describes how the source term was implemented into the transport model. Monthly release quantities to the Columbia River for a subset of the radionuclides examined from *all* reactors were provided in Heeb and Bates (1994) and compiled in a Microsoft Excel® spreadsheet. Unfortunately, release quantities were not segregated by reactor. For the HEDR study, this was not a major issue because the model domain extended ~480 km (~300 mi). However, the screening model domain was considerably smaller (~105 km [~65 miles]), and the distance separating each reactor may have been significant. Therefore, it was necessary to segregate release quantities by reactor. Releases were apportioned to each reactor based on the monthly energy production reported in Appendix A of Heeb and Bates (1994). We assumed that the quantity of radioactivity released to the Columbia River was proportional to the energy production from the reactors. The validity of this assumption is illustrated in Figure 4-4, which shows the monthly gross beta activity plotted against the monthly energy production for all reactors. The radioactivity released from each reactor by month was equal to the monthly energy production for a given reactor divided by the total energy production from all reactors multiplied by the total radioactivity released from all reactors.

$$q_{i,j} = \frac{E_{i,j}}{\sum_{i=1}^{8} E_{i,j}} Q_j \qquad (4\text{-}22)$$

where

$q_{i,j}$ = radionuclide release rate for reactor i and month j (Ci $month^{-1}$)
Q_j = total radionuclide activity released from all eight reactors for month j (Ci $month^{-1}$)
$E_{i,j}$ = energy production for reactor i and month j (MWd).

The method only approximates the monthly release from each reactor because incidents such as a fuel-element failure occurring in one reactor were apportioned across all the reactors.

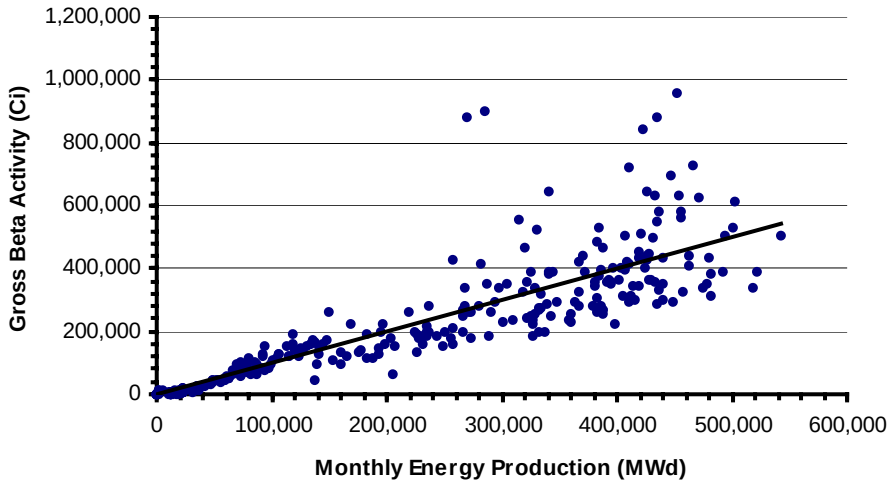

Figure 4-4. Gross monthly beta activity versus monthly energy production from all eight reactors. The Pearson product moment correlation coefficient was 0.873.

The term y_s represented the release point of reactor effluent in the Columbia River as measured from the near shore. All reactors were situated on the near shore. For most reactors, effluent was first discharged to retention ponds to allow thermal cooling and decay of some of the short-lived fission products. The effluent was then discharged via gravity flow through a 42 to 60-inch (106.68 to 152.4 cm) pipe that extended into the center of the river channel, about 100 to 200 m (109 to 219 yd) from the reactor shoreline (Walters et al. 1992). However, during seasons of high river flows, problems developed in this discharge system because of the hydraulic head differential between the discharge basin and the water-surface level. In cases of high river flow, reactor effluent was discharged to the river at the shoreline. Two exceptions were noted for this discharge system: the 100-F reactor discharge pipe only extended ~50 m (55 yd) from the shoreline, and, at the 100-D and 100-DR reactors, the river channel was divided by an island and effluent was discharged over the island and into the far channel. Table 4-3 presents the modeled distances (y_s) from the near shore for reactor effluent. Shoreline distances were kept at their minimum estimated value to account for the times of high flow where effluent was discharged to the shoreline.

For some radionuclides, source terms were not available in Heeb and Bates (1994), but were instead approximated by the relative concentrations of known radionuclides in reactor effluent. Radionuclides for which these approximations were made include ^{45}Ca, ^{60}Co, ^{64}Cu, ^{69,69m}Zn, ^{89}Sr, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{133}I, and ^{137}C$_s$. See Chapter 2 for details.

Table 4-3. Distance from Near Shore that Reactor Effluent was Discharged and Distance of each Reactor from RM 385

Reactor	River mile	River meter[a]	Discharge distance from near shore, *ys* (m)
100B	384	1,609	100
100C	383.6	2,253	100
100KW	381.8	5,150	100
100KE	381.4	5,794	100
100D	377.6	11,909	300
100DR	377.6	11,909	300
100H	372.5	20,117	100
100F	369	25,750	50

[a] As measured from RM 385. River meter = (385 – River mile) × 1609.344 m mile^{-1}. Distances are rounded to nearest meter.

For some radionuclides, source terms were not available in Heeb and Bates (1994), but were instead approximated by the relative concentrations of known radionuclides in reactor effluent. Radionuclides for which these approximations were made include ^{45}Ca, ^{60}Co, ^{64}Cu, ^{69m}Zn, ^{89}Sr, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{133}I, and ^{137}C$_s$. See Chapter 2 for details.

4.3.6. Dilution Factor for the Snake and Yakima Rivers

The added dilution from the Snake and Yakima Rivers joining the Columbia River at RM 325 and RM 335 respectively was accounted for by multiplying the radionuclide concentration in river water by a dilution factor, *DF*.

$$DF = \frac{F_c}{F_c + F_s + F_y} \tag{4-23}$$

F_c = Flow rate in the Columbia River (m^3 s^{-1})
F_s = Flow rate in the Snake River (rounded to 1,528 m^3 s^{-1} from the value reported in Walters et al. 1992)
F_y = Flow rate in the Yakima River (rounded to 104 m^3 s^{-1} from the value reported in Walters et al. 1992).

If the exposure location was upstream of RM 335 (Yakima River) then F_s and F_y were set to zero and *DF* = 1. If the exposure location was positioned between RM 335 and RM 325 (Snake River), then F_s was set to zero.

4.4. Computation Details

Equations 4-1–4-5, 4-10, 4-11, 4-15–4-17, and 4-19–4-21 were coded into a FORTRAN program (RVRDSP) that

- Read model inputs and performed initial unit conversions

- Computed the convolution integral (Equation 4-4) and source superposition (Equation 4-5)
- Calculated carcinogenic risk based on user-supplied exposure factors
- Wrote output to ASCII files.

Input file formats and user instructions are presented in Appendix D. The convolution integral (Equation 4-4) was approximated using Simpson Rule integration as described in Press et al. (1992). Within the integration range from 0 to *t*, some terms can be nearly zero, contributing little to the integral. For this reason, Codell et al. (1982) computed integration limits such that terms within the integration range were either greater than zero or greater than a specified value that was considered insignificant. The integration limits, $t_{1,2}$ were given by

$$t_{1,2} = t - 0.5\left[\frac{2\,x\,u/R_d + 4E_x\,\gamma/R_d}{\left(u/R_d\right)^2 + 4E_x\gamma/R_d} \pm \sqrt{\left(\frac{2\,x\,u/R_d + 4E_x\gamma/R_d}{\left(u/R_d\right)^2 + 4E_x\lambda/R_d}\right)^2 - \frac{4x^2}{\left(u/R_d\right)^2 + 4E_x\lambda/R_d}}\right] \tag{4-24}$$

where γ was a number chosen such that

$$\exp\left[-\frac{\left(x - \dfrac{u(t-\tau)}{R_d}\right)^2}{4E_x/R_d\,(t-\tau)} - \lambda(t-\tau)\right] \tag{4-25}$$

was at least exp(–γ). Equations 4-24 and 4-25 have been modified from Codell et al. (1982) to include retardation. Codell used a value of 50 for γ and we retained this value in the code. Additional restrictions placed on $t_{1,2}$ were given as follows:

$$\begin{aligned} &t_1 \geq 0 \\ &t_2 \leq t \\ &t_2 \leq \text{length of release function, } q(t) \end{aligned} \tag{4-26}$$

The infinite series term in Equation 4-2 was used to calculate cross-channel mixing. Before calculation of this term in Equation 4-2, the standard deviation of the plume in the transverse direction (σ_y) was determined.

$$\sigma_y = \sqrt{2\,E_y t/R_d} \tag{4-27}$$

If $\sigma_y > 2.8W$, then complete mixing was assumed and $C(x,y,t)$ was given by

$$C(x,y,t) = \frac{1}{\sqrt{4\pi\,E_x t/R_d}\,DW\,R_d}\exp\left[-\frac{\left(x - ut/R_d\right)^2}{4\,E_x t/R_d} - \lambda t\right] \tag{4-28}$$

which was the one-dimensional solution to Equation 4-1 for complete horizontal mixing.

To improve computational efficiency, an alternative form of Equation 4-2 was used when

$$t \le \frac{W^2}{\pi E_y / R_d} \quad (4\text{-}29).$$

When the condition given in Equation 4-29 was true, then the exponential in the infinite series given in Equation 4-2 and reproduced in Equation 4-30,

$$\exp\left(-\frac{n^2\pi^2 E_y t/R_d}{W^2}\right) \quad (4\text{-}30)$$

decreased slowly with increasing n and could take many terms to achieve convergence. In such cases, an alternative form of infinite series was used which made use of the identity (Whittaker and Watson 1962)

$$\sum_{n=-\infty}^{\infty} \exp\left(-\pi\theta(n-a)^2\right) = \frac{1}{\sqrt{\theta}}\left(1 + 2\sum_{n=1}^{\infty} \exp\left(-n^2\pi/\theta\right)\cos 2n\pi a\right) \quad (4\text{-}31)$$

and

$$2\cos\frac{n\pi\, ys}{W}\cos\frac{n\pi\, y}{W} = \cos\frac{n\pi(ys-y)}{W} + \cos\frac{n\pi(ys+y)}{W} \quad (4\text{-}32)$$

where $\theta > 0$ and was given by

$$\theta = \frac{W^2}{\pi E_y / R_d t} \quad (4\text{-}33).$$

Substitution and rearrangement gave the following alternative expression for Equation 4-2.

$$C(x,y,t) = \frac{1}{4\pi D t\sqrt{E_x E_y}} \exp\left[-\frac{(x-ut/R_d)^2}{4E_x t/R_d} - \lambda t\right] \times \sum_{n=-\infty}^{\infty}\left\{\exp\left(-\frac{W^2}{E_y t/R_d}\left(n - \frac{ys-y}{2W}\right)^2\right) + \exp\left(-\frac{W^2}{E_y t/R_d}\left(n - \frac{ys+y}{2W}\right)^2\right)\right\} \quad (4\text{-}34)$$

In both cases (Equation 4-2 and its alternate form in Equation 4-34), the infinite series was truncated when

$$abs(\beta_{n-1} - \beta_n) \le \varepsilon\, \beta_n \quad (4\text{-}35)$$

where β_n = the value of the series for n terms, β_{n-1} = the value of the series for n–1 terms, and ε = a convergence criteria value hardwired into the code at 1×10^{-16}.

The sediment submodel did not use the analytical expression (Equation 4-20) in the code, and instead Equation 4-19 was solved using a 4th order Runga-Kutta solver described in Press et al. (1992). The choice of a numeric solution for the sediment submodel was made to allow for temporally-variable sediment deposition velocities. Although in these calculations, only a constant value for sediment deposition velocity was allowed in the code.

The numerical error in the Simpson rule integration was controlled by a user-defined parameter discussed in Appendix D.

4.5. Code Verification

Code verification is defined here as confirmation that the model has been coded and implemented in the computer code correctly. To do this, quantities calculated in RVRDSP (such as water concentrations) were compared with like quantities calculated using other codes or analytical expressions. The RVRDSP was benchmarked against three analytical expressions for steady-state releases, an analytical expression for an instantaneous release, and output from the RIVLAK code as presented in Codell et al. (1982). Two analytical expressions for steady-state releases were obtained from NCRP (1996); a third expression was derived from analytically integrating Equation 4-2 with respect to time. These analytical expressions verified the steady-state concentrations calculated with RVRDSP. The RIVLAK and the analytical expression for an instantaneous release verified RVRDSP for short-term and transient releases. Twelve benchmark problems were considered (Appendix E), however, two of the benchmark problems (1 and 3) used earlier versions of RVRDSP and were not presented. Discrepancies were expressed as percent differences and are summarized in Table 4-4. Negative percent differences represented positive RVRDSP bias. Checks on other intermediate quantities calculated in the code such as dispersion coefficients and partitioning of radioactivity to sediments were also performed. An additional benchmark problem provided verification of the risk calculation, which is described in a later section.

The benchmark problem that exhibited the greatest discrepancies (number 2) used the code that RVRDSP was based on (RIVLAK). Review of the RIVLAK code revealed several errors in its implementation, in particular, the linear interpolation routine erroneously returned the value of zero instead of the correct source strength for the time corresponding to the start of the source, and thereby underestimated the source strength. It was therefore not surprising that RVRDSP predicted a higher concentration relative to RIVLAK. For steady-state releases, RVRDSP provided results that were nearly identical to those derived from the analytical integrand. We noted differences between results derived from the analytical solutions for steady-state release provided in NCRP (1996) and those from RVRDSP and the integrated form of Equation 4-2. These differences were generally <0.09%. We concluded that the RVRDSP code provided correct answers for the conditions that were modeled for the Columbia River.

Table 4-4. Summary of Code Verification Benchmark Problems in Appendix E

Number	Comparison code, expression[a]	Comments	Average difference[b]
2	RIVLAK, page 2.56, Figure 2.17 in Codell et al. (1982)		–0.280%
4	Analytical expression for instantaneous release (Equation 4-2)		–0.002%
5	(1) NCRP Equations for steady state release and (2) integrated form of Equation 4-2 for steady-state release	Complete horizontal mixing	(1) 0.048% (2) 0.000%
6	(1) NCRP Equations for steady state release and (2) integrated form of Equation 4-2 for steady-state release	Incomplete horizontal mixing	(1) 0.088% (2) 0.000%
7	Integrated form of Equation 4-2 for steady-state release for ~20 km receptor	Plume cross-section examined	0.000%
8	Integrated form of Equation 4-2 for steady-state release for ~38 km receptor	Plume cross-section examined	0.000%
9	Integrated form of Equation 4-2 for steady-state release for ~63 km receptor	Plume cross-section examined	0.000%
10	Integrated form of Equation 4-2 for steady-state release for ~63 km receptor	Includes retardation; intermediate values checked	0.000%
11	Integrated form of Equation 4-2 for steady-state release for ~63 km receptor, radionuclide inventory in sediments checked	Plume cross-section examined	0.000%
12	Integrated form of Equation 4-2 for steady-state release for 100 m receptor, radionuclide inventory in sediments checked	Includes retardation; intermediate values checked	–0.002%

[a] All RVRDSP results produced using Version 1.1 dated 07/29/02

[b] Average difference = $\left(\sum_{i}^{n} \frac{C_{a_i} - C_{r_i}}{C_{a_i}} \times 100 \right) \Big/ n$ where C_a = the concentration calculated by analytical solutions or other codes, C_r = the concentration calculated by RVRDSP, and n = number of observations.

4.6. Model Calibration

Model calibration is defined in this report as the process of parameter adjustment to match model predictions with observations. The sorption coefficient, K_d, was the primary calibration parameter. A value for the fixed sediment bed thickness, T_b, was also selected during this process. The parameter, T_b was radionuclide independent while K_d was radionuclide dependent. The calibration procedure involved first selecting a thickness for the fixed sediment bed and then adjusting K_d values for each radionuclide so that model predicted concentrations in water agreed with observations as determined by several performance measures discussed later in this section. Predicted concentrations were particularly sensitive to the assumed sorption coefficient for radionuclides whose half-lives were comparable to the mean water travel time from the reactors to the predicted concentration location. In some cases, adjustments to source term were made to achieve calibration. These adjustments were discussed on a case-by-case basis.

Our primary calibration objective was to minimize the bias in the average predicted concentrations over the measurement period. If bias was unavoidable, then efforts were made to assure that the bias was positive (overprediction), and thereby provide an upper bound estimate of the concentration. A second calibration objective was to minimize the residuals between the predicted and observed concentrations.

The metrics used to evaluate model calibration incorporate several performance measures commonly used in evaluation of atmospheric transport models (Fox 1981; EPA 1988; Cox and

Tikvart 1990). These measures were the fractional bias (*FB*) and normalized mean square error (*NMSE*). The *FB* was given by

$$FB = \frac{2\left(\overline{C_o} - \overline{C_p}\right)}{\left(\overline{C_o} + \overline{C_p}\right)} \tag{4-36}$$

where C_p and C_o were the predicted and observed concentrations, respectively. Overbars indicated averages over the sample. The *NMSE* was given by

$$NMSE = \frac{\overline{\left(C_o - C_p\right)^2}}{\overline{C_o}\,\overline{C_p}} \tag{4-37}$$

The *FB* is a measure of the mean bias. A *FB* of 0.67 is equivalent to model underprediction by a factor of 2. A negative value indicates model overprediction. A *FB* value of ±0.3 indicates model bias is roughly ±25%. That is, model predictions are either over- or underpredicted by factor of 1.35.

The *NMSE* is a measure of model variance. A *NMSE* value of 1.0 indicates that the typical difference between predictions and observations is approximately equal to the mean. A perfect model would have a *FB* and *NMSE* of zero. Our calibration targets for *FB* and NMSE were abs(*FB*) ≤ 0.3 and NMSE ≤ 0.5, although these targets were not met in all cases. Many of the excursions of abs(*FB*) above 0.3 involved negative *FB* values indicating model overprediction.

The calibrated parameters presented in this section are not unique, and in fact, calibration could be achieved using a different set of parameters. This problem (i.e., the non-unique solution to the calibration problem) is often encountered in environmental transport problems and requires some degree of subjective judgement on the choice of parameter values and consideration of the modeling objectives. In the calibration procedure, the values of K_d and T_b were constrained within values reported in the literature or other sources. However, exceptions were made to this procedure for the K_d if sediment data existed.

In general, the median estimated source terms from Heeb and Bates (1994) were used as the basis for source term estimates. Radionuclide source terms that were based on ratios of radioactivity in effluent waters (^{60}Co, ^{64}Cu, ^{69,69m}Zn, ^{90}Sr, ^{89}Sr, ^{93}Y, ^{137}Cs, ^{45}Ca, ^{133}I, ^{122}Sb) used the geometric mean ratio times the median estimated source term from Heeb and Bates (1994). In many cases, these ratios spanned several orders of magnitude, and therefore, if calibration using the range of K_d values reported in the literature was unacceptable, adjustment to the ratio was considered.

Sampling locations used in the calibration are listed in Table 4-5 and illustrated in Figures 2-1a and 2-1b. It was not stated in Walters et al. (1992) where samples were taken relative to the shoreline, and we have assumed a nominal distance of 50 m in all cases. Three types of water measurement data were available; 1) grab samples taken about once a month, 2) continuous monitoring data, and 3) annual average concentrations. Sampling data were obtained from HEDR project files and compiled in spreadsheets. The predicted concentration for the day the grab sample was taken was compared to the corresponding grab sample measurement. Continuous data represented the average concentration over the sampling period, typically seven consecutive days.

These data were converted to monthly averages by taking the values recorded for each month and averaging them to provide monthly-averaged concentrations. Sediment data included measurements of radioactivity per unit mass of sediment for a limited number of radionuclides and surface exposure readings in the Hanford Slough for ^{60}Co and ^{137}Cs.

Table 4-5. Distances to Downstream Sampling Locations

Location name	River Mile	River Meter[a]	y [b] (m)	y_{shore} [c] (m)
Richland Pumping Station	340	72,420	50	N/A
Pasco Pumping Station	329	90,123	50	N/A
300 Area	345	64,374	50	N/A
Ringold far shore	354	49,890	-50	N/A
Hanford Slough	364	33,796	N/A	225
McNary Reservoir[d]	300	136,794	250	0

[a] The river meter is the distance to the receptor from RM 385 converted to meters and rounded to the nearest meter.

[b] Transverse distance from the shoreline. A positive value indicates the distance is measured from the near shore. A negative value indicates the distance is measured from the far shore.

[c] Distance from the center of the river channel where sediment deposition is computed. A positive value indicates the distance is to the near shore; a negative value indicates the distance to the far shore.

[d] This receptor represents measurements made in the McNary reservoir. At this distance, the plume is completely mixed across the river channel.

A summary of the K_d values found in the literature is given in Table 4-6. The values reported in Kincaid et al. (1998) were specific for the Hanford Reservation, however, they were intended to represent conditions in unsaturated and saturated subsurface lithology, and not the sediments in the Columbia River.

Table 4-6. Summary of Linear Sorption Coefficients (K_d) Reported in the Literature (mL g^{-1})

	Sheppard and Thibault[a]						
Element	Sand	Silt	Clay	Organic	Kincaid[b]	Baes[c]	NCRP[d,e]
As						200	110
Ca	5	30	50	90		4	6.7
Co	60	1300	550	1000		45	60
Cr	70	30	1500	270		850	30
Cs	280	4600	1900	270	1500	1000	270
Cu						35	30
Ga						1500	
I	1	5	1	25	0.5	60	1
Mn	50	750	180	150		65	50
Na						100	76
Np	5	25	55	1200	15	30	5
P	5	25	35	90		3.5	8.9
Sb	45	150	250	550		45	45
Sc						1000	310
Sr	15	20	110	150	20	35	15
Y	170	720	1000	2600		500	190
Zn	200	1300	2400	1600		40	200
Zr	600	2200	3300	7300	1000	3000	580

[a] Sheppard and Thibault (1990).
[b] Kincaid et al. (1998).
[c] Baes et al. (1984).
[d] NCRP (1996).
[e] The units stated in NCRP (1996) of m^3 kg^{-1} are incorrect. The correct units are mL g^{-1}.

4.6.1. Sediment Bed Thickness

Both the sediment bed thickness and the sorption coefficient affected the retardation factor, which in turn affected radionuclide migration in the river channel. As discussed earlier, retardation only affected the steady-state concentration of those radionuclides that decayed significantly during transport from source to receptor. Also, the same R_d value can be obtained from different combinations of T_b and K_d. Maximizing the K_d value will presumably result in overestimation of sediment concentrations, and thereby provide conservative (overestimated) estimates of exposure and risk from the sediment pathways. Ideally, we would like to have radioactivity per unit mass of sediment and water concentration data taken concurrently for all radionuclides to determine the optimum K_d value to use in the simulation. Unfortunately, this was not the case and sediment data were limited to only a few radionuclides. Because sediment data were limited, we took the approach that minimized the sediment bed thickness (thereby maximizing K_d) in the selection of T_b. Using a value of 0.001 m as suggested by Marshall Richmond of PNNL (see the earlier discussion in Section 4.3.3 and 4.3.4) and the minimum literature-reported K_d value, we calculated the *FB* and *NMSE* for five radionuclides that had half-lives of less than a day (and therefore, would be impacted by retardation). Results of this exercise (Table 4-7) show that except for ^{64}Cu and ^{69m}Zn, concentrations were overestimated. For the other

radionuclides (^{24}Na, ^{72}Ga, ^{56}Mn), the K_d was increased (higher value) for final calibration. For ^{64}Cu and ^{69,69m}Zn, some adjustment to the source term was necessary for model calibration.

Table 4-7. Fractional Bias and Normalized Mean Square Error Calculated for Minimum K_d Values and a Sediment Bed Thickness of 0.001 m

Radionuclide	Half-life (d)	Minimum K_d (mL g^{-1})	FB	NMSE	Mean Predicted (pCi L^{-1})	Mean Measured (pCi L^{-1})	Concentration Location
^{24}Na	0.623	76	–0.383	0.240	3270	2220	Richland
^{72}Ga	0.5875	1500	–0.0134	0.608	249	246	Ringold (grab)
^{64}Cu	0.5292	30	0.226	0.452	2650	3330	Richland (grab)
^{56}Mn	0.10743	50	–0.793	0.868	999	432	Richland
$^{69, 69m}$Zn	0.5525	40	0.804	1.32	43.3	102	Ringold (grab)

4.6.2. Calibration of K_d Values to Measured Water and Sediment Data

Results from the calibration of river water concentrations are presented in Table 4-8. The number of significant digits presented was not justified by the accuracy of the predictions and observations, but was retained for documentation purposes. Radionuclides that required source term adjustment, or had K_d values outside the range reported in the literature are discussed in separate subsections. With two exceptions (^{69,69m}Zn and ^{60}Co), all *FB* values were less than 0.3. Particular difficulty was encountered with ^{60}Co and two alternate calibrations were presented.

Table 4-8. Final Model Calibration Results for Columbia River Water Concentrations

Radionuclide/Sample type	K_d (mL g^{-1})	*n*	*FB*	*NMSE*	Average predicted concentration (pCi L^{-1})	Average observed concentration (pCi L^{-1})
^{76}As	200					
Annual average data, Richland and Pasco		15	–0.083	0.052	799.7	736
^{60}Co[a]	1300					
Continuous data, 300 Area		3	–0.829	0.965	19.24	7.97
Continuous data, Richland		5	0.001	0.182	62.99	63.04
^{60}Co[b]						
Continuous data, 300 Area		3	0.597	0.421	4.23	7.97
Continuous data, Richland		5	1.27	2.87	14.1	63.04
^{51}Cr	250					
Grab samples, Ringold		21	–0.077	0.196	2274	2106
Continuous data, 300 Area		8	0.055	0.148	7884	8333
Continuous data, Richland		31	–0.007	0.029	5034	4998
Continuous data, Pasco		21	–0.117	0.049	5467	4864
Annual average data, Richland and Pasco		16	–0.185	0.342	5615	4666
^{137}Cs[c]	1500					

Table 4-8. Final Model Calibration Results for Columbia River Water Concentrations

Radionuclide/Sample type	K_d (mL g^{-1})	*n*	*FB*	*NMSE*	Average predicted concentration (pCi L^{-1})	Average observed concentration (pCi L^{-1})
Annual Average, Richland		1	N/A	N/A	0.11	10.4
^{64}Cu[d]	35					
Grab samples, Ringold		21	–0.096	0.358	1729	1571
Grab samples, Richland		37	0.088	0.358	3047	3326
^{72}Ga	1500					
Grab samples, Ringold		21	–0.013	0.608	249.1	245.8
^{131}I[e]	60					
Continuous data, 300 Area		8	–0.684	1.501	26.47	12.99
Continuous data, Richland		31	–0.276	0.614	10.64	8.06
Continuous data, Pasco		21	–0.624	1.005	13.75	7.21
Annual average data, Richland and Pasco		13	–0.756	1.576	22.06	9.95
^{56}Mn	750					
Grab samples, Ringold		21	–0.044	2.813	1213	1161
Annual average data, Richland		5	–0.443	0.267	677.9	432
^{24}Na[f]	100					
Annual average data Richland		9	–0.074	0.068	2386	2216
Annual average data Pasco		6	–0.884	1.061	3934	1523
^{239}Np	1200					
Grab samples, Ringold		21	0.124	0.553	469	531.2
Grab samples, 300 Area		10	–0.369	0.352	3487	2401
Grab samples, Richland		39	–0.144	0.127	2086	1805
^{32}P	35					
Continuous data, 300 Area		8	–0.094	0.180	202.4	184.2
Continuous data, Richland		31	–0.027	0.109	133.6	130.1
Continuous data, Pasco		21	–0.418	0.382	138	90.37
Annual average data, Richland and Pasco		16	0.080	0.094	145.2	157.4
^{46}Sc	1000					
Annual average data, Richland		5	–0.069	0.554	65.4	61.0
^{90}Sr[g]	20					
Grab samples, 300 Area		9	–0.095	0.123	1.69	1.53
Grab samples, Richland		38	0.018	0.286	1.25	1.27
Grab samples, Pasco		16	–0.018	0.120	1.28	1.26
Annual average data, Richland and Pasco		13	–0.669	1.144	1.61	0.80
^{65}Zn	2600					
Continuous data, 300 Area		8	0.052	0.049	238.8	251.6
Continuous data, Richland		31	0.295	0.395	158.1	212.8
Continuous data, Pasco		21	0.025	0.094	153.5	157.3

Table 4-8. Final Model Calibration Results for Columbia River Water Concentrations

Radionuclide/Sample type	K_d (mL g^{-1})	*n*	*FB*	*NMSE*	Average predicted concentration (pCi L^{-1})	Average observed concentration (pCi L^{-1})
Annual average data, Richland and Pasco		16	–0.146	0.528	240.6	207.9
$^{69,69m}Zn$[h]	2600					
Grab samples, Ringold		20	0.332	0.388	72.66	101.6

[a] A scaling factor of 0.388 × Q_P (where Q_P is the median ^{32}P release rate) was used as a source term.
[b] A scaling factor of 0.0868 × Q_P was used as a source term.
[c] A scaling factor of 0.01 × Q_Y (where Q_Y is the median ^{90}Y release rate) was used as a source term.
[d] A scaling factor of 0.54 × Q_P was used as a source term.
[e] The minimum estimate of the source term given in Heeb and Bates (1994) was used.
[f] The minimum estimate of the source term given in Heeb and Bates (1994) was used.
[g] A scaling factor of 0.0044 × Q_Y was used as a source term.
[h] A scaling factor of 2.75 × Q_Z (where Q_Z is the median ^{65}Zn release rate) was used as a source term.

Sediment data are presented in Tables 4-9–4-11. Again the number of significant digits presented in these tables was not justified by the accuracy of the predictions and observations, but was retained for documentation purposes. Measured values of radioactivity per unit mass of sediment were obtained from Walters et al. (1992, Table 7.6 and on page 9.16). This medium was difficult to evaluate because it was unclear how many years of deposition were represented by the sample. Additionally, contributions from weapons fallout were not subtracted from the results. For purposes of comparison to measured data, each sample was assumed to represent ~1 year of deposition in McNary reservoir. Sediment concentrations were computed by dividing the total radioactivity accumulated in deposited sediments for the year (Ci) by the sediment mass accumulated for that year (g). The sediment submodel was used for these computations and accounted for decay during the accumulation period. In general, the predicted-to-observed (P/O) ratios for 1957 were close to 1.0; however, the model consistently underpredicted sediment values for 1971. One possible reason for this was that radioactivity in sediments in 1971 may have represented previously deposited sediments in the river channel that were suspended during high water flows. Radioactivity levels in these previously deposited sediments may have reflected earlier reactor operations when radioactivity release rates were higher. The screening model did not account for such processes. It is entirely possible that the ^{137}Cs observed in sediments may have been due to weapons fallout and not directly related to the reactors.

Surface exposure measurements taken in the Hanford Slough as reported in Walters et al. (1992, page 8.8) were converted to surface radioactivity concentrations (in pCi m^{-2}) by first computing the exposure at 10 cm (assumed value) above an infinite plane surface containing a unit concentration of radioactivity (1 μCi cm^{-2}). Dividing this value into the surface exposure reading (with unit corrections) provided an estimate of the surface radioactivity per unit area. Exposure estimates were performed using the Microshield code, Version 5.05 (Grove Engineering 1998). Results are discussed in the discussion section that follows.

Table 4-9. Predicted and Observed Radioactivity in Sediment Behind McNary Dam for 1957[a]

Radionuclide	Measured (pCi g^{-1})	Predicted (pCi g^{-1})[b]	P/O
^{65}Zn	357	349	0.98
^{51}Cr	87	108	1.24
^{60}Co[c]	5	9.97	1.99
^{60}Co[d]	5	44.6	8.91

[a] Measured values reported on page 9.16 of Walters et al. (1992).
[b] Radioactivity accumulated in sediments for 1957.
[c] A scaling factor of 0.0868 × Q_P was used as the source term. Q_P = median ^{32}P release rate.
[d] A scaling factor of 0.388 × Q_P was used as the source term.

Table 4-10. Predicted and Observed Radioactivity in Sediment Behind McNary Dam for 1971[a]

Radionuclide	Measured (dpm g^{-1})	Measured (pCi g^{-1})	Predicted (pCi g^{-1})[b]	P/O
^{65}Zn	240	108.11	40.41	0.37
^{46}Sc	120	54.05	1.66	0.03
^{60}Co[c]	60	27.03	1.40	0.05
^{60}Co[d]	60	27.03	6.28	0.23
^{137}Cs	9	4.05	0.75	0.19

[a] Measured values reported on page 7.6 of Walters et al. (1992). Measurements were made in April, 1971.
[b] Radioactivity accumulated in sediments for 1970.
[c] A scaling factor of 0.0868 × Q_P was used as the source term. Q_P = median ^{32}P release rate.
[d] A scaling factor of 0.388 × Q_P was used as the source term.

Table 4-11. Predicted and Observed Surface Radioactivity in Sediment in the Hanford Slough for 1974[a]

Radionuclide	Measured exposure (mR h^{-1})	mR h^{-1} per μCi cm^{-2} [b]	Surface radioactivity (pCi m^{-2})	Predicted surface radioactivity (pCi m^{-2})[c]	Decay factor	Predicted radioactivity, 4/74 (pCi m^{-2})	P/O
^{60}Co[d]	0.022	546.50	4.03×10^{5}	2.24×10^{-8}	0.743681	1.67×10^{4}	0.04
^{60}Co[e]	0.022	546.50	4.03×10^{5}	1.00×10^{-7}	0.743681	7.46×10^{4}	0.19
^{137}Cs	0.001	131.40	7.61×10^{4}	1.52×10^{-8}	0.949308	1.45×10^{4}	0.19

[a] Measured values reported on page 8.8 of Walters et al. (1992). Measurements were made between March and April, 1974.
[b] Calculated with Microshield (Grove Engineering 1998).
[c] The predicted radioactivity includes all radioactivity accumulated in deposited sediment from the startup of reactors (1944) to December, 1971.
[d] A scaling factor of 0.0868 × Q_P was used as the source term. Q_P = median ^{32}P release rate.
[e] A scaling factor of 0.388 × Q_P was used as the source term.

4.6.3. Discussion of Specific Radionuclides

In this section we discuss calibration results for radionuclides that require additional explanation and justification.

4.6.3.1. Cobalt-60

Cobalt-60 was a particularly troublesome radionuclide because of the large discrepancies between predicted and observed values for both sediment and water. Using the geometric mean $^{60}Co/^{32}P$ radioactivity ratio (0.031) as a basis for the source term resulted in significant underprediction in all cases. The ratio was increased to 0.0868 by multiplying the geometric mean value (0.031) by the geometric standard deviation (2.8). Model underprediction was still prevalent, except for the 1957 sediment values, where the model overpredicted by about a factor of 2.

To achieve excellent agreement between predicted and observed concentrations at Richland a $^{60}Co/^{32}P$ radioactivity ratio of 0.388 was required. However, this value was about an order of magnitude higher than the geometric mean ratio of 0.031 that was calculated from reactor effluent data reported in the HEDR spreadsheets.

The discussion of shoreline exposure measurements in Walters et al (1992) provided an important piece of information that may have some bearing on the large discrepancies observed for this radionuclide. During a survey conducted in the spring and summer months of 1979 between the 100-B reactor and the Snake River confluence, discrete particles of ^{60}Co were detected in the shoreline sediments along the river. As Walters et al. (1992) states:

> "Locations with the greatest number of particles were the island at RM 375 (below 100-D island); the 100-F Area flood plain; and the islands at RM 367, RM 353, and RM 350. The particles tended to decrease in number downstream and were found both in flat, rocky, unvegetated areas and above the daily high-water level."

These particles were metallic flakes suspected to have come from stellite valve and pump components used in production reactors. Release of such particles probably occurred as discrete events and may have gone undetected in the effluent monitoring systems. Certainly, some of the high measurements that we omitted from the calculation of the $^{60}Co/^{32}P$ radioactivity ratios from the HEDR spreadsheets (see Chapter 2) could have contained such particles.

The ratio approach used to derive the source term was inadequate for describing the release of discrete particles derived from failed components in the reactor. Furthermore, the particles would not have behaved the same way as a dissolved substance would in river water, and additional model development would have been necessary to accurately model their transport. Further examination of the ^{60}Co source term and modeling discrete particle transport in the river was beyond the scope of this project. We have attempted to bound potential exposures by using a $^{60}Co/^{32}P$ radioactivity ratio of 0.388 as one alternative source term in the risk calculations.

4.6.3.2. Cesium-137

In general, ^{137}Cs concentrations in river water and sediments were underpredicted. However, contributions from weapons testing fallout was not included in the model (or subtracted from the measurements), and this source alone could have accounted for much of the activity observed in

environmental media. For example, Lee and Lee (2000) measured ^{137}Cs in Korean volcanic and granite soils in 1999. Activity concentrations ranged from 0.138 to 7.7 pCi g^{-1}, with higher concentrations occurring in volcanic soils. Decay correcting these values to 1965 gave a range of ^{137}Cs activity concentrations from ~0.3 to ~17 pCi g^{-1}. While predicted levels of ^{137}Cs in sediments at the Hanford Slough and McNary Dam were about a factor of 5 less than observed values, the observed values were only slightly more than what might be expected from weapons testing fallout. Only one water measurement was available for ^{137}Cs during the assessment period and the predicted concentration was substantially lower than the measured value. We suspect that the high ^{137}Cs concentrations observed for 1971 may have been a result of resuspension of previously deposited sediments upstream of Richland or desorption of ^{137}Cs radioactivity that had accumulated in river sediments from past reactor effluent releases or weapons testing fallout.

4.6.3.3. Copper-64

The ^{64}Cu/^{32}P radioactivity ratio was increased from the geometric mean value of 47 obtained from the HEDR spreadsheets to 54 to obtain better agreement between predicted and observed concentrations. This value was well within the distribution of ^{64}Cu/^{32}P ratios in reactor effluent.

4.6.3.4. Iodine-131

The median estimated source term provided by Heeb and Bates (1994) for ^{131}I resulted in gross overprediction of measured river water concentrations at all sampling locations. Increasing the K_d to its maximum reported value in the literature (60 mL g^{-1}) only slightly decreased predicted river water concentrations. For this reason, the minimum source term values estimated by Heeb and Bates (1994) were used in the calibration. Despite using the minimum source term values, model overprediction was still prevalent. We suspect that other loss mechanisms not considered in the modeling (such as volatilization) affected ^{131}I concentrations in river water.

4.6.3.5. Sodium-24

The median estimated source term provided by Heeb and Bates (1994) for ^{24}Na resulted in gross overprediction of river water concentrations at the Pasco sampling location. Increasing the K_d value to its maximum reported in the literature (100 mL g^{-1}) only slightly decreased concentrations. For this reason, the minimum source term values estimated by Heeb and Bates (1994) were used in the calibration. Despite using the minimum source term values, model overprediction was still prevalent at the Pasco location.

4.6.3.6. Strontium-90

The ^{90}Sr/^{90}Y radioactivity ratio was increased from its geometric mean value of 0.0015 obtained from the HEDR spreadsheets to 0.0044 to obtain better agreement between predicted and observed concentrations. This value was well within the distribution of ^{90}Sr/^{90}Y ratios in reactor effluent. We recognize however, that some of the ^{90}Sr detected in water may have been from global fallout.

4.6.3.7. Zinc-65

The calibrated K_d value of 2600 mL g^{-1} was based on sediment measurements behind McNary Dam taken in 1957. This value was slightly higher than the maximum value of 2400 mL g^{-1} reported in the literature.

4.6.3.8. Zinc-69, Zinc-69m

The $^{69,69m}Zn/^{65}Zn$ radioactivity ratio was increased from its geometric mean value of 1.1 obtained from the HEDR spreadsheets to 2.75 because predicted concentrations were grossly underestimated using the ratio of 1.1 and a K_d of 2600 mL g^{-1} determined for ^{65}Zn using sediment data. The value of 2.75 was obtained by multiplying the geometric mean ratio by the geometric standard deviation. This value was therefore within the distribution of $^{69,69m}Zn/^{65}Zn$ ratios in reactor effluent.

4.6.4. Summary of Calibration

Predicted and observed concentrations for selected radionuclides are shown for Richland (Figure 4-5), Pasco (Figure 4-6), and Ringold (Figure 4-7). For some radionuclides (^{51}Cr), temporal trends were matched extremely well by the model for all locations, while for others, (^{72}Ga) the temporal history appears to have been aligned improperly. Discrepancies in the temporal trend of concentrations as exhibited by ^{72}Ga were, in most cases, traced directly back to the HEDR source term. For ^{24}Na, observed concentrations at Richland were reasonably well represented by the model, while at the Pasco location, the model substantially overpredicted concentrations (despite using minimum estimated source terms which on average, were ~35% less than the median estimated values). Concentrations calculated in HEDR as reported in Walters et al. (1994) also exhibited a similar pattern; however, concentrations at Pasco were overpredicted to a lesser extent. For the two years where concurrent data were taken (1963 and 1964), concentrations at both Richland and Pasco were overestimated. Further investigation of discrepancies such as these was beyond the scope of this project.

The overall results of the model calibration were summarized qualitatively by observing the relationship between predicted and observed concentration (Figure 4-8). Quantitatively, results were expressed by the distribution of P/O ratios (Figure 4-9). Model-predicted monthly-averaged concentrations were generally within a factor of 2 of their observations. The Pearson product moment correlation coefficient between the predicted and observed monthly-averaged concentrations was 0.93. The distribution of P/O ratios were shown for monthly-averaged data and annual-average data in Figure 4-9. As expected, the monthly-averaged data exhibited more variability. Both the monthly- and annual-averaged data sets exhibit little bias. The 50^{th} percentile P/O ratio was 1.05 for monthly-averaged data and 1.2 for annual-averaged data.

The work presented in this section represents the most comprehensive comparison of predicted and observed Columbia River water concentrations in the Hanford Reach to date. Many of the observed discrepancies were traced back to the source terms. Sediment transport probably influenced river water concentrations for some radionuclides, and the screening model used in this assessment is not equipped to handle this process in explicit detail. However, the model as parameterized, should have provided conservative estimates of radioactivity in sediments for the purpose of evaluating this pathway.

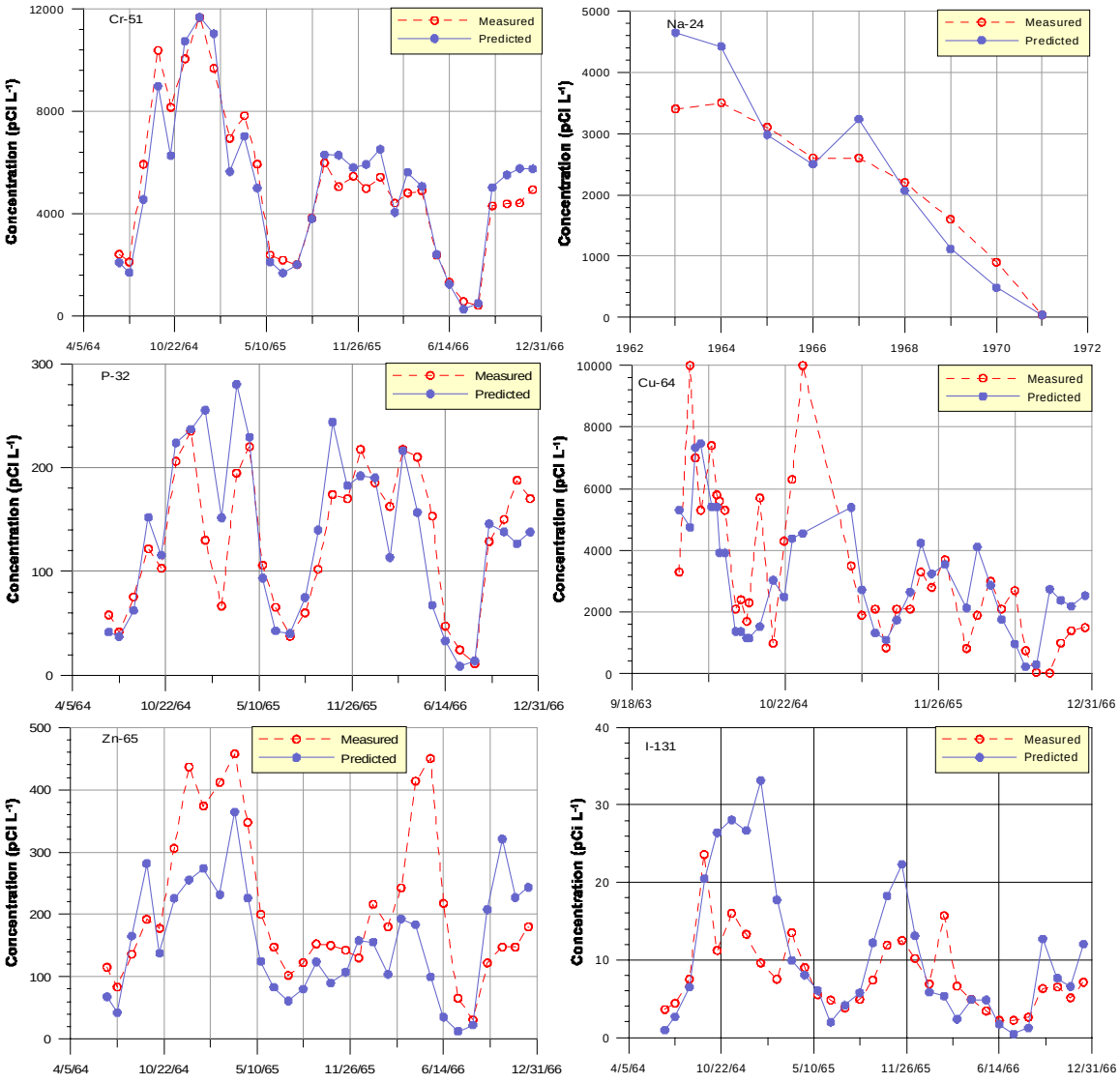

Figure 4-5. Predicted and measured concentrations in river water for selected radionuclides at the Richland location. Measured concentrations of ^{51}Cr, ^{32}P, ^{131}I, and ^{65}Zn represent monthly averages as determined by the continuous monitoring data. The predicted concentrations for these radionuclides also represent monthly averages. Measured concentrations of ^{64}Cu represent grab sample data and the predicted concentration is for the day the grab sample was taken. Annual-average predicted and measured concentrations are shown for ^{24}Na.

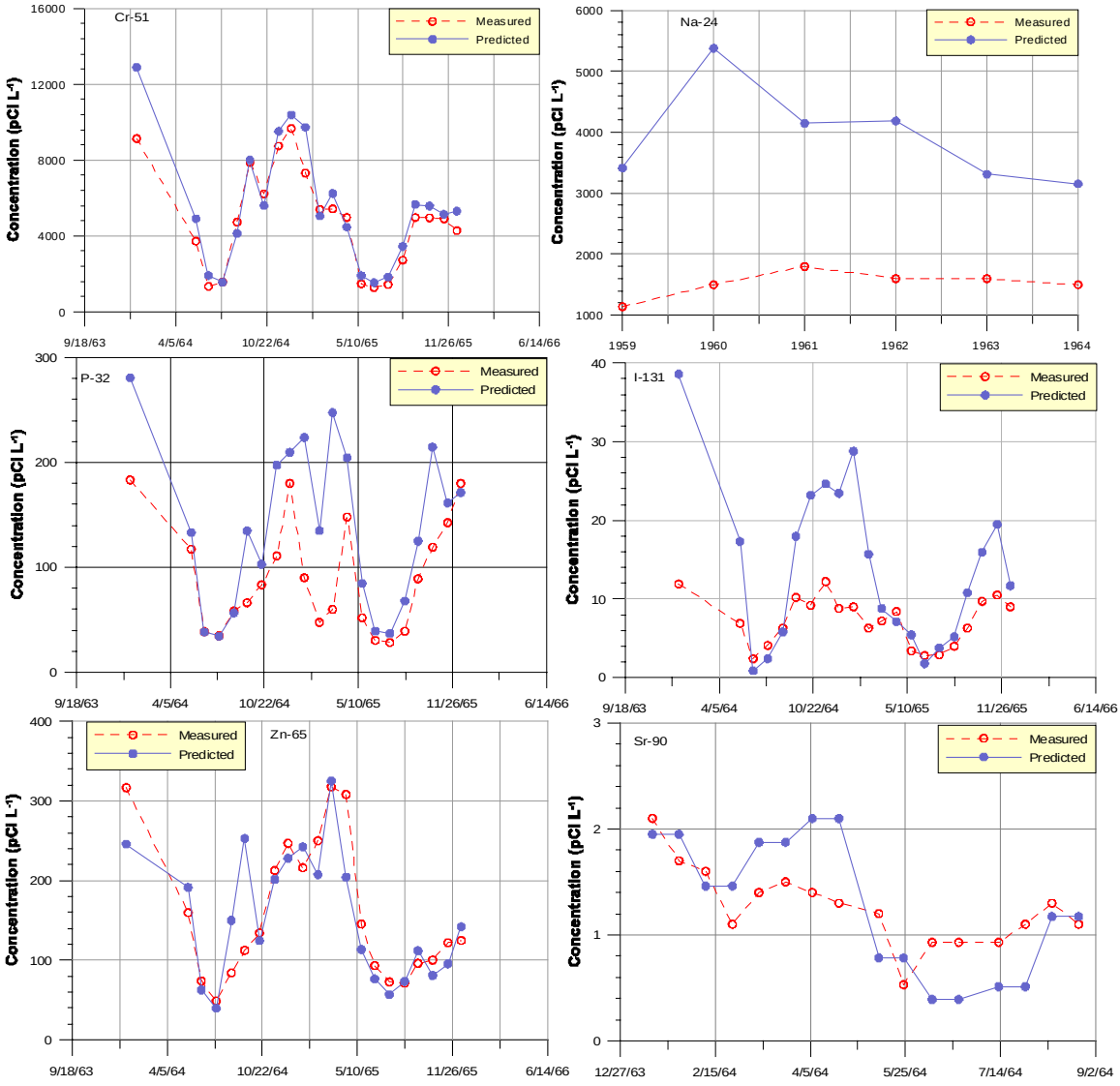

Figure 4-6. Predicted and measured concentrations in river water for selected radionuclides at the Pasco location. Measured concentrations of ^{51}Cr, ^{32}P, ^{131}I, and ^{65}Zn represent monthly averages as determined by the continuous monitoring data. The predicted concentrations for these radionuclides also represent monthly averages. Measured concentrations of ^{90}Sr represent grab sample data and the predicted concentration is for the day the grab sample was taken. Annual-average predicted and measured concentrations are shown for ^{24}Na.

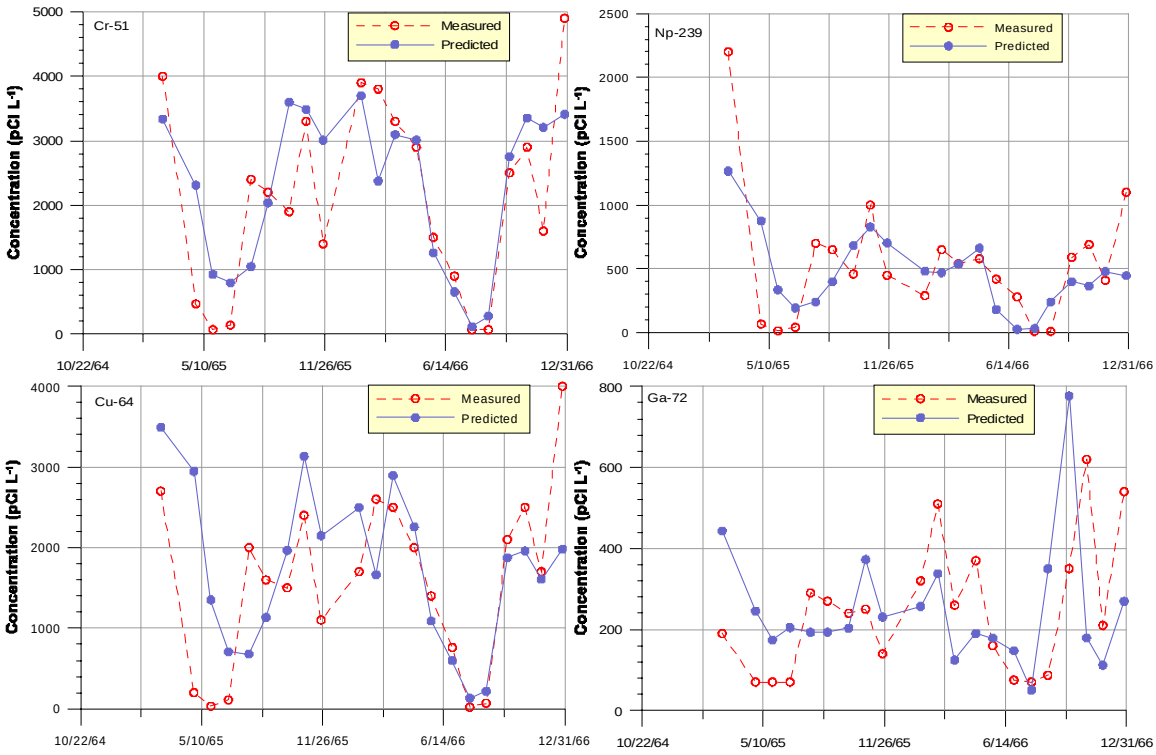

Figure 4-7. Predicted and measured concentrations in river water for selected radionuclides at the Ringold location. Measured concentrations of ^{51}Cr represent monthly averages as determined by the continuous monitoring data. Measured concentrations of ^{64}Cu, ^{239}Np, and ^{72}Ga represent grab sample data and the predicted concentration is for the day the grab sample was taken.

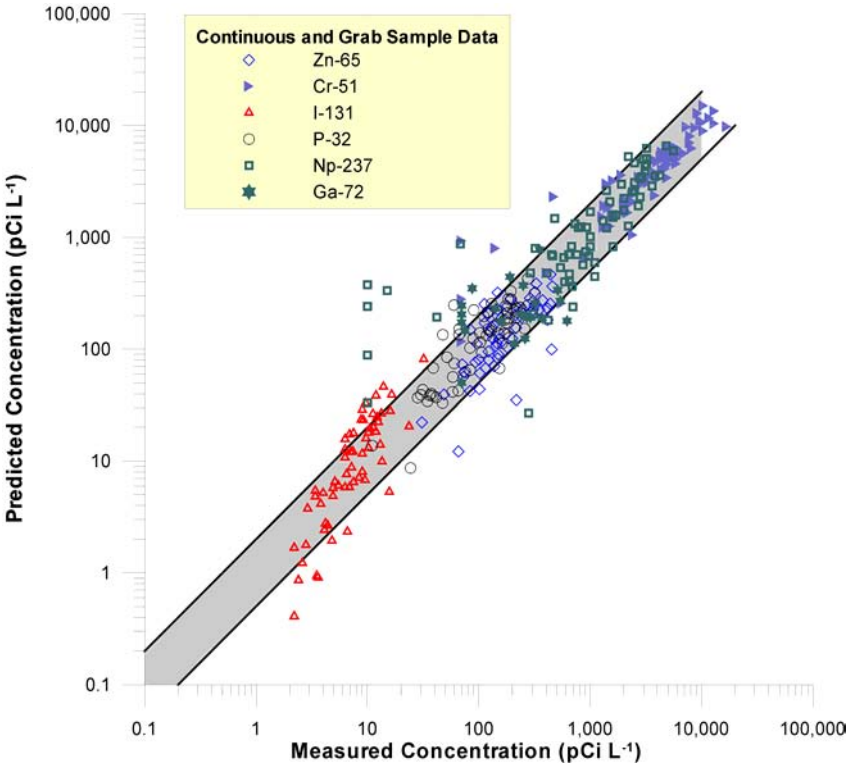

Figure 4-8. Predicted concentration in river water as a function of the measured concentration for monthly-averaged continuous data and grab samples. The shaded area represents model predictions that are within a factor of 2 of the observations.

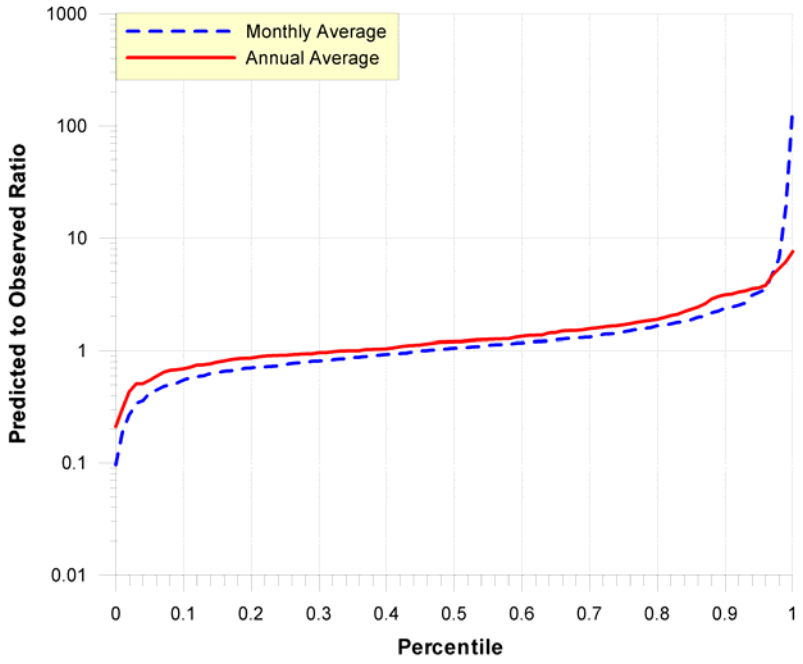

Figure 4-9. Distribution of predicted-to-observed ratios for monthly and annual-averaged data.

4.6.5. Predicted and Observed Concentrations in Fish

Because of the overall importance of the fish ingestion pathway, predicted and observed concentrations in freshwater and anadromous fish were compared for ^{65}Zn, ^{32}P, ^{76}As, and ^{239}Np (Table 4-12 and Figure 4-10). There was substantial variability in the predicted-to-observed ratios as indicated by geometric standard deviations (GSD) that ranged from 2.1 to 10. For ^{65}Zn and ^{76}As, the geometric mean (GM) predicted-to-observed ratios were near 1.0. For other radionuclides (^{32}P, and ^{239}Np), the model tended to underpredict concentrations in fish. Model underprediction for these radionuclides did not affect the overall results and conclusions of this study because these nuclides exhibited risks that were never near a decision criteria.

Table 4-12. Geometric Mean and Standard Deviation of Predicted-to-Observed Ratios in Freshwater and Anadromous Fish

Radionuclide	Freshwater[a]	*n*[b]	Anadromous[a]	*n*[b]
^{32}P	0.46 (3.4)	133	0.11 (10)	9
^{65}Zn	0.89 (2.1)	128	0.47 (4.3)	7
^{76}As	1.0 (6)	5	–	–
^{239}Np	0.67 (4.2)	5	–	–

[a] Geometric mean (geometric standard deviation)
[b] number of observations

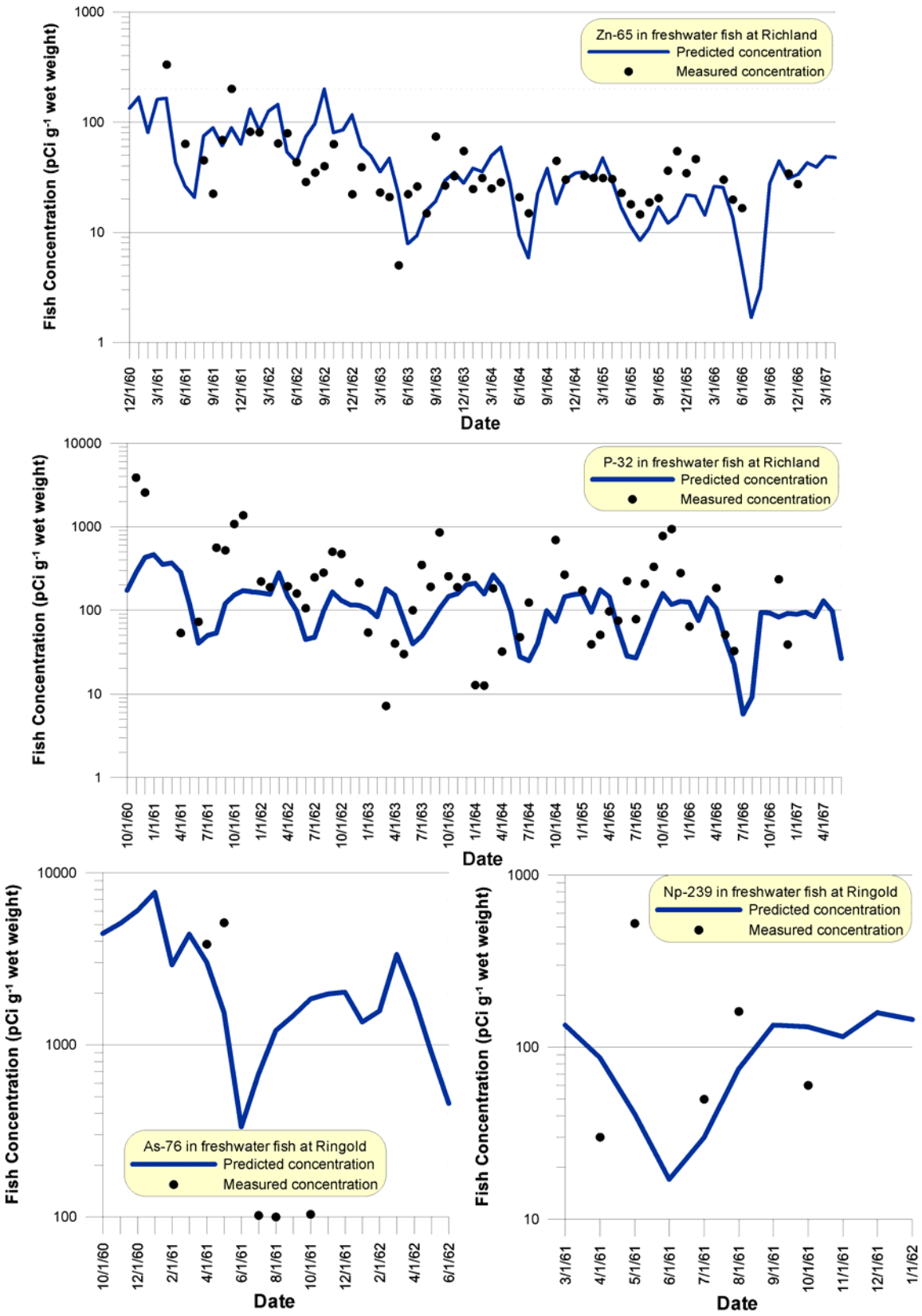

Figure 4-10. Predicted and observed concentrations in freshwater fish at Ringold and Richland.

4.6.6. Screening Value Calculation

Calculation of the screening value (i.e., incremental lifetime cancer incidence risk) was performed by multiplying the radionuclide water concentration or radionuclides accumulated in sediments by an exposure factor and summing over the exposure period.

$$SV_l = \sum_{j=1}^{k} \sum_{i=1}^{n} C_{i,j} \; EF_{i,l} \; \Delta t \qquad (4\text{-}38)$$

where

SV_l = screeening value (incremental lifetime cancer incidence risk) for the l^{th} pathway

$C_{i,,j}$ = concentration in environmental media for the i^{th} day of year and j^{th} year of the simulation (Ci m^{-3} or Ci m^{-2} for sediment pathways)

$EF_{i,,l}$ = exposure factor for i^{th} day of year and l^{th} pathway (m^3 Ci^{-1} d^{-1} or m^2 Ci^{-1} d^{-1} for sediment pathways)

Δt = time step (1 day)

k = number of years in the simulation

n = number of days in a year (365 or 366 for leap years).

Derivation of exposure factors is discussed in Chapter 5. Exposure factors include media intake, exposure time, and incremental lifetime cancer incidence risk coefficients, and are expressed in terms of the incremental lifetime cancer incidence risk per day per unit concentration in environmental media. These factors are calculated on a monthly basis and are selected based on the current day of year of the simulation year. The screening value is calculated on a daily basis by pathway and summed accross the exposure period and all pathways to yield the total screening value. Exposure factors for nuclides that would be in secular equilibrium with their parent (specifically, ^{90}Y *derived* from the decay and ^{90}Sr, ^{69m}Zn and ^{69}Zn, and ^{137}Cs and ^{137m}Ba) are added together into a single exposure factor.

5. EXPOSURE PATHWAYS

The ways in which people were exposed to radionuclides released into the Columbia River are called exposure pathways. The different groups of people who used the river and their various activities were considered to identify exposure pathways to ensure that all important pathways were addressed in the screening analysis and that the parameters used to quantify the exposure pathway were not underestimated. The intent of the screening methodology was to produce screening estimates of risk for each pathway that were very unlikely to underestimate the actual risk to exposed individuals, and, for most situations, overestimated the risks. Through this process, those radionuclides and/or exposure pathways that were above the predefined risk decision criterion of 10^{-4} (discussed in the Risk-based Decision Criteria section of Chapter 1) were identified for further study, and those that fell below that level were recommended to be excluded from further analysis.

The exposure pathways included in this screening analysis and the parameter values used to quantify them are discussed below. Each pathway was identified based on knowledge about the transfer characteristics of the radionuclides, the exposure pathways to humans from the Columbia River environment, and historical evidence that suggested the pathway represented an opportunity for substantial human exposures. We reviewed the literature carefully to select parameter values for the initial screening that represented realistic maximum exposures so the potential exposure from any pathway was not underestimated. Where there was variability or uncertainty associated with a parameter value, a value from the upper end of the distribution was selected.

In the second-step, three exposure scenarios were defined to represent the most exposed river users, a Native American, a local resident of Richland, and a migrant worker. More than one exposure scenario was required to cover the range of river users because of their differing habits and activities. The parameter values for the three exposure scenarios were selected to represent an average individual in the group rather than the most exposed individual. The focus was on assigning the parameter values consistently to allow the relative significance of the different radionuclides and exposure pathways to be assessed.

In this methodology, screening risk values were calculated at locations with the highest predicted radionuclide concentrations in river water and sediment. This conservatism was applied to reduce the likelihood that the risks associated with any exposure pathway were underestimated.

Thirteen exposure pathways were considered in the screening calculations. These were designed to account for the different types of individuals, activities, and practices that may have resulted in exposure to radionuclides released to the Columbia River. Explicit consideration was given to Native American tribes potentially impacted by releases from the Hanford Site because they lived in closest proximity to the river and their lifestyle activities were intimately linked with the river.

The exposure pathways considered were

- Direct ingestion of river water
- Inhalation of river water aerosols
- External exposure to sediments
- Ingestion of sediments
- Exposure to sediments through dermal contact
- Swimming in river water
- Ingestion of river water during swimming
- External exposure while boating

- Ingestion of fish
- Ingestion of waterfowl
- Irrigation of pasture or produce with river water and
  - Milk consumption
  - Meat consumption
  - Produce consumption

The exposure parameters assumed for the initial screening and the three exposure scenarios are presented in the Exposure Scenario Chapter in Table 6-1.

5.1. Drinking Water Ingestion

The most direct exposure pathway for the Columbia River was to use it as a source of drinking water. The EPA recommended a drinking water intake rate of 2 L d^{-1} for adults for exposure assessment (EPA 1999a). This value represents upper percentile tapwater intake rates and includes drinking water consumed in the form of juices and other beverages containing tapwater, such as coffee. Because the tribes reported to CDC a maximum estimate of 2.1 L d^{-1} for drinking water intake (CDC 2000), we assumed this drinking water intake rate (U_w) (2.1 L d^{-1}) for the screening analysis. This value accounted for water used by Native Americans to prepare teas from *Ledum groenlandicum*, mint (*Mentha arvensis*), wild bergamot (*Monarda fistulosa),* wild rose stems, and various flowers. We further assumed that 100% of the drinking water was obtained directly from the Columbia River without treatment or holdup time and that drinking water was consumed at the same rate all year long (i.e., F_{cw} = 1; EF = 365 d y^{-1}).

The drinking water ingestion screening factor ($SF_{ing,water}$) was given by

$$SF_{ing,water} = C_w \cdot U_w \cdot F_{cw} \cdot EF \cdot ED \cdot RF_{ing,w} \quad (5\text{-}1)$$

where

C_w = radionuclide concentration in river water (Bq L^{-1})
U_w = daily consumption rate of drinking water (L d^{-1})
F_{cw} = fraction of water consumed that is contaminated (unitless)
EF = exposure frequency (d y^{-1})
ED = exposure duration (y)
$RF_{ing,w}$ = lifetime morbidity risk coefficient for ingestion of water (Risk Bq^{-1}).

Lifetime morbidity risk coefficient values for this and all pathways were taken from EPA Federal Guidance Report 13 (EPA 1999b) unless otherwise stated.

5.2. Inhalation of River Water Aerosols

A number of activities may have resulted in the inhalation of aerosols of river water. Some of these were specific to Native Americans and others were applicable to a wider group of river users. Inhalation of aerosols of river water may have occurred during fishing activities, such as from dip-net platforms near waterfalls (Hewes 1998) or from inside sweat lodges when river water was applied to hot rocks (Harris and Harper 1997). For both of these activities, we estimated exposure as exposure to volatilized radionuclides in a shower. For the river water spray, we allowed this spray to be mixed with ambient air. For the sweat lodge, we assumed that the air inside the sweat lodge was well-mixed but not mixed with air outside the sweat lodge. These activities and their exposure factors are considered below.

5.2.1. River Water Spray

In estimating the exposure to river water spray, we used the American Petroleum Institute (API) model for exposure to volatilized chemicals in a shower, replacing chemical parameters with similarly selected radionuclide parameters (API 1999).

For inhalation rate, we used the EPA exposure factor standard breathing rate of 20 $m^3\ d^{-1}$. The hourly breathing rate was then 0.83 $m^3\ h^{-1}$ (EPA 1999a). We assumed that 2 h d^{-1} throughout the year were spent doing activities in locations where river spray could have been a factor. These locations would most likely have been near waterfalls, rocky areas where river flow was increased, or possibly dam outlets when water was being released.

The river water spray inhalation screening factor (SF_{spray}) was given as

$$SF_{spray} = IR \cdot C_{spray} \cdot ET \cdot EF \cdot ED \cdot R_{inh} \qquad (5\text{-}2)$$

where

IR	=	inhalation rate ($m^3\ h^{-1}$)
C_{spray}	=	concentration of radionuclide in air due to river water spray (Bq m^{-3})
ET	=	exposure time (h d^{-1})
EF	=	exposure frequency (d y^{-1})
ED	=	exposure duration (y)
R_{inh}	=	lifetime morbidity risk coefficient for inhalation (Risk Bq^{-1}).

The contaminant concentration in river water spray was estimated using the API model mentioned above. We adapted this model for the river spray conditions because the shower model assumed no mixing with outside air, and in a location where river spray was a factor, mixing with ambient air would have been a factor. Using simple first-order mixing, the contaminant concentration in river spray was estimated by the following equation:

$$C_{spray} = \frac{R}{F} \qquad (5\text{-}3)$$

where

R = rate of contaminant release/aerosol production (Bq min^{-1})
F = flow rate of air through the system (m^3 min^{-1}).

We assumed the system to be a 1 × 1 × 2-m (3.3 × 3.3 × 6.6-ft) cell in which the receptor was located and river water spray was produced. The flow rate of air through the system was given by taking the cross-sectional area of the "cell" of air and multiplying that by the wind speed. The cross sectional area was 2 m^2 and the wind speed was assumed to be 2 m s^{-1} for a flow rate of air through the system of 4 m^3 s^{-1} or 240 m^3 min^{-1}.

The rate of contaminant release or aerosol production was given by the following equation:

$$R = f_v \cdot Q \cdot C_w \tag{5-4}$$

where
f_v = efficiency of contaminant release (unitless)
Q = volumetric flow rate of water (L min^{-1})
C_w = contaminant concentration in water (Bq L^{-1}).

We assumed the volumetric flow rate of water was 10 L min^{-1}, similar to flow rate in showers. The efficiency of contaminant release estimated the volatilization of the contaminant by the following equation:

$$f_v = 1 - e^{\left(\frac{-K'_L \cdot t}{(d/6)\cdot 3600}\right)} \tag{5-5}$$

where
K'_L = the overall mass transfer coefficient at the temperature of the water (cm h^{-1})
t = the water droplet drop time (s)
d = the representative diameter of the water droplet (cm)
3600 = conversion factor from hours to seconds.

For the water droplet time and diameter of a water droplet, we used values that were representative of showering situations, assuming that the river spray situation would be similar. The water droplet time used is 2 s and the diameter used is 0.2 cm.

The overall mass transfer coefficient was estimated using the two-film boundary theory, as shown in the following equation:

$$K_L = \left(\frac{1}{k_l} + \frac{1}{H' \cdot k_g}\right)^{-1} \tag{5-6}$$

where

K_L = overall mass transfer coefficient at a known calibration temperature, T_c (cm h^{-1})
k_l = liquid-phase mass transfer coefficient (cm h^{-1})
H' = Henry's Law constant (dimensionless)
k_g = gas-phase mass transfer coefficient (cm h^{-1}).

Because we estimated the volatilization of water containing dissolved radionuclides, we calculated the Henry's Law constant for water and assumed the vapor concentration of the nuclide was the same as its liquid phase. The Henry's Law constant for water is shown below (Lyman et al. 1990):

$$H = \frac{P_{vp}}{S} \tag{5-7}$$

where

P_{vp} = vapor pressure of water at temperature T (atm)
S = solubility (mol m^{-3}).

The dimensionless Henry's Law constant (H') was then given by

$$H' = \frac{H}{R \cdot T} \tag{5-8}$$

where

R = universal gas constant (8.2 x 10^{-5} atm m^3 mol^{-1} K^{-1})
T = temperature (K).

For the river water aerosols, the temperature of the river water was assumed to be 15°C (288 K).

The values for the liquid- and gas-phase mass transfer coefficients were calculated, at a calibration temperature of 20°C (293 K) by the following equations:

$$k_g = 3000 \cdot \left(\frac{18}{MW_{cont}} \right)^{0.5} \tag{5-9}$$

$$k_l = 20 \cdot \left(\frac{44}{MW_{cont}} \right)^{0.5} \tag{5-10}$$

where

MW_{cont} = the molecular weight of the contaminant,

The values of 3000 and 20 represented the mass transfer coefficients of water and carbon dioxide, respectively, and 18 and 44 were the molecular weights of water and carbon dioxide, respectively.

Finally, the overall mass transfer coefficient was adjusted to the temperature of the water using the following equation:

$$K'_L = K_L \left(\frac{T_{water} \cdot \mu_c}{T_c \cdot \mu_{water}} \right)^{0.5} \tag{5-11}$$

where

T_{water} = temperature of the water (K)
μ_c = viscosity of water at T_c (g s m^{-1})
T_c = calibration temperature (K)
μ_{water} = viscosity of water at T_{water} (g s m^{-1}).

The calibration temperature used for these calculations was 20°C (293 K), at which the viscosity of water is 1.002 g s m^{-1}. The viscosity of water at T_{water} was calculated, when T <20°C, as

$$\mu_w = 100 \cdot 10^y \tag{5-12}$$

$$y = \left[\frac{1301}{998.33 + 8.1855(T-20) + 0.00585(T-20)^2} \right] - 3.30233 \tag{5-13}$$

The viscosity of water when T_{water} >20°C was

$$\mu_w = 1.002 \cdot 10^y \tag{5-14}$$

$$y = \frac{-1.3272(T-20) - 0.001053(T-20)^2}{T+105} \tag{5-15}$$

For the case of the river water spray, the temperature of the river water was assumed to be 15°C (289 K).

5.2.2. Sweat Lodges

For the example of the sweat lodge, we also estimated volatilization of the contaminants using the API shower model. For this case, however, we assumed that there was no mixing with outside air. For inhalation rate, we used the EPA exposure factor standard breathing rate of 20 m^3 d^{-1} (EPA 1999a). The hourly breathing rate was then 0.83 m^3 h^{-1}. We assumed that 1 h d^{-1} throughout the year was spent in sweat lodge activities.

The sweat lodge inhalation screening factor (SF_{lodge}) was

$$SF_{lodge} = IR \cdot C_{lodge} \cdot ET \cdot EF \cdot ED \cdot R_{inh} \quad (5\text{-}16)$$

where

IR	=	inhalation rate (m^3 h^{-1})
C_{lodge}	=	concentration of radionuclide in sweat lodge air (Bq m^{-3})
ET	=	exposure time (h d^{-1})
EF	=	exposure frequency (d y^{-1})
ED	=	exposure duration (y)
R_{inh}	=	lifetime morbidity risk coefficient for inhalation (Risk Bq^{-1}).

For the sweat lodge, because air does not mix with outside air, the concentration in air was

$$C_{lodge} = \frac{A_{lodge}}{V_{lodge}} \quad (5\text{-}17)$$

where

A_{lodge}	=	radioactivity released to sweat lodge air (Bq)
V_{lodge}	=	volume of sweat lodge (m^3).

The volume of the sweat lodge was assumed to be 20 m^3. The activity of contaminants in sweat lodge air was estimated using the following equation:

$$A_{lodge} = f_v \cdot Q \cdot C_w \cdot t_{sl} \quad (5\text{-}18)$$

where

f_v	=	efficiency of contaminant release (unitless)
Q	=	volumetric flow rate of water (L min^{-1})
C_w	=	contaminant concentration in water (Bq L^{-1})
t_{sl}	=	time water is flowing within the sweat lodge (min).

The efficiency of contaminant release was calculated in the same manner as for the river water spray, except the temperature of the sweat lodge water was assumed to be 100°F (37.8°C), or 310.8 K. The flow rate of water was 10 L min^{-1}, and the time water is flowing within the sweat lodge was assumed to be 60 min.

5.3. Sediment Exposure Pathways

Several potential exposure pathways were associated with the accumulation of contaminated sediments along the shores or in shallower sections of the river with slow moving waters. A variety of river users may have been exposed to contaminated sediment along the shores of the Columbia River. These included Native Americans, recreational fishermen, hikers, campers, and swimmers. The sediment exposure pathways are discussed below.

5.3.1. External Exposure from Sediments

The natural discharge into the Columbia River exhibited a marked seasonal fluctuation, with the largest discharges occurring during the summer months (June, July, and August) and the smallest discharges during the winter season (November, December, and January). This effect was reflected in a shoreline radiation survey (McConnon 1962) conducted in 1961 and 1962 between Ringold and Richland where beaches surveyed in October were submerged during the July survey. The Columbia River discharge also varied from year to year; therefore, the extent to which beaches and other areas of sediment were exposed varies not only throughout the year, but also between years. Despite these fluctuations, some beaches and areas of sediment accumulation remained accessible throughout the year. For this reason, we assumed that external exposure to contaminated sediments could occur throughout the year. However, it was not reasonable to assume that a person would be exposed to contaminated sediment for 24 hours a day every day of the year. Harris and Harper (1997) assumed an exposure duration and frequency of 12 h d^{-1} for 180 d y^{-1} (2160 h y^{-1}) to shoreline sediment in defining a Native American exposure scenario. The NCRP (1996) recommended an exposure time of 2000 h y^{-1} for screening calculations, which is roughly equivalent to 5.5 h d^{-1} for 365 d y^{-1}. The EPA did not address this issue specifically but recommended a value of 1.5 h d^{-1} for the time an adult spends outdoors as compared to 5 to 7 h d^{-1} for children (3 to 11 years of age).

Screening calculations for historical radionuclide releases to the Clinch River from X-10 on the Oak Ridge Reservation in Tennessee (Apostoaei et al. 1999) assumed a person (fisherman or camper) was exposed to sediment 25% of the year (~91 days). A distinction was made between low and high water levels, which uncovered more or less of the sediment, respectively, and a unitless shielding factor (0.6) was applied to the high water level conditions.

For these screening calculations, we assumed that exposure occurs each day throughout the year for 6 h d^{-1} for a total of 2190 h y^{-1}. We assumed no shielding. The screening factor for external exposure to sediments ($SF_{ext,sed}$) was given by the following equation:

$$SF_{ext,sed} = C_{sed} \cdot ET \cdot F_{si} \cdot RF \cdot CF \cdot EF \cdot ED \qquad (5\text{-}19)$$

where

C_{sed} = time integrated sediment concentration (Bq kg^{-1})
ET = exposure time (h d^{-1})
F_{si} = sorption adjustment factor (dimensionless) for radionuclide i
RF = risk per unit dose (Risk m^2 Bq^{-1} s^{-1})
CF = conversion factor (s h^{-1})
EF = exposure frequency (d y^{-1})
ED = exposure duration (y).

5.3.2. Sediment Ingestion

Activities occurring where river sediments have accumulated may have resulted in the inadvertent ingestion of some sediment. Such activities included sitting, playing, grubbing for worms, and collecting driftwood. Furthermore, materials such as reeds collected from along the shores and banks of the Columbia River may have had sediments closely associated with them. Activities such as basket and mat weaving could have resulted in sediment ingestion because of oral contact to wet the reed tips. Similarly, the use of roots, tubers, or vegetation gathered from areas of river sediment and soil for food preparation or medicinal purposes could have resulted in sediment ingestion.

While data on sediment ingestion rates were lacking, data regarding soil ingestion rates were relevant. EPA recommended a central estimate value of 0.05 g d^{-1} for daily soil ingestion by adults and suggested a value of 0.1 g d^{-1} as a conservative central estimate (EPA 1999a). However, data on soil ingestion rates were limited, particularly in adults and, therefore, they were uncertain. NCRP recommended a soil ingestion rate of 0.25 g d^{-1} for screening calculations.

For the screening methodology, we recognized the uncertainty associated with the documented ingestion rates and adopted a conservative approach. A sediment ingestion rate of 0.25 g d^{-1} was used for the screening calculation. The exposure frequency for this ingestion rate was assumed to be each day from April through September, for a total of approximately 180 d y^{-1}, based on the amount of time Harris and Harper (1997) estimated Native Americans in the Columbia River Basin region spend in various subsistence activities.

The equation that describes the screening factor for ingestion of sediment ($SF_{ing,sed}$) is shown below:

$$SF_{ing,sed} = C_{sed} \cdot \frac{1}{d \cdot \rho} \cdot U_{sed} \cdot F_{csed} \cdot EF \cdot ED \cdot RF_{ing,d} \qquad (5\text{-}20)$$

where

C_{sed} = concentration of sediments (Bq $kg^{-=1}$)
d = depth of sediment (m)
ρ = density of sediment (g m^{-3})
U_{sed} = ingestion rate of sediment (g d^{-1})
F_{csed} = fraction of sediment ingested that is contaminated
EF = exposure frequency (d y^{-1})

ED = exposure duration (y)
$RF_{ing,d}$ = lifetime morbidity risk coefficient for dietary ingestion (Risk Bq^{-1}).

5.3.3. Dermal Absorption

Although the skin is permeable to a large number of primarily lipophilic toxicants, it is relatively impermeable to most ions and aqueous solutions. Therefore, dermal absorption was unlikely to be a significant exposure pathway for radioactive contaminants released into the Columbia River from the Hanford Site.

5.3.4. Dermal Contact

Activities such as reed gathering and driftwood collection along the shoreline could have resulted in contaminated sediment adhering to the skin and allowing exposure of the skin to penetrating radiations (e.g., electrons). Electrons would probably not be energetic enough to be the cause of much external exposure from standing on the shoreline, but when sediment was applied directly to the skin, exposure became more likely. This exposure pathway was referred to as dermal contact. Harris and Harper (1997) suggested a daily adherence rate of 1 mg cm^{-2} over 5000 cm^{-2}, which is approximately 25% of the total skin surface area (EPA 1992) as a reasonable value. An exposure frequency of 180 d y^{-1} was used for this study.

For the purposes of this screening analysis, we considered dermal contact as a special case because no risk factors existed for these types of exposures. Our ability to assess this pathway according to recommended exposure parameters was limited, but we used the information available on the dose delivered by dermal contact to assess the potential risk due to this pathway.

Dose rate conversion factors have been estimated by Kocher and Eckerman (1987) for some of the nuclides considered for this work. Dose coefficients were not identified for radionuclides with shorter half-lives (on the order of about 1 day or less), so risks were not calculated for those nuclides. Kocher and Eckerman assumed that radioactivity was uniformly distributed over the entire body surface instead of just over some fraction of the body's surface area.

For this exposure, we calculated a risk screening factor (SF_{dermal}) using the following equation:

$$SF_{dermal} = C_{sed} \cdot ET \cdot EF \cdot ED \cdot DCF_{dermal} \cdot RC \cdot CF_t \cdot CF_a \quad (5\text{-}21)$$

where
C_{sed} = average sediment concentration over exposure period (Bq m^{-2})
ET = exposure time (hr d^{-1})
EF = exposure frequency (d y^{-1})
ED = exposure duration (y)
DCF_{dermal} = dose rate conversion factor (Sv y^{-1} per Bq cm^{-2})
RC = lifetime risk coefficient (Risk Sv^{-1}).
CF_t = conversion factor for time (y hr^{-1})
CF_a = conversion factor for area (m^2 cm^{-2}).

The average sediment concentrations over the exposure period were calculated using our river model. We assumed exposure to occur 1 h d^{-1}, 180 d y^{-1}, for 30 years. EPA Federal Guidance Report 13 (EPA 1999b) does not provide morbidity risk coefficients for dermal exposure therefore a lifetime risk coefficient of 6.0×10^{-2} Sv^{-1} was assumed for *RC* based on ICRP Publication 60 (1991). This risk coefficient includes the probability of fatal and non-fatal cancers.

5.4. Swimming

A swimmer in the Columbia River was directly exposed to radionuclides from immersion in the contaminated water and as a result of inadvertent ingestion of river water while swimming. This exposure pathway accounted for any activity where an individual is partly or totally immersed in the river water, for example, bathing and washing of plant materials. Exposure from activities where someone was only partly immersed would be overestimated.

In the HEDR Project, early screening calculations for this pathway assumed a "maximum individual," swam 100 h y^{-1} as compared to 10 h y^{-1} for a "typical individual" (Napier 1993). In the final HEDR dose calculations for the Columbia River pathway, a "maximum representative individual" defined as a significant user of the Columbia River, was assumed to swim for 5 hours every month from April through November giving a total of 40 h y^{-1} (Farris et al. 1994a). Walker and Pritchard (1999) defined a "maximum river user" scenario for Native American fishermen who swam 42 h mo^{-1} from May through September (210 h y^{-1}). The Native American exposure scenario developed by Harris and Harper (1997) assumed 2.6 h d^{-1} was spent swimming for 70 d y^{-1} (180 h y^{-1}).

Migrant farm workers have been identified as another group of river users where this exposure pathway could have been significant as a result of bathing and swimming in the vicinity of the Columbia River, predominantly in irrigation ditches. The months when this occurred coincided with those defined by Walker and Pritchard for Native American fishermen. We assumed that the irrigation water comes from the Columbia River, and that the concentration of the irrigation water would, at most, have been equal to the concentration in the Columbia River. Given the same exposure parameters, the risk to the migrant workers would have been equivalent to the risk to Native Americans. We incorporated this risk into the migrant worker scenario, described in Chapter 6. For this screening analysis, we assumed the river user swam 1.4 h d^{-1} from May through September (~210 h y^{-1}).

The equation that described the screening factor for immersion (SF_{imm}) in river water is shown below:

$$SF_{imm} = C_w \cdot ET_s \cdot DCF_{imm} \cdot EF \cdot ED \cdot RC \cdot CF \qquad (5\text{-}22)$$

where

C_w = concentration of radionuclide in water (Bq L^{-1})
ET_s = exposure time for swimming (h d^{-1})
DCF_{imm} = dose conversion factor for immersion (Sv s^{-1} per Bq L^{-1})
EF = exposure frequency (d y^{-1})

ED = exposure duration (y)
RC = lifetime risk coefficient (Risk Sv^{-1})
CF = units conversion (s h^{-1}).

We took dose conversion factors for swimming exposure from EPA Federal Guidance Report No. 12 (EPA 1993). EPA Federal Guidance Report 13 (EPA 1999b) does not provide morbidity risk coefficients for immersion therefore a lifetime risk coefficient of 6.0×10^{-2} Sv^{-1} was assumed for RC based on ICRP Publication 60 (1991). This risk coefficient includes the probability of fatal and non-fatal cancers.

Swimming exposure could also have resulted in some inadvertent ingestion of river water. The quantity ingested would not have been very large, certainly not as large as the amount of water ingested for dietary reasons each day. The EPA recommended an incidental ingestion rate of 0.05 L h^{-1} (EPA 1999a). The screening factor for ingestion of river water ($SF_{ing,inad}$) is shown below:

$$SF_{ing,inad} = C_w \cdot U_{wi} \cdot F_{cw} \cdot ET_{sw} \cdot EF_{sw} \cdot ED \cdot RF_{ing,w} \quad (5\text{-}23)$$

where
C_w = radionuclide concentration in river water (Bq L^{-1})
U_{wi} = inadvertent ingestion rate of river water while swimming (L h^{-1})
F_{cw} = fraction of water ingested that is contaminated (unitless)
ET_{sw} = exposure time for swimming (h d^{-1})
EF_{sw} = exposure frequency for swimming (d y^{-1})
ED = exposure duration (y)
$RF_{ing,w}$ = lifetime morbidity risk coefficient for ingestion of water (Risk Bq^{-1}).

These two screening factors for immersion in and ingestion of river water were summed to obtain the total screening factor for the swimming pathway.

5.5. Boating

The dose rate in a boat located on contaminated water is about one-half that of swimming in the same water. However, the number of hours that an individual may spend boating in a year was considerably larger than for swimming. We evaluated the external exposure from the boating pathway using the same approach used for the swimming immersion pathway. However, we used a dose rate that was one-half the dose rate for swimming.

Although swimming probably occurred only during a limited portion of the year, it was possible that boating activities took place on the river throughout the entire year. The HEDR Project dose calculations (Farris et al. 1994a) assumed a monthly boating exposure of 42 h mo^{-1} throughout the year for a total exposure of 504 h y^{-1} for a maximum representative individual. A higher exposure duration (~240 h mo^{-1} for a total exposure of 2864 h y^{-1}) was defined in the HEDR Project for an occupational representative individual, such as a ferry or barge worker. It was unrealistic to assume that such exposures were representative of the relatively short reach of

the Columbia River considered for the current screening (Figures 2-1a, 2-1b). For Native American populations, Wolfe and Walker (1987) defined a maximum boating exposure of 240 h mo^{-1} during April through October, totaling 1680 h y^{-1}. This exposure duration was representative of Native American at the numerous fishing sites located significantly further downstream (eg. White Salmon/Cascade Locks at RM 165). For Native Americans just below McNary Dam, Wolfe and Walker (1987) defined a boating exposure of 120 h mo^{-1} during April through October, totaling 840 h y^{-1}. This was just downstream of the model domain for the current screening (Figures 2-1a, 2-1b).

For these screening calculations, we assumed a boating exposure of 2 h d^{-1} for the entire year, for a total exposure of 730 h y^{-1}. This was larger than assumed in the HEDR Project for the maximum representative individual, and very slightly less than assumed by Wolfe and Walker (1987) for the reach of the Columbia River immediately downstream of the current model domain.

The screening factor for boating exposure (SF_{boat}) is shown below.

$$SF_{boat} = C_w \cdot ET_b \cdot \frac{1}{2} DCF_{imm} \cdot EF \cdot ED \cdot RC \cdot CF \qquad (5\text{-}24)$$

where

C_w	=	concentration of radionuclide in water (Bq L^{-1})
ET_b	=	exposure time for boating (h d^{-1})
DCF_{imm}	=	dose conversion factor for immersion (Sv s^{-1} per Bq L^{-1})
EF	=	exposure frequency (d y^{-1})
ED	=	exposure duration (y)
RC	=	lifetime risk coefficient (Risk Sv^{-1})
CF	=	units conversion (s h^{-1}).

5.6. Fish Consumption

Fish consumption was one of the primary exposure pathways identified for radionuclide releases to the Columbia River, and there was concern that the parameters used in the HEDR Project dose calculations (Farris et al. 1994a) underestimated the significance of this pathway for Native American users of the river. An annual fish consumption of 42.1 kg was assumed in the HEDR Project for a maximum river user (Table 5-1). To provide some perspective, the EPA (1999a) recommended a mean fish consumption value of 70 g d^{-1} (25 kg annually) and a 95th percentile value of 170 g d^{-1} (62 kg annually) for Native American subsistence populations based on studies by the Columbia River Inter-Tribal Fish Commission (CRITFC 1994), and by Wolfe and Walker (1987) on harvest rates of subsistence communities in Alaska. Walker and Pritchard (1999) defined a maximum Native American river user with an annual fish consumption of 237 kg (Table 5-2).

Table 5-1. Fish Consumption Rates (kg) and Holdup Times (d) for a Maximum Representative Individual Defined in the HEDR Project[a]

Fish category[b]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Holdup[c] (days)
Omnivore	3.0	2.0	0.2	0.2	0	0	0	0.2	1.1	2.0	2.0	3.0	13.7	7
1st order predator	0.3	1.2	2.8	2.8	3	3	3	2.8	2.0	1.2	1.2	0.3	23.6	2
2nd order predator	0	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.1	0.1	0	2.3	2
Salmon	--	--	--	--	--	--	--	--	2.5	--	--	--	2.5	15

[a] From Farris et al. (1994a).
[b] Omnivorous fish include bullhead, catfish, suckers, whitefish, chiselmouth, chub, sturgeon, minnows, and shiners. First-order predators include perch, crappie, punkinseed, and bluegill. Second-order predators include bass, trout, and squawfish.
[c] The time between obtaining fish from the river and consuming it.

Table 5-2. Fish Consumption Rates (kg) and Holdup Times (d) for a Maximum River User as Defined in Walker and Pritchard (1999)

Fish category[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Holdup[b] (days)
Omnivore	4	4	4	2	2	2	2	2	2	2	4	4	34	3
1st order predator	--	--	--	--	--	--	--	--	--	--	--	--	0	0
2nd order predator	4	4	4	2	2	2	2	2	2	2	4	4	34	3
Salmon	3	3	3	22	22	22	22	22	22	22	3	3	169	14

[a] Omnivorous fish include bullhead, catfish, suckers, whitefish, chiselmouth, chub, sturgeon, minnows, and shiners. First-order predators include perch, crappie, punkinseed, and bluegill. Second-order predators include bass, trout, and squawfish.
[b] The time between obtaining fish from the river and consuming it.

To define a Native American exposure scenario for risk assessment purposes, Harris and Harper (1997) used a fish consumption rate of 540 g d^{-1} comprised of 135 g d^{-1} of fresh fish and 135 g d^{-1} of dried fish. It was assumed that 405 g of fresh fish yield 135 g of dried fish, which is equivalent to an annual fish consumption of 197.1 kg. They considered this a reasonable intake for subsistence fishing based on a review of the literature and interviews with tribal members.

A number of Native American tribes in the Columbia River region have summarized fish consumption rates for CDC in greater detail than the earlier information available to the HEDR Project. Mean annual consumption rates ranged from 17 to 110 kg. Upper bound estimates were generally in the range of 220 kg, with one value as large as 411 kg. These estimates included fresh fish, stored fish, and shellfish. The highest consumption rates were reported for the spring season.

A distinction is usually made between the different types of fish that are consumed because the radionuclide concentrations vary. Resident fish in the Columbia River downstream of Hanford tend to have higher concentrations of a given radionuclide than nonresident fish because resident fish spend their entire lives in the Columbia River and have more time to accumulate

radionuclides (Hanf et al. 1992). Furthermore, omnivorous fish tend to have higher radionuclide concentrations than predator fish.

The nonresident or anadromous species hatch in freshwater, grow and migrate to the ocean and eventually return to freshwater to spawn. Anadromous species that use the Columbia River as a migration route include the chinook salmon, sockeye salmon, coho salmon, and steelhead trout. These were important fish for Native Americans as well as sport fishermen.

In the HEDR Project, resident fish of importance to Native Americans and sport fishermen were identified as mountain whitefish, white sturgeon, smallmouth bass, crappie, channel catfish, walleye, and yellow perch (Walters et al. 1992). Resident fish that were not usually eaten (carp, shiners, suckers, and squawfish) were not considered further in the HEDR Project. However, the highest reported concentrations of radionuclides in large fish were for suckers (Davis et al. 1958 cited in Walters et al. 1992), which Native Americans consumed.

Based on the information provided in Walker and Pritchard (1999) and the information provided by the Native American tribes, a reasonable upper bound screening estimate for ingestion of fish was 238 kg annually. For the screening scenario calculation we assumed an annual consumption of 68 kg of resident fish and 170 kg anadromous fish. Monthly consumption rates were assumed to vary in the same manner as estimated by Walker and Pritchard (1999). The assumed average daily harvest rates for fish are presented on a monthly basis in Table 5-3.

Table 5-3. Average Daily Harvest Rates of Fish for Each Month of the Year (kg d^{-1})

	Jan-Mar	April-Aug	Sept-Oct	Nov-Dec	Total (kg y^{-1})
Screening Scenario					
Resident (fresh fillet)	0.27	0.13	0.13	0.27	68.59
Anadromous (fresh fillet)	0.10	0.72	0.14	0.10	133.8
Anadromous (dried whole)	0	0	0.58	0	35.38
Total (kg y^{-1})[a]					238
Native American Scenario					
Resident (fresh fillet)	0.11	0.06	0.06	0.11	29.45
Anadromous (fresh filleted)	0.03	0.35	0.07	0.03	62.35
Anadromous (dried whole)	0	0	0.28	0	17.08
Total (kg y^{-1})[a]					109
Resident Scenario					
Resident (fresh fillet)	0.015	0.008	0.008	0.015	3.977
Anadromous (fresh fillet)	0.004	0.05	0.05	0.004	11.304
Anadromous (dried whole)	0	0	0	0	0
Total (kg y^{-1})[a]					15
Migrant Worker Scenario					
Resident (fresh fillet)	0	0.008	0.008	0	1.712
Anadromous (fresh fillet)	0	0.05	0.05	0	10.7
Anadromous (dried whole)	0	0	0	0	0
Total (kg y^{-1})[a]					12

[a] These values are rounded to the nearest whole number

The anadromous species are carnivorous fish that actively feed on juveniles in the river and as they mature in the ocean, but they do not feed during the spawning migration. Because of this lack of feeding during the time that the fish spend in the Columbia River, it is often suggested that they do not reach equilibrium concentrations for all radionuclides. For the HEDR Project calculations, the bioconcentration factors for anadromous fish were assumed to be the same as those reported for second order predator resident fish. Our analysis of the data supported the more cautious approach used in the HEDR Project. The limited data for salmon and steelhead trout did not indicate that minimal radioactivity entered these fish because they do not eat during upstream migration (see Model Calibration section of Chapter 4).

Table 5-4 shows the radionuclide-specific bioconcentration factors (BCFs) selected for these screening calculations for resident fish and anadromous fish. The bioconcentration factor distributions compiled by Thiede et al. (1994) in the HEDR Project for ^{76}As ^{51}Cr ^{239}Np ^{24}Na ^{32}P and ^{65}Zn were used directly. These values were based on historical fish concentration measurements and river concentrations modeled using WSU-CHARIMA (Holly et al. 1993; Walters et al. 1994). We used the mean values of the distributions, which were somewhat larger than the median values that were used in the HEDR Project. The mean value was more reflective of the average concentration in fish consumed by an individual, as noted by Hoffman et al. (1998). A seasonal difference was observed for zinc and phosphorus, with greater uptake during the warm season. The observed BCFs for the warm and cool seasons were used (Table 5-4). The peak concentration of phytoplankton and periphyton (benthic microflora) was observed in April and May, with a secondary peak in late summer/early autumn. The spring pulse was probably related to increasing light and water temperature rather than to nutrient availability. Zooplankton population densities were lowest in the winter and highest in summer.

For the remaining radionuclides, a variety of sources of information were used in selecting bioconcentration factors including Napier (1993), NCRP (1996), Hoffman et al. (1998), Till and Meyer (1983), IAEA (1994), Theide et al. (1994), Walker and Pritchard (1999), and Farris et al. (1994a). The selected values are shown in Table 5-4. For the strontium isotopes, bioconcentration factors for fish flesh (fillets) and whole fish that includes the bones were defined. For some elements, NCRP reported element specific bioconcentration factors that were too conservative for the short-lived isotopes of that element. In those cases, the element-specific bioconcentration factors were adapted by the biological half-life and radiological half-life of the nuclide to produce nuclide-specific factors. The element-specific bioconcentration factor were multiplied by a factor (K), calculated using the following equation:

$$K = \frac{\lambda_b}{\lambda_i + \lambda_b} \tag{5-25}$$

where

λ_b = biological decay constant = $0.693 t_b^{-1}$ (d^{-1})
λ_i = radiological decay constant = $0.693 t_i^{-1}$ (d^{-1})
t_b = biological half-life (d)
t_i = radiological half-life (d).

A biological half-life of 30 days was assumed (NCRP 1996).

Table 5-4. Fish Bioconcentration Factors Used in Current Screening Calculations

	Resident (L kg^{-1})		Anadromous (L kg^{-1})	
Radionuclide	Cool	Warm	Cool	Warm
^{24}Na	9	9	9	9
^{32}P	790	3000	190	2100
^{45}Ca	170	170	170	170
^{46}Sc	75	75	75	75
^{51}Cr	5	5	5	5
^{56}Mn	0.25	0.25	0.25	0.25
^{60}Co	300	300	300	300
^{64}Cu	3.5	3.5	3.5	3.5
^{65}Zn	160	340	100	160
^{69}Zn	1.3	1.3	1.3	1.3
^{69m}Zn	19	19	19	19
^{72}Ga	7.7	7.7	7.7	7.7
^{76}As	550	550	550	550
^{89}Sr – fillet	40	40	40	40
^{90}Sr – fillet	60	60	60	60
^{89}Sr – whole fish	1500	1500	1500	1500
^{90}Sr – whole fish	2400	2400	2400	2400
^{90}Y	2.5	2.5	2.5	2.5
^{93}Y	0.4	0.4	0.4	0.4
^{95}Zr	220	220	220	220
^{122}Sb	8.2	8.2	8.2	8.2
^{131}I	8.4	8.4	8.4	8.4
^{133}I	1.1	1.1	1.1	1.1
^{137}Cs	2000	2000	100	100
^{239}Np	50	50	50	50

The fish ingestion exposure factor ($SF_{ing,fish}$) is given by the following equation:

$$SF_{ing,fish} = C_{w,i}\left[\left(BCF_{fw,i}\cdot U_{fw}\cdot Hf_{fw}\right)+\left(BCF_{an,i}\cdot U_{an}\cdot Hf_{an}\right)+\left(BCF_{and,i}\cdot U_{and}\cdot Hf_{and}\right)\right]\cdot RF_{ing,d}\cdot EF\cdot ED \qquad (5\text{-}26)$$

where

$C_{w,i}$ = concentration of radionuclide *i* in river water (Bq L^{-1})
$BCF_{fw,i}$ = bioaccumulation factor for radionuclide *i* in resident fish (L kg^{-1})
U_{fw} = average daily harvest of resident fish (kg d^{-1})
Hf_{fw} = average integrated holdup factor for resident fish (unitless)
$BCF_{an,i}$ = bioaccumulation factor for radionuclide *i* in anadromous fish consumed fresh (L kg^{-1})
U_{an} = average daily harvest of anadromous fish consumed fresh (kg d^{-1})
Hf_{an} = average integrated holdup factor for anadromous fish consumed fresh (unitless)

$BCF_{and,i}$ = bioaccumulation factor for radionuclide *i* in anadromous fish consumed dried including bones (L kg^{-1})
U_{and} = average daily harvest rate of anadromous fish consumed dried (kg d^{-1})
Hf_{and} = average integrated holdup factor for anadromous fish consumed dried (unitless)
$RF_{ing,d}$ = lifetime morbidity risk coefficient for dietary ingestion (Risk Bq^{-1}).
EF = exposure frequency (d y^{-1})
ED = exposure duration (y)

Note that U_{fw}, U_{an}, and U_{and} refer not to the consumption, but to the harvest of wild fish. We assumed all fish that are harvested were eventually consumed. Decay between harvest and consumption was accounted for by the average integrated holdup factor and given by

$$Hf = \frac{\int_0^{t_c} e^{-\lambda t}\, dt}{t_c} = \frac{1-\exp(-\lambda t_c)}{\lambda t_c} \qquad (5\text{-}27)$$

where
t_c = the time period over which the fish are consumed (d)
λ = radioactive decay constant (d^{-1}).

The average integrated holdup factor multiplied by the fish concentration represented the average concentration in fish over the consumption period. Holdup factors (i.e., $e^{-\lambda\ th}$ where *th* is the holdup time) were typically applied to agriculture crops where a fixed time was typically encountered between production of the product and distribution to the consumer. The same analogy cannot be applied to harvest of wild game, where in many cases, the game may have been consumed immediately after harvest, shortly thereafter, or preserved for later consumption. Because of this difference between agriculture products and wild game, we have used the average of the integrated holdup factor over the consumption period instead of the holdup factor (which represents the decay during a fixed time between harvest and consumption) to account for decay during the consumption period of wild game.

The reported seasonal pattern of fish consumption for Native Americans during the years immediately following the Second World War was almost exclusively for fresh fish with little or no holdup time during the period from late April to early October. Starting in early September, with the fall Chinook run, the bulk of winter stores were accumulated (Hunn 1990, p.132). A large portion of the fish caught would be dried, either by smoking or by filleting. The fish fillets were pounded and set on mats to dry. Once dried, they were pulverized, and packed into baskets and could be kept “for months” (Landeen and Pinkham 1999, p.160). For some of the catch, the whole fish was prepared for storage by cutting the fish in half, removing the entrails, and pounding the fish into a meal. In this preparation, the bones were not removed and were eaten along with the flesh. Because strontium isotopes can accumulate in the bones of fish, the bioconcentration factors applied to this portion of the catch were different from the bioconcentration factors for flesh. For dried whole fish, bioconcentration factors for strontium account for the presence of radioactivity in both the flesh and bone. For the other radionuclides, the bioconcentration factor for flesh was used for the dried whole anadromous fish. The average

integrated holdup factor accounts for decay of radioactivity during the November-to-March consumption period.

Consumption times are presented in Table 5-5 for the screening scenario and the three scenarios used to define representative individuals. For the screening scenario, a minimum consumption time of 1 day was used. We assumed that the migrant worker did not have access to refrigeration, and consumed the catch within a 1-day period. The same assumption was made for the Native American with regard to resident fish and the fresh anadromous fish that was filleted. A consumption time of 150 days (November–March) was assumed for the dried anadromous fish (including bones) for the Native American scenario. For the resident scenario, we assumed a consumption period of 5 days for resident and anadromous fish.

Table 5-5. Consumption Times (days) used in Calculation of the Fish Exposure Factors

	Screening Scenario	Native American	Resident	Migrant Worker
Resident	1	1	5	1
Anadromous (fillet)	1	1	5	1
Anadromous (dried whole fish)	N/A	150	N/A	N/A

Average daily harvest rates are given by month in Table 5-3. The average daily harvest rate was the mass of fish harvested for the month divided by the number of days in the month and was based on daily consumption rates of fish. All fish that were harvested were eventually consumed over the consumption time (Table 5-5) and the average integrated holdup factor accounted for radioactive decay during that time.

5.7. Waterfowl Consumption

In the HEDR dose calculations, the annual consumption of waterfowl for the maximum representative individual was estimated as 20 kg (fresh weight) (Napier 1993). Consumption was not constant throughout the year with October and November assumed to have the highest consumption rates (4 kg mo^{-1}). For December through May, the consumption rate was assumed to be 2 kg mo^{-1}, and no consumption was assumed for June through September. A holdup time of 7 days was assumed to elapse before the waterfowl was consumed.

A number of Native American tribes in the Columbia River region have reported to CDC a mean annual consumption rate for wildfowl of 6.2 kg with an upper bound estimate of 222 kg. These values included upland birds and waterfowl. Based on reports of actual hunting success in game management regions around DOE's Hanford Site cited in Harris and Harper (1997), it was estimated that approximately 80% of waterfowl ingestion was from waterfowl and 20% from upland birds. This suggested a mean annual consumption for waterfowl of 5 kg, with an approximate upper bound estimate of 178 kg. Harris and Harper (1997) estimated an intake rate of 35 g d^{-1} for waterfowl (meat and eggs), equivalent to an annual consumption of 12.8 kg for defining a Native American exposure scenario.

For the current screening analysis, it was more appropriate to assume an annual consumption of 21 kg for waterfowl based on the maximum representative individual defined in the HEDR Project. We assumed the variation in consumption throughout the year of 4 kg mo^{-1} in October

and November, 2 kg mo^{-1} in December through May, and no consumption in June through September.

Historical data from Hanford on radionuclide concentrations in waterfowl identified ^{32}P, ^{40}K, ^{65}Zn, ^{90}Sr, and ^{137}Cs in waterfowl (Hanf et al. 1992). HEDR calculated bioconcentration factors for ^{32}P and ^{65}Zn only. The values presented in Table 5-6 were based on measurements of puddle duck, the preferred species for human consumption. Puddle ducks feed in shallow water on plants, grain, and small invertebrates on or near the sediment surface. Because the historical data reported concentrations of ^{90}Sr and ^{137}Cs, which were included in our screening, we estimated BCFs for ^{90}Sr and ^{137}Cs using the relationship between the BCFs for resident fish and waterfowl for ^{32}P and ^{65}Zn. Table 5-6 shows the values used for our screening calculations.

Table 5-6. Waterfowl Bioconcentration Factors for Current Screening Calculations

Radionuclide	BCF for waterfowl (L kg^{-1})
^{32}P	960
^{65}Zn	90
^{90}Sr	20
^{137}Cs	500

An average integrated holdup factor for waterfowl (Hf_w) was defined according to Equation 5-27, except that t_c was the time period in days over which the waterfowl was consumed.

The screening factor for waterfowl ingestion ($SF_{ing,fowl}$) was given as:

$$SF_{ing,fowl} = C_{w,i} \cdot BCF_{w,i} \cdot U_{wf} \cdot F_{cwf} \cdot Hf_w \cdot RF_{ing,d} \cdot ED \cdot EF \quad (5\text{-}28)$$

where

$C_{w,i}$ = concentration of radionuclide i in river water (Bq L^{-1})
$BCF_{w,i}$ = bioaccumulation factor for radionuclide i in waterfowl (L kg^{-1})
U_{wf} = average daily harvest of waterfowl (kg d^{-1})
F_{cwf} = fraction of waterfowl consumed that is contaminated (1.0) (unitless)
Hf_w = average integrated holdup factor for waterfowl (unitless)
$RF_{ing,d}$ = lifetime morbidity risk coefficient for dietary ingestion (Risk Bq^{-1}).
EF = exposure frequency (d y^{-1})
ED = exposure duration (y).

5.8. Irrigation

Irrigation with Columbia River water is known to have occurred in fields used for grazing cows in the Riverview area near Pasco, Washington, and in the Ringold area. Measurable concentrations of ^{65}Zn were reported in milk from these cows (Foster and Junkins 1960). Therefore milk consumption from cows grazing irrigated pasture was included as an exposure pathway in the screening analysis. We also included beef ingestion and food crop ingestion as exposure pathways, assuming beef cattle were grazed on irrigated pasture, and crops were

irrigated with river water. The irrigation pathway may not have related to Native Americans, but it may have been significant for other users of the Columbia River.

5.8.1. Milk Consumption

Radionuclide contamination of milk from the Columbia River could have occurred because of dairy cattle ingesting contaminated river water and contaminated forage. We used the NCRP screening models methodology (NCRP 1996) to calculate the concentration in forage due to direct irrigation and buildup in soil over a 30-year time period.

Milk ingestion, for the purposes of this screening calculation, was assumed to occur each day throughout the year. The EPA Exposure Factors Handbook (EPA 1999a) indicated that the median intake of milk for the U.S. population was 8 g kg^{-1} d^{-1}. For the average 71.8-kg adult, this was approximately 0.6 L d^{-1} of milk consumption. The distribution of values for this parameter had a 95th percentile value of 2.3 L d^{-1}. NCRP suggested a usage value for milk ingestion of 300 L y^{-1}, or approximately 0.8 L d^{-1} (NCRP 1996). For these screening calculations, we assumed milk ingestion of 0.8 L d^{-1}, with all the milk that was being consumed contaminated.

NCRP also recommended values for dairy cattle ingestion of water and forage of 60 L d^{-1} and 16 kg d^{-1}, respectively. The irrigation rate recommended by NCRP for these calculations was 2 L m^{-2} d^{-1} (NCRP 1996).

The screening factor for milk consumption ($SF_{ing,milk}$) was given by

$$SF_{ing,milk} = \left[C_{milk(water)} + C_{milk(for)}\right] \cdot U_{milk} \cdot F_{cd} \cdot EF \cdot ED \cdot RF_{ing,d} \quad (5\text{-}29)$$

where

U_{milk} = daily milk ingestion (L d^{-1})
F_{cd} = fraction of consumed milk that is contaminated (unitless)
EF = exposure frequency (d y^{-1})
ED = exposure duration (y)
$RF_{ing,d}$ = lifetime morbidity risk coefficient for dietary ingestion (Risk Bq^{-1})

and

$$C_{milk(water)} = C_w \cdot Q_{wd} \cdot F_{cw} \cdot F_m \quad (5\text{-}30)$$

$$C_{milk(for)} = C_{for} \cdot Q_{fd} \cdot F_{cf} \cdot F_m \quad (5\text{-}31)$$

where

$C_{milk(water)}$ = radionuclide concentration in milk due to cattle ingestion of contaminated water (Bq L^{-1})
C_w = transfer coefficient (d L^{-1})
$C_{milk(for)}$ = radionuclide concentration in milk due to cattle ingestion of contaminated forage (Bq L^{-1})
C_{for} = radionuclide concentration in forage (Bq kg^{-1})

Q_{fd} = ingestion rate of forage by dairy cattle (kg d^{-1})
F_{cf} = fraction of consumed forage that is contaminated (unitless)
F_m = transfer coefficient to milk (d L^{-1})

and

$$C_{for} = C_w \cdot F_{ir} \cdot CF_{for,i} \quad (5\text{-}32)$$

where
C_{for} = concentration of contamination in forage (Bq kg^{-1})
C_w = concentration of water (Bq L^{-1})
F_{ir} = irrigation rate (L m^{-2} d^{-1})
$CF_{for,i}$ = transfer factor for radionuclide *i*, including buildup in soil (Bq kg^{-1} per Bq m^{-2} d^{-1}).

5.8.2. Meat Consumption

Radionuclide contamination of meat could occur if beef cattle ingested contaminated Columbia River water and contaminated forage. We used the NCRP screening models methodology (NCRP 1996) to calculate the concentration in forage due to direct irrigation and buildup in soil over a 30-year time period in the same manner as for milk.

Meat ingestion, for the purposes of this screening calculation, was assumed to occur each day throughout the year with no holdup time between butchering the cattle and ingestion of the beef. The EPA Exposure Factors Handbook (EPA 1999a) indicated that the median intake of beef for the U.S. population was 2.1 g kg^{-1} d^{-1}. For the average 71.8-kg adult, this was approximately 0.15 kg d^{-1} of meat consumption. The distribution of values for this parameter had a 95th percentile value of 0.37 kg d^{-1}. NCRP suggested a usage value for meat ingestion of 100 kg y^{-1}, or approximately 0.27 kg d^{-1} (NCRP 1996). For these screening calculations, we assumed meat ingestion of 0.3 kg d^{-1}, with all the meat that was being consumed contaminated.

NCRP also recommended values for beef cattle ingestion of water and forage of 50 L d^{-1} and 12 kg d^{-1}, respectively. The irrigation rate recommended by NCRP for these calculations was 2 L m^{-2} d^{-1} (NCRP 1996).

The screening factor for meat consumption ($SF_{ing,meat}$) was given by

$$SF_{ing,meat} = \left[C_{meat(water)} + C_{meat(for)}\right] \cdot U_{meat} \cdot F_{cb} \cdot EF \cdot ED \cdot RF_{ing,d} \quad (5\text{-}33)$$

where
U_{meat} = daily meat ingestion (kg d^{-1})
F_{cd} = fraction of consumed meat that is contaminated (unitless)
EF = exposure frequency (d y^{-1})
ED = exposure duration (y)
$RF_{ing.d}$ = lifetime morbidity risk coefficient for dietary ingestion (Risk Bq^{-1})

and

$$C_{meat(\,water\,)} = C_{water} \cdot Q_{wb} \cdot F_{cw} \cdot F_b \quad (5\text{-}34)$$

$$C_{meat(\,for\,)} = C_{for} \cdot Q_{fb} \cdot F_{cf} \cdot F_b \quad (5\text{-}35)$$

where

$C_{meat(water)}$ = radionuclide concentration in meat due to cattle ingestion of contaminated water (Bq kg^{-1})
C_{water} = radionuclide concentration in water (Bq L^{-1})
Q_{wb} = ingestion rate of water by beef cattle (L d^{-1})
F_{cw} = fraction of consumed water that is contaminated (unitless)
F_b = transfer coefficient (d kg^{-1})
$C_{meat(for)}$ = radionuclide concentration in meat due to cattle ingestion of contaminated forage (Bq kg^{-1})
C_{for} = radionuclide concentration in forage (Bq kg^{-1})
Q_{fb} = ingestion rate of forage by beef cattle (kg d^{-1})
F_{cf} = fraction of consumed forage that is contaminated (unitless)
F_b = transfer coefficient to beef (d kg^{-1})

and

$$C_{for} = C_w \cdot F_{ir} \cdot CF_{for,i} \quad (5\text{-}36)$$

where

C_{for} = concentration of contamination in forage (Bq kg^{-1})
C_w = concentration of water (Bq L^{-1})
F_{ir} = irrigation rate (L m^{-2} d^{-1})
$CF_{for,i}$ = transfer factor for radionuclide *i*, including buildup in soil (Bq kg^{-1} per Bq m^{-2} d^{-1}).

5.8.3. Food Crop Consumption

Food crops consumed by individuals could have become contaminated by irrigation by both direct interception of contaminated water and from uptake of radionuclides through roots growing in contaminated soils. We used the NCRP screening models methodology (NCRP 1996) to calculate the concentration in fresh vegetables due to direct irrigation and buildup in soil over a 30-year time period.

Fresh vegetable ingestion, for the purposes of this screening calculation, was assumed to occur each day throughout the year. The EPA Exposure Factors Handbook (EPA 1999a) indicated that the median intake of vegetables for the U.S. population was 4.3 g kg^{-1} d^{-1}. For the average 71.8 kg adult, this was approximately 0.31 kg d^{-1} of vegetable consumption. The distribution of values for this parameter had a 95th percentile value of 0.72 kg d^{-1}. NCRP suggested a usage value for meat ingestion of 200 kg y^{-1}, or approximately 0.55 kg d^{-1} (NCRP

1996). For these screening calculations, we assumed vegetable ingestion of 0.55 kg d^{-1}, with all the vegetables that were being consumed contaminated.

The screening factor for ingestion of contaminated food crops ($SF_{ing,crop}$) is shown below.

$$SF_{ing,crop} = C_{veg} \cdot U_{prod} \cdot F_{cp} \cdot ED \cdot EF \cdot RF_{ing,d} \quad (5\text{-}37)$$

where

U_{prod} = ingestion rate of contaminated produce (kg d^{-1})
F_{cp} = fraction of consumed produce that is contaminated (unitless)
ED = exposure duration (d y^{-1})
EF = exposure frequency (y)
$RF_{ing,d}$ = lifetime morbidity risk coefficient for dietary ingestion (Risk Bq^{-1})

and

$$C_{veg} = C_w \cdot F_{ir} \cdot CF_{veg,i} \quad (5\text{-}38)$$

where

C_{veg} = concentration of contamination in vegetables (Bq kg^{-1})
C_w = concentration of water (Bq L^{-1})
F_{ir} = irrigation rate (L m^{-2} d^{-1})
$CF_{veg,I}$ = transfer factor for radionuclide *i*, including buildup in soil (Bq kg^{-1} per Bq m^{-2} d^{-1}).

6. EXPOSURE SCENARIOS

For the second part of the methodology we defined three exposure scenarios to represent the differing habits and activities of the most exposed river users. These were a Native American, local resident, and migrant worker scenario. The parameter values for the scenarios were selected to represent a more typical individual in the group rather than the most exposed individual. The focus was on assigning the parameter values consistently to assess the relative significance of the 15 radionuclides that remained after the initial screening and to identify the most important exposure pathways. The resulting risk-based screening values were expected to overestimate actual risks because the exposures were assumed to have occurred throughout the entire period of releases from the Hanford nuclear site (1944–1972) with the representative individual located at Richland. The equations described in the previous chapter apply to these scenarios as well.

The values for the Native American and migrant worker scenarios were adapted primarily from interviews and data collected from Native peoples along the Columbia River during the course of this study. Data for Native Americans from the EPA Exposure Factors handbook was also used (EPA 1999a). The EPA handbook was used to develop the local resident scenario.

Table 6-1 shows the parameter values used for the initial screening, which included all exposure pathways, and for the Native American, local resident, and migrant worker exposure scenarios. We show the initial screening scenario parameter values described in the previous chapter for comparison.

Table 6-1. Exposure Scenarios for the Columbia River[a]

Pathway	Screening	Native American	Resident	Migrant worker
Drinking water (L d^{-1})	2.1	2.1	2.1	2.1 (Apr–Oct)
Fraction contaminated	1	1	0.5	1
Total L y^{-1} water ingestion	***770***	***770***	***380***	***450***
Fish harvest/ingestion[b] (kg d^{-1})				
Resident (Jan–Mar)	0.27	0.11	0.015	0
Resident (Apr–Aug)	0.13	0.06	0.008	0.008
Resident (Sept–Oct)	0.10	0.06	0.008	0.008
Resident (Nov–Dec)	0.27	0.11	0.015	0
Anadromous (fillet) (Jan–Mar)	0.10	0.03	0.004	0
Anadromous (fillet) (Apr–Aug)	0.72	0.35	0.05	0.05
Anadromous (fillet) (Sept–Oct)	0.14	0.07	0.05	0.05
Anadromous (fillet) (Nov–Dec)	0.10	0.03	0.004	0
Anadromous (dried) (Sept–Oct)	0.58	0.28	0	0
Fraction contaminated	1	1	1	1
Total kg y^{-1} fish ingestion	***240***	***109***	***15***	***12***
Swimming (h d^{-1})	1.4 (May–Sept)	1 (May–Sept)	0.5 (Jun–Aug)	1 (May–Sept)
Total h y^{-1} swimming	***214***	***153***	***46***	***153***
Swimming ingestion (L h^{-1})	0.05 (May–Sept)	0.05 (May–Sept)	0.05 (Jun–Aug)	0.05 (May–Sept)
Total L y^{-1} water ingestion	***11***	***8***	***2***	***8***
Waterfowl harvest/ing (kg d^{-1})				

Table 6-1. Exposure Scenarios for the Columbia River[a]

Pathway	Screening	Native American	Resident	Migrant worker
(Oct–Nov)	0.13	0.045	0.02	0
(Dec–May)	0.07	0.02	0.01	0
(Jun–Sept)	0	0	0	0
Fraction contaminated	1	1	1	0
Total kg y^{-1} waterfowl ingestion	***21***	***6.4***	***3.0***	***0***
Sediment external exposure (h d^{-1})	6	4	1 (Jun–Aug)	1 (Apr–Oct)
Total h y^{-1} exposure	***2190***	***1460***	***92***	***214***
Sediment ingestion (g d^{-1})	0.25 (Apr–Oct)	0.25 (Apr–Sept)	0.25 (Jun–Aug)	0.25 (Apr–Oct)
Total g y^{-1} ingestion	***54***	***46***	***23***	***54***
Dermal contact exposure (h d^{-1})	1 (Apr–Oct)	1 (Apr–Sept)	0.5 (Jun–Aug)	1 (Apr–Oct)
Total h y^{-1} exposure	***214***	***183***	***46***	***214***
River water aerosols (h d^{-1})	2	2	0	1 (Apr–Oct)
Total h y^{-1} inhalation	***730***	***730***	***0***	***214***
Sweat lodge (h d^{-1})	1	1	0	0
Total h y^{-1} inhalation	***365***	***365***	***0***	***0***
Boating exposure (h d^{-1})	2	1	1 (Jun–Aug)	0
Total h y^{-1} exposure	***730***	***365***	***92***	***0***
Milk ingestion (L d^{-1})	0.8	0	0.6	0.6 (Apr–Oct)
Fraction contaminated	1	0	1	1
Total L y^{-1} ingestion	***292***	***0***	***219***	***128***
Meat ingestion (kg d^{-1})	0.3	0	0.15	0.15 (Apr–Oct)
Fraction contaminated	1	0	1	1
Total kg y^{-1} ingestion	***110***	***0***	***55***	***32***
Produce ingestion (kg d^{-1})	0.55	0.3 (Jun–Oct)	0.25 (Jun–Oct)	0.3 (Apr–Oct)
Fraction contaminated	1	1	1	1
Total kg y^{-1} ingestion	***200***	***46***	***38***	***64***

[a] Values are shown to 2 significant digits to show consistent mathematical additivity.

[b] All harvested fish are consumed over the consumption time (see Table 5-5).

7. SCREENING RISK ESTIMATES

7.1. Initial Screening

The initial screening values were calculated for the Ringold and Richland locations. The highest screening values were calculated for Richland because this exposure location was closer to the plume centerline than the Ringold far shore. Therefore, the Richland location was used for the initial screening of radionuclides (see Appendix F for a detailed accounting of the risk-based screening values).

We defined a risk-based screening criterion of 10^{-4} for the initial screening of 23 radionuclides released to the Columbia River from the Hanford nuclear facility (see Section 1.2 and Table 2-2). Ten radionuclides (^{45}Ca, ^{51}Cr, ^{56}Mn, ^{64}Cu, ^{69,69m}Zn, ^{89}Sr, ^{93}Y, ^{122}Sb, and ^{133}I) had screening values less than 10^{-4} at the Richland location (Table 7-1, shaded area). For most radionuclides the screening value was dominated by the fish ingestion pathway, but in a few cases, direct consumption of river water was the dominant pathway. Most of the exposure was incurred over the years 1952 to 1964 (Figure 7-1) when the highest radionuclide releases from the Hanford reactors occurred.

Table 7-1. Initial Screening Values for Richland and Primary Exposure Pathway by Radionuclide

Radionuclide	Screening value	Percent of total	Primary pathway	Percent contribution[a]
^{76}As	2.3×10^{-2}	60	Fish ingestion	99
^{239}Np	4.9×10^{-3}	13	Fish ingestion	92
^{32}P	4.3×10^{-3}	11	Fish ingestion	75
^{65}Zn	3.3×10^{-3}	8.5	Fish ingestion	82
^{95}Zr	6.2×10^{-4}	1.6	Fish ingestion	93
^{137}Cs	4.7×10^{-4}	1.2	Fish ingestion	87
^{60}Co	4.6×10^{-4}	1.2	Fish ingestion	87
^{24}Na	3.2×10^{-4}	0.81	Fish ingestion	31
^{46}Sc	2.6×10^{-4}	0.66	Fish ingestion	86
^{90}Sr	2.4×10^{-4}	0.62	Fish ingestion	95
^{72}Ga	2.1×10^{-4}	0.53	Fish ingestion	53
^{90}Y	1.5×10^{-4}	0.37	Water consumption[b]	47
^{131}I	1.3×10^{-4}	0.34	Fish ingestion	58
^{133}I	7.9×10^{-5}	0.20	Water consumption[b]	53
^{51}Cr	6.9×10^{-5}	0.18	Fish ingestion	36
^{64}Cu	6.8×10^{-5}	0.17	Water consumption[b]	49
^{69,69m}Zn	4.5×10^{-5}	0.12	Fish ingestion	62
^{89}Sr	4.3×10^{-5}	0.11	Fish ingestion	95
^{122}Sb	4.2×10^{-5}	0.11	Fish ingestion	64
^{56}Mn	3.2×10^{-5}	0.08	Water consumption[b]	40
^{93}Y	3.0×10^{-5}	0.08	Water consumption[b]	81
^{45}Ca	1.9×10^{-5}	0.05	Fish ingestion	95
Total	**3.9×10^{-2}**			

[a] Percent of risk from primary pathway for each radionuclide
[b] Direct (not inadvertent ingestion during swimming)

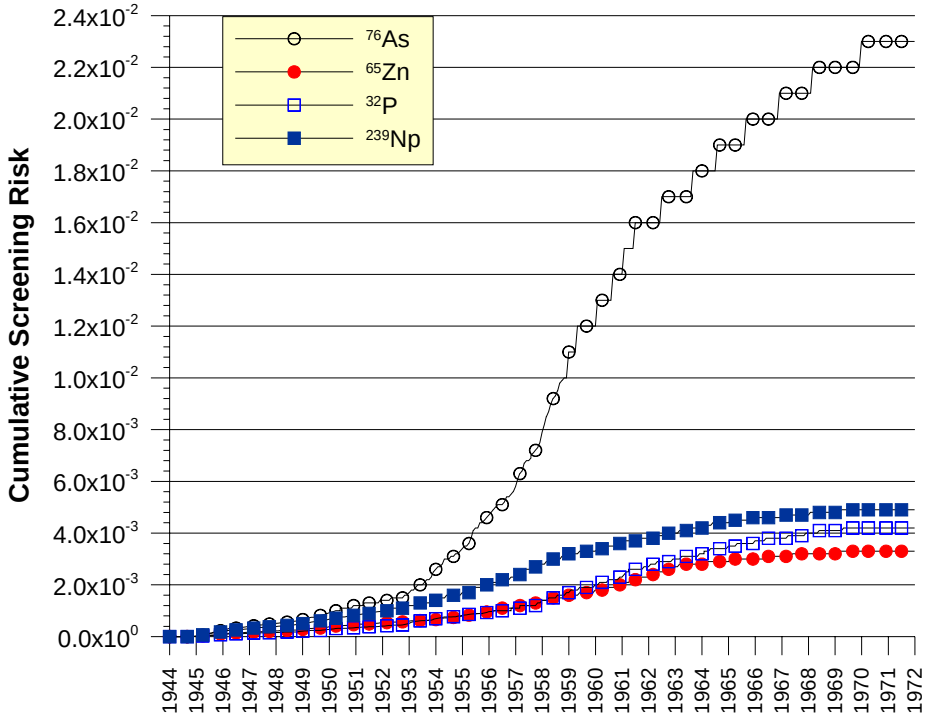

Figure 7-1. Cumulative screening values at Richland as a function of year for the initial screening scenario. The four nuclides illustrated are the dominant contributors to the initial screening values.

Table 7-2 shows that fish ingestion accounts for 92% of the total (all radionuclide) screening value. Pathways of least importance in terms of the total risk (all radionuclides) included swimming immersion, inadvertent water ingestion from swimming, external exposure to shoreline sediments, inadvertent sediment ingestion, aerosol inhalation, and produce ingestion. Combined, these exposure pathways contributed less than ~0.4% to the total screening value. However, for some radionuclides, these pathways were important in terms of their contribution to the total individual radionuclide screening value. For this methodology, no pathways were eliminated in the initial screening, only radionuclides.

Based on the screening criterion of 10^{-4}, ten radionuclides were eligible for elimination from further analysis (highlighted by shading in Table 7-1). The uncertainty associated with the screening values was examined before reaching a final decision regarding their elimination. This process is described in the following section.

Table 7-2. Percentage Contribution of Exposure Pathways to Total Screening Risk at Richland

Exposure pathway	Percentage contribution to total (all radionuclides) screening value
Direct water ingestion	2.33
Fish ingestion	91.67
Swimming-immersion	0.13
Swimming-ingestion	0.02
Waterfowl	3.26
Sediment-external	0.16
Sediment dermal	0.26
Sediment ingestion	0.00
Aerosol inhalation	0.04
Boating	0.29
Produce ingestion	0.05
Meat ingestion	0.82
Milk ingestion	0.98

7.1.1. Uncertainty in Initial Screening Values

We did not perform a comprehensive evaluation of uncertainty. Rather, we performed a limited uncertainty analysis to evaluate the potential for identifying false negatives during the screening process (i.e., removing a nuclide from consideration when it should have been retained). We calculated the uncertainty in the initial screening values for the ten radionuclides (^{45}Ca, ^{51}Cr, ^{54}Mn, ^{64}Cu, ^{69,69m}Zn, ^{89}Sr, ^{93}Y, ^{122}Sb, and ^{133}I) that had screening values less than 10^{-4} at the Richland location.

Three elements of uncertainty were considered; source term, transport, and fish bioconcentration factor. Additional uncertainty also existed in the risk coefficients, and food product transfer factors; however, quantification of uncertainty in the risk coefficients was beyond the scope of this screening exercise and ingestion of food products (milk, meat, and produce) accounted for very little of the screening values. The HEDR Project considered uncertainty in the source term, transfer coefficients, bioconcentration factors, dose conversion factors, and exposure scenario parameters. Uncertainty in the transport model was considered insignificant and was not considered in the HEDR Project evaluation.

Uncertainty was evaluated by multiplying risk estimates by random variables whose distributions express the uncertainty of a given parameter. We represented the calculation by the equation

$$R = \xi\left(\varphi R_{fish} + \sum_{i=1}^{n} R_i\right) \tag{7-1}$$

where

R = total (all pathways) screening risk value from 1944 to 1971 for a given radionuclide

ξ = random variable representing uncertainty associated with source term and radionuclide transport in the river
R_{fish} = risk from fish ingestion from 1944 to 1971
φ = random variable representing uncertainty associated with the fish bioconcentration factor
R_i = risk from other pathways excluding fish from 1944 to 1971
n = number of pathways excluding fish.

For radionuclides that had measured concentrations in river water to compare to, the value of ξ was estimated by

$$\xi = \frac{1}{P/O} \tag{7-2}$$

where P/O was the distribution of P/O ratios for annual average concentration estimates as discussed in Chapter 4. The value of ξ was assumed to represent the uncertainty in both the source term and the transport. Although this value was based on annual average predicted and observed concentrations in river water, we applied it to any long-term (≥1 year) estimate of river water concentration. This essentially treated the uncertainty in annual average concentration estimates as being correlated from year-to-year and likely resulted in an overestimation of the uncertainty due to transport and source term. The distribution ξ used in the analysis was not fit to a known probability distribution but instead was sampled directly from the empirical distribution developed in Chapter 4. If a radionuclide lacked river water concentration measurements, then ξ represented the uncertainty in the source term as discussed in Chapter 2 (Table 2-2).

Uncertainty in the bioconcentration factors was represented by a random variable that was multiplied by the risk from fish ingestion. Distributions of the bioconcentration uncertainty factor were based on Hoffman et al. (1998) and Hoffman (1999). Parameter uncertainty distributions are summarized in Table 7-3.

Table 7-3. Summary of Uncertainty Factors

Radionuclide	Source term	Source term/transport	Fish BCF uncertainty factor
^{51}Cr	–	empirical distribution	log-normal, GM=1.0, GSD=2.0
^{69,69m}Zn	–	empirical distribution	log-normal, GM=1.0, GSD=1.6
^{133}I	GM=1.0, GSD=3.2	–	log-uniform; min=0.1, max=10
^{64}Cu	–	empirical distribution	log-uniform; min=0.1, max=10
^{56}Mn	–	empirical distribution	log-uniform; min=0.1, max=10
^{45}Ca	GM=1.0, GSD=2.3	–	log-uniform; min=0.1, max=10
^{89}Sr	GM=1.0, GSD=3.7	–	log-uniform; min=0.1, max=10
^{93}Y	GM=1.0, GSD=1.9	–	log-uniform; min=0.1, max=10
^{122}Sb[a]	–	empirical distribution	log-uniform; min=0.1, max=10

[a] Source term uncertainty was not estimated for this radionuclide, therefore, the source term/transport uncertainty factor was applied.

Monte Carlo analysis using simple random sampling was used to propagate the uncertainty distributions to the final screening values. The model was run for 5000 realizations using the Crystal Ball software (Decisioneering 2000).

The screening value distributions (Table 7-4) revealed that there was greater than 74 percent probability that the screening value was less than 10^{-4} at the Richland location for all radionuclides except ^{133}I and ^{89}Sr. The radionuclides ^{69,69m}Zn, ^{56}Mn, and ^{93}Y had greater than 95 percent probability that the screening value at Richland was less than 10^{-4}. There was less certainty that the screening value at Richland was less than 10^{-4} for ^{133}I and ^{89}Sr. Also, the uncertainty bounds for ^{133}I and ^{89}Sr were relatively large and sensitivity analysis showed that the source term uncertainty accounted for 50 percent of the variability in the screening value for ^{89}Sr, and 96 percent of the variability in the screening value for ^{133}I. For these reasons, ^{89}Sr and ^{133}I were not eliminated in the initial screening. Eight radionuclides were eliminated in the screening, these were ^{45}Ca, ^{51}Cr, ^{54}Mn, ^{64}Cu, ^{69,69m}Zn, ^{93}Y, and ^{122}Sb.

Table 7-4. Distribution Percentiles for the Screening Values at Richland

Radionuclide	5th percentile	50th percentile	95th percentile	$p(R<10^{-4})$[a]
^{51}Cr	1.8×10^{-5}	6.0×10^{-5}	1.5×10^{-4}	0.83
^{69,69m}Zn	1.1×10^{-5}	3.8×10^{-5}	9.5×10^{-5}	0.96
^{133}I	1.3×10^{-5}	8.7×10^{-5}	6.5×10^{-4}	0.55
^{64}Cu	1.7×10^{-5}	6.1×10^{-5}	2.3×10^{-4}	0.74
^{56}Mn	9.1×10^{-6}	2.7×10^{-5}	6.0×10^{-5}	0.99
^{45}Ca	1.7×10^{-6}	1.9×10^{-5}	2.3×10^{-4}	0.85
^{89}Sr	2.6×10^{-6}	4.3×10^{-5}	9.3×10^{-4}	0.67
^{93}Y	1.1×10^{-5}	3.1×10^{-5}	9.1×10^{-5}	0.96
^{122}Sb	8.1×10^{-6}	3.6×10^{-5}	2.3×10^{-4}	0.79

[a] probability that the screening value is less than 10^{-4}.

7.1.2. Summary of Radionuclides Eliminated by the Initial Screening

The initial screening resulted in the following eight radionuclides being eliminated from further consideration based on a screening criterion of 10^{-4}: ^{45}Ca, ^{51}Cr, ^{56}Mn, ^{64}Cu, ^{69,9m}Zn, ^{93}Y, and ^{122}Sb.

The initial screening of 23 radionuclides was based on conservative assumptions with regard to the exposure location, duration, and pathway characteristics. The availability of extensive monitoring data allowed us to make realistic estimates of radionuclide concentrations in the Columbia River water and sediment. Screening values were calculated at two locations immediately downstream of the Hanford nuclear facility, Ringold and Richland. The highest screening values were calculated for Richland and were therefore used for the analysis. When a risk-based screening criterion of 10^{-4} was applied, there were ten radionuclides (^{45}Ca, ^{51}Cr, ^{56}Mn, ^{64}Cu, ^{69,69m}Zn, ^{89}Sr, ^{93}Y, ^{122}Sb, and ^{133}I) with screening values less than 10^{-4} at the Richland location. When the uncertainty associated with the screening values was assessed, it was decided that two of the radionuclides (^{89}Sr and ^{133}I), should not be eliminated in the screening. As a consequence, eight radionuclides were eliminated.

7.2. Exposure Scenarios for Representative Individuals

We used three scenarios (Native American, migrant worker, and local resident) to represent the most exposed river users. This allowed us to explore the relative significance of the 15 radionuclides that remained after the initial screening, and to identify the most important exposure pathways. Two exposure locations were evaluated, Richland (RM 340) and Pasco (RM 329). Pasco was included to examine the change in significance of radionuclides and pathways at an exposure location further downstream. The screening risk values for the Native American, migrant worker, and local resident scenarios were prioritized by radionuclide in Tables 7-5, 7-6 and 7-7, respectively. For each radionuclide the primary exposure pathway, and its percent contribution to the screening value for that radionuclide was also reported.

For all three scenarios, ^{76}As accounted for the highest exposure risk. The Native American scenario had the highest calculated screening values and the local resident scenario the lowest. For all three scenarios, four radionuclides accounted for more than 80% of the total risk, although the ranking varied. These were ^{76}As, ^{239}Np, ^{32}P and ^{65}Zn. For the migrant worker and local resident scenarios, ^{24}Na ranked fifth and accounted for 4% and 5% of the total risk, respectively. For the Native American scenario ^{24}Na ranked eighth and accounted for less than 1% of the total risk. Three radionuclides, ^{60}Co, ^{137}Cs, and ^{95}Zr, had marginally higher screening values but each contributed less than 2% to the total risk. This difference was attributed, in part, to the substantially higher fish ingestion rates for the Native American scenario compared to the other scenarios.

The screening values for the Pasco location were all smaller than those for Richland. This reflected the longer travel times downstream to this exposure location resulting in more radioactive decay, and greater cross channel dispersion. There was very little difference in the prioritization of the radionuclides between these two locations. The relative importance of ^{72}Ga decreased from Richland to Pasco because of its shorter half-life as compared to the radionuclides that ranked just below it at Richland.

For some radionuclides the dominant exposure pathway changed in the representative scenarios as compared to the initial screening. For example, for the Native American and migrant worker scenarios the dominant exposure pathway for ^{24}Na was direct ingestion of river water whereas, fish ingestion was the dominant exposure pathway for the initial screening scenario. Similarly, dermal contact replaced fish ingestion as the primary exposure pathway for ^{60}Co and ^{137}Cs in the migrant worker scenario as compared to the initial screening scenario, and milk ingestion replaced fish ingestion as the dominant exposure pathway for ^{24}Na and ^{131}I in the local resident scenario as compared to the initial screening scenario. A detailed accounting of nuclide-specific risk by pathway can be found in Appendix F. The change in relative significance of exposure pathways between the initial screening and the representative scenarios was expected and reflected the changes in the parameter values used to characterize them. The representative scenarios were designed to assess the relative significance of radionuclides and exposure pathways, whereas the initial screening was designed to determine those radionuclides that were of little importance from a health-risk perspective.

The risks, as represented by the screening values for the local resident scenario at Richland are illustrated in Figures 7-2 and 7-3 by decade of exposure for some key radionuclides. The greatest risks were incurred during the 1950s and 1960s.

Table 7-5. Native American Screening Risks and Primary Exposure Pathway by Radionuclide

	Richland				Pasco			
Radio-nuclide	Screening value	Percent of total risk	Primary pathway	Percent of risk[a]	Screening value	Percent of total risk	Primary pathway	Percent of risk[a]
^{76}As	1.0×10^{-2}	59.17	Fish-Ing	98.21	7.9×10^{-3}	57.49	Fish-Ing	98.28
^{239}Np	2.3×10^{-3}	13.76	Fish-Ing	86.19	1.9×10^{-3}	13.50	Fish-Ing	85.83
^{32}P	1.7×10^{-3}	10.30	Fish-Ing	80.57	1.5×10^{-3}	10.82	Fish-Ing	80.32
^{65}Zn	1.4×10^{-3}	8.20	Fish-Ing	86.74	1.3×10^{-3}	9.17	Fish-Ing	86.90
^{95}Zr	2.8×10^{-4}	1.67	Fish-Ing	88.87	2.6×10^{-4}	1.87	Fish-Ing	89.11
^{60}Co	2.2×10^{-4}	1.30	Fish-Ing	82.02	2.0×10^{-4}	1.42	Fish-Ing	81.64
^{137}Cs	2.0×10^{-4}	1.17	Fish-Ing	86.46	1.8×10^{-4}	1.33	Fish-Ing	86.86
^{24}Na	1.6×10^{-4}	0.97	Direct-Ing	34.28	1.2×10^{-4}	0.87	Direct-Ing	33.21
^{72}Ga	1.3×10^{-4}	0.78	Direct-Ing	51.39	9.0×10^{-5}	0.65	Direct-Ing	50.06
^{46}Sc	1.2×10^{-4}	0.71	Fish-Ing	81.43	1.1×10^{-4}	0.79	Fish-Ing	81.52
^{90}Sr	1.1×10^{-4}	0.67	Fish-Ing	97.14	1.0×10^{-4}	0.74	Fish-Ing	97.07
^{90}Y	9.7×10^{-5}	0.57	Direct-Ing	71.24	8.2×10^{-5}	0.59	Direct-Ing	70.77
^{131}I	5.3×10^{-5}	0.31	Fish-Ing	64.60	4.6×10^{-5}	0.33	Fish-Ing	64.93
^{133}I	4.8×10^{-5}	0.29	Direct-Ing	86.99	3.7×10^{-5}	0.27	Direct-Ing	86.70
^{89}Sr	2.1×10^{-5}	0.12	Fish-Ing	95.42	1.9×10^{-5}	0.14	Fish-Ing	95.42
Total risk	1.7×10^{-2}				1.4×10^{-2}			

[a] Percent of risk from primary exposure pathway for each radionuclide

Table 7-6. Migrant Worker Screening Risks and Primary Exposure Pathway by Radionuclide

	Richland				Pasco			
Radio-nuclide	Screening value	Percent of total risk	Primary pathway	Percent of risk[a]	Screening value	Percent of total risk	Primary pathway	Percent of risk[a]
^{76}As	1.3×10^{-3}	55.13	Fish-Ing	93.38	1.0×10^{-3}	53.42	Fish-Ing	93.37
^{239}Np	3.9×10^{-4}	16.61	Fish-Ing	61.97	3.2×10^{-4}	16.97	Fish-Ing	61.88
^{65}Zn	1.7×10^{-4}	7.13	Fish-Ing	66.17	1.5×10^{-4}	7.92	Fish-Ing	66.28
^{32}P	1.1×10^{-4}	4.68	Fish-Ing	85.19	9.8×10^{-5}	5.17	Fish-Ing	85.33
^{24}Na	9.4×10^{-5}	4.03	Direct-Ing	28.75	7.1×10^{-5}	3.74	Direct-Ing	28.05
^{72}Ga	5.4×10^{-5}	2.30	Direct-Ing	70.82	3.7×10^{-5}	1.95	Direct-Ing	70.18
^{95}Zr	5.3×10^{-5}	2.25	Fish-Ing	51.39	4.7×10^{-5}	2.48	Fish-Ing	50.86
^{60}Co	4.7×10^{-5}	2.04	Sed-Dermal	56.87	4.2×10^{-5}	2.21	Sed-Dermal	56.95
^{90}Y	3.7×10^{-5}	1.60	Direct-Ing	85.85	3.2×10^{-5}	1.66	Direct-Ing	85.62
^{133}I	3.0×10^{-5}	1.31	Direct-Ing	62.43	2.4×10^{-5}	1.25	Direct-Ing	63.00
^{137}Cs	2.5×10^{-5}	1.06	Sed-Dermal	60.72	2.3×10^{-5}	1.20	Sed-Dermal	61.43
^{46}Sc	2.4×10^{-5}	1.03	Fish-Ing	45.72	2.2×10^{-5}	1.14	Fish-Ing	45.64
^{131}I	1.7×10^{-5}	0.72	Direct-Ing	38.36	1.5×10^{-5}	0.78	Direct-Ing	38.35
^{90}Sr	1.8×10^{-6}	0.08	Fish-Ing	60.74	1.6×10^{-6}	0.09	Fish-Ing	60.74
^{89}Sr	7.6×10^{-7}	0.03	Fish-Ing	56.69	6.8×10^{-7}	0.04	Fish-Ing	56.97
Total risk	2.3×10^{-3}				1.9×10^{-3}			

[a] Percent of risk from primary exposure pathway for each radionuclide

Table 7-7. Local Resident Screening Risks and Primary Exposure Pathway by Radionuclide

	Richland				Pasco			
Radio-nuclide	Screening value	Percent of total risk	Primary pathway	Percent of risk [a]	Screening value	Percent of total risk	Primary pathway	Percent of risk [a]
^{76}As	8.1×10^{-4}	34.66	Fish-Ing	86.62	6.4×10^{-4}	32.90	Fish-Ing	86.59
^{32}P	3.7×10^{-4}	15.94	Fish-Ing	48.43	3.3×10^{-4}	16.95	Fish-Ing	48.88
^{239}Np	3.7×10^{-4}	15.82	Fish-Ing	56.93	3.1×10^{-4}	15.84	Fish-Ing	55.60
^{65}Zn	3.5×10^{-4}	15.17	Fish-Ing	48.06	3.2×10^{-4}	16.34	Fish-Ing	47.55
^{24}Na	1.2×10^{-4}	5.14	Milk-Ing	45.03	8.6×10^{-5}	4.47	Milk-Ing	45.17
^{95}Zr	4.8×10^{-5}	2.04	Fish-Ing	79.99	4.3×10^{-5}	2.21	Fish-Ing	79.64
^{133}I	4.3×10^{-5}	1.83	Direct-Ing	49.30	3.3×10^{-5}	1.69	Direct-Ing	49.16
^{90}Y	4.2×10^{-5}	1.80	Direct-Ing	83.43	3.5×10^{-5}	1.81	Direct-Ing	82.97
^{72}Ga	4.0×10^{-5}	1.73	Direct-Ing	84.31	2.8×10^{-5}	1.43	Direct-Ing	83.52
^{60}Co	3.7×10^{-5}	1.57	Fish-Ing	68.24	3.2×10^{-5}	1.68	Fish-Ing	67.84
^{131}I	3.6×10^{-5}	1.56	Milk-Ing	30.28	3.2×10^{-5}	1.67	Milk-Ing	30.72
^{137}Cs	3.5×10^{-5}	1.49	Fish-Ing	66.00	3.2×10^{-5}	1.65	Fish-Ing	66.10
^{46}Sc	2.3×10^{-5}	1.00	Fish-Ing	64.64	2.1×10^{-5}	1.11	Fish-Ing	65.54
^{90}Sr	4.5×10^{-6}	0.19	Fish-Ing	35.46	4.0×10^{-6}	0.21	Fish-Ing	35.36
^{89}Sr	1.2×10^{-6}	0.05	Fish-Ing	47.16	1.1×10^{-6}	0.06	Fish-Ing	47.29
Total risk	2.3×10^{-3}				1.9×10^{-3}			

[a] Percent of risk from primary exposure pathway for each radionuclide

Prioritization of the radionuclides resulted in different sets of significant nuclides for each exposure scenario. If we used a 1% cutoff, so that any radionuclide that contributed <1% to the total risk in all three scenarios was considered unimportant, the following radionuclides would have also been eliminated from further consideration: ^{89}Sr and ^{90}Sr. Interestingly, ^{133}I which was almost eliminated in the initial screening would have remained in the analysis.

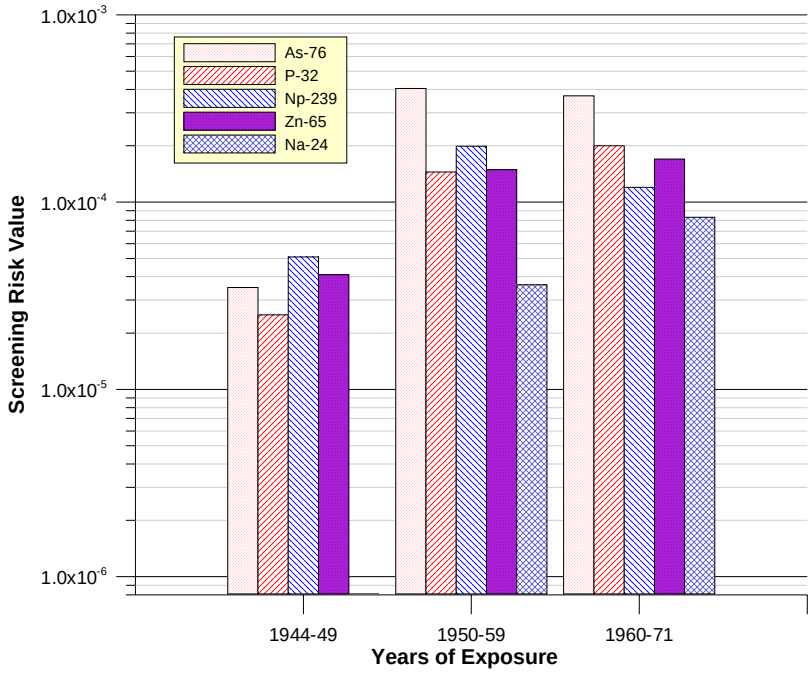

Figure 7-2. Risk by decade of exposure for ^{76}As, ^{32}P, ^{239}Np, ^{65}Zn, and ^{24}Na. Risks represent those of the local resident at Richland.

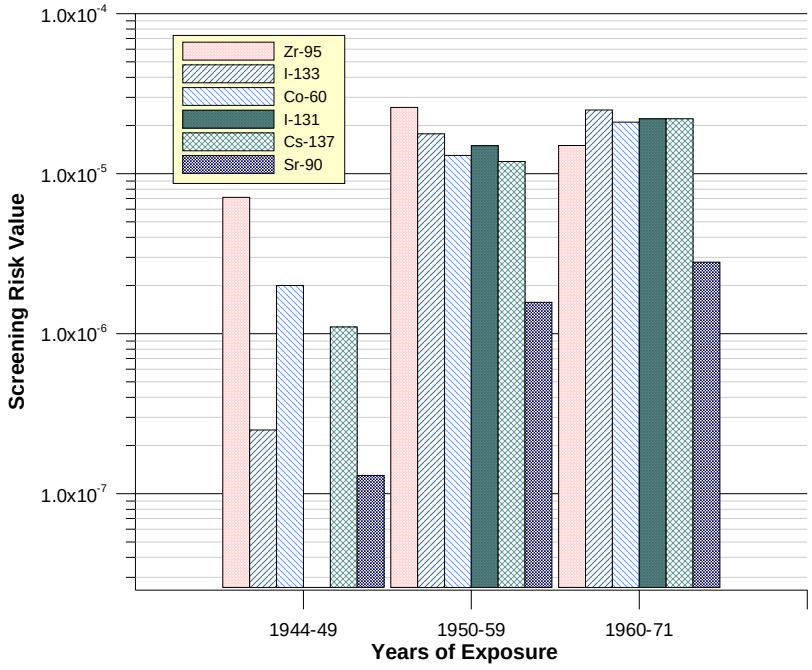

Figure 7-3. Risk by decade of exposure for ^{95}Zr, ^{133}I, ^{60}Co, ^{131}I, ^{137}Cs, and ^{90}Sr. Risks represent those of the local resident at Richland.

7.3. Discussion

The five nuclides for which dose calculations were made in the HEDR Project (Farris et al. 1994a) (^{24}Na, ^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np), all had initial screening values greater than 10^{-4}, and with the exception of ^{24}Na were the dominant contributors to risk. In the three representative scenarios that were subsequently examined (Native American, migrant worker, local resident), the same four radionuclides (^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np) were the primary sources of risk, with ^{76}As accounting for the highest risk (>50% in all cases). Our initial screening identified 11 additional radionuclides that may have been of potential significance. These were ^{95}Zr, ^{137}Cs, ^{60}Co, ^{24}Na, ^{46}Sc, ^{90}Sr, ^{72}Ga, ^{90}Y, ^{131}I, ^{133}I and ^{89}Sr. Based on their prioritization in the Native American, migrant worker, and local resident scenarios, ^{95}Zr, ^{137}Cs, ^{60}Co, and ^{24}Na were the next most significant radionuclides, each accounting for about 1 to 3% of the total risk. Strontium-89, ^{90}Sr, and ^{131}I were of least significance. This result differed from the HEDR screening (Napier 1993) that identified ^{24}Na, ^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np as the primary contributors to risk. Napier (1993, Appendix C) identified ^{60}Co as potentially significant based on reported releases during 1959 to 1971. However, the final screening was based on releases in 1961, the year of peak releases, and since no release data were available for ^{60}Co at that time period, it was not identified and was dropped from the analysis. A similar situation occurred for ^{95}Zr. No release estimates were available for 1961, and it appeared to have also been dropped from the analysis. In contrast, ^{137}Cs was never identified as a potential radionuclide of concern in Napier (1993) and was not included in the screening analysis.

As discussed in Chapter 4, it was difficult to reconcile predicted and observed measurements of ^{60}Co in water and sediment. Using a ratio of ^{60}Co/^{32}P of 0.388 resulted in reasonable agreement between predicted and observed concentrations in water and sediment. Such an activity ratio would produce ^{60}Co risk estimates that were about a factor of 4.5 higher than the values listed in Tables 7-1, 7-5, 7-6 and 7-7. The initial screening risk value at Richland for ^{60}Co (Table 7-1) would have increased from 4.6×10^{-4} to 2.1×10^{-3}– higher than that of ^{65}Zn. Cobalt-60 would have been one of the five highest risk contributors using this ratio (^{60}Co/^{32}P = 0.388) for all the scenarios considered. However, the discrepancy between predicted and observed concentrations may have been a result of activated metal flakes containing ^{60}Co that were released to the Columbia River and may have gone undetected in the effluent monitoring systems. These flakes were observed in shoreline sediments downstream of the reactors during surveys conducted in 1974 (Walters et al. 1992). If the activated metal flakes were a substantial source of ^{60}Co to the river, then the risks from fish ingestion might be considerably lower because metallic cobalt would more likely pass through the gastrointestinal tract of the fish and not accumulate in the flesh in the same way as dissolved cobalt.

It is possible that the potential significance of ^{137}Cs was overestimated in our screening. The release estimates for ^{137}Cs were based on a single measurement in 1964 that was reported by Soldat (1969). The source of ^{137}Cs in river water measurements could have been fallout from atmospheric weapons testing as opposed to releases from the Hanford reactors. As discussed in Chapter 4, activity concentrations measured in sediments are close to what might be expected in soil or sediment from atmospheric weapons testing fallout. For example, Hardy et al. (1980) measured ^{137}Cs in sediment cores from a reservoir near Denver, Colorado. Activity concentrations ranged from 0.9 pCi g^{-1} for deposition that occurred in ~1974 to 2.7 pCi g^{-1} for deposition that occurred in ~1964. Without a clear understanding of background activity

concentrations of ^{137}Cs in sediment and water, it is difficult to judge whether the source term estimated by Soldat (1969) is reasonable. Nevertheless, this source term yielded screening values for ^{137}Cs that never exceeded 2 percent of the total risk, and it is likely that the risk from exposure to ^{137}Cs from weapons fallout sources exceed those resulting from reactor releases to the Columbia River.

7.3.1. Comparison with HEDR Project Results

A comparison of exposure estimates from the HEDR Project (Farris et al. 1994a) and estimates calculated in this study was made by converting the HEDR Project estimated cumulative effective dose equivalent to risk for a given exposure scenario. In the HEDR Project, a maximum representative individual was defined to estimate the doses to a significant user of the Columbia River. This hypothetical individual approximated a segment of the general population who had maximum or near maximum ingestion rates for resident fish and waterfowl and spent time in or on the river. Of the three exposure scenarios defined in this study to prioritize the screened radionuclides, the Native American scenario represented the maximum exposed individual and was therefore compared to the maximum representative individual in the HEDR Project. A *median* annual fish consumption rate of 109 kg was assumed for the Native American scenario compared to a *maximum* annual fish consumption rate of 42.1 kg in the HEDR Project. This can be compared to the *maximum* annual fish consumption rate of 240 kg assumed for the initial screening. The median HEDR Project cumulative effective dose equivalent for exposures from 1950 to 1971 for the maximum representative individual at Richland was ~2000 mrem or 0.02 Sv (from Figure 5.2 in Farris et al. 1994a). The 5th and 95th percentiles of the distribution were ~1500 mrem and ~4300 mrem, respectively. Assuming a cancer incidence risk of 6×10^{-2} Sv^{-1}, the corresponding median cancer incidence risk to this individual was 1.2×10^{-3}, ranging from 9×10^{-4} to 2.6×10^{-3}.

In comparison, the total screening risk for the Native American scenario at Richland for exposures from 1944 to 1972 was 1.7×10^{-2} (see Table 7-5 and Appendix E). This is roughly a factor of 10 higher than the median risk to the maximum representative individual in the HEDR Project. Most of the difference was attributed to the fish consumption rates.

Prioritization of nuclides, as illustrated for the local resident, Native American, and migrant worker scenarios in Tables 7-5–7-7 demonstrated the difficulties of using this approach in the absence of an absolute risk decision criterion to identify radionuclides of little significance to risk. Differences among individual exposure scenarios and locations resulted in different rankings of the radionuclides. For example, ^{133}I was ranked 7th for the local resident scenario but was ranked 14th for the Native American scenario and 10th for the migrant worker scenario. A qualitative evaluation of the ranking yielded several nuclides that consistently showed up at the bottom of the ranking. These nuclides included ^{89}Sr, ^{90}Sr, ^{46}Sc, and ^{131}I. Another way to analyze the results was to identify those radionuclides that consistently ranked high. Applying this procedure to the local resident, Native American, and migrant worker scenarios identified the same five radionuclides (^{32}P, ^{76}As, ^{65}Zn, ^{24}Na, and ^{239}Np) that were identified in the HEDR Project along with ^{95}Zr, ^{137}Cs, and ^{60}Co as potentially significant in terms of overall risk.

Another notable difference between the results of this study and those of HEDR was that in this study, ^{76}As was shown to be the most important radionuclide for both the Richland and Pasco

exposure locations whereas in HEDR, ^{32}P and ^{65}Zn were shown to be the dominant radionuclides. The reason for this difference was threefold.

First, the dietary intake risk coefficient for ^{76}As was proportionally higher than ^{65}Zn and ^{32}P compared to the ingestion dose conversion factors for these nuclides (Table 7-8). The ratio of the ^{76}As/^{65}Zn risk coefficient was 0.923 while the ratio of the ^{67}As/^{65}Zn dose conversion factor was 0.457. Therefore, using cancer incidence risk as an endpoint resulted in ^{76}As being relatively more important compared to using effective dose equivalent as an endpoint. A similar finding was observed for ^{32}P (Table 7-8).

Table 7-8. Ratios of ^{76}As/^{65}Zn and ^{76}As/^{32}P Dose Conversion Factors (*DCF*) and Dietary Ingestion Risk Coefficients (*RC*)

Nuclide	HEDR *DCF* (mrem pCi^{-1})[a]	Ratio ^{76}As *DCF* to *DCF*	Risk coefficient (Bq^{-1})[b]	Ratio ^{76}As *RC* to *RC*
^{76}As	4.80×10^{-6}	1.0	3.83×10^{-10}	1.0
^{65}Zn	1.40×10^{-5}	0.343	4.15×10^{-10}	0.923
^{32}P	7.70×10^{-6}	0.623	3.32×10^{-10}	1.15

[a] HEDR ingestion dose conversion factor from DOE 1988
[b] EPA 1999b

Second, the treatment of radioactive decay during holdup between the time of catch and time of consumption differed between HEDR and this study. The HEDR Project assumed no ingestion of the fish until the stated holdup time, which varied between 2, 7, or 14 days depending on the type of fish, whereas we assumed the fresh fish were consumed over a period of 1 or 5 days (see Tables 5-1, 5-5). The rationale for this assumption (stated previously in Chapter 5) was that wild game can be consumed any time after harvest whereas for commercially harvested crops, there is typically a delay between harvest and availability to the consumer. The differences in the methodologies are illustrated in Table 7-9. We calculated a weighted decay factor based on the maximum individual for the HEDR data. The weighted decay factor was given by:

$$WDF = \sum_{i=1}^{n} \exp(-\lambda\, th_i)\frac{I_i}{I_T} \qquad (7\text{-}3)$$

where

WDF = ingestion-weighted decay factor
th_i = holdup time for i^{th} fish species (d)
I_i = ingestion the i^{th} fish species (kg)
I_T = total fish ingestion (kg).

Three types of fish were considered in HEDR: omnivorous (th = 7 d, I = 13.7 kg), first and second order predators, (th = 2 d, I = 25.9 kg), and salmon (th = 15 d, I = 2.5 kg). The decay factor applied in this study (termed the holdup factor) was given in Chapter 5 and represented the average concentration in fish during the 5-day consumption period for the local resident scenario. Results of the calculation showed little difference in the ^{65}Zn and ^{32}P holdup factors and weighted decay factors. However, for ^{76}As, the holdup factor was about a factor of 1.7 higher than the weighted decay factor.

Table 7-9. Comparison of Weighted Decay and Holdup Factors Applied to Fish

Nuclide	HEDR weighted decay factor	Holdup factor for 5-day consumption period
^{76}As	0.178	0.303
^{65}Zn	0.988	0.993
^{32}P	0.819	0.888

Third, the bioconcentration for ^{76}As used in this study was a factor of 2.3 higher than what was used in HEDR (550 L kg^{-1} compared to 240 L kg^{-1} used in HEDR). All three factors combined resulted in ^{76}As being more important than ^{65}Zn or ^{32}P in the results for this study.

7.3.2. Inclusion of ^{60}Co, ^{90}Sr and ^{131}I

In a review of the HEDR dose estimates for ATSDR, Hoffman et al. (1998) suggested that ^{60}Co, ^{90}Sr and ^{131}I should also have been included in the HEDR dose calculations for the Columbia River. The concern with ^{60}Co related to the potential buildup of ^{60}Co in sediments, which was accounted for explicitly in the river transport model used in this study. In our initial screening, ^{60}Co was identified as a potentially important radionuclide, as a result of fish ingestion and not external irradiation from exposure to shoreline sediments. The screening risk value for external exposure to shoreline sediments via all radionuclides was below 10^{-4}, indicating this was not a significant exposure pathway for historical radionuclide releases to the Columbia River. However, dermal contact was shown to be a more important pathway than external exposure. For the three exposure scenarios (Native American, migrant worker, local resident) ^{60}Co consistently accounted for 1 to 2% of the total risk. Fish ingestion was the primary exposure pathway for the Native American and local resident scenarios, and dermal contact was the primary exposure pathway for the migrant worker. Therefore the current screening results suggested that ^{60}Co was a potentially significant radionuclide, but that the primary exposure pathways were fish ingestion and dermal contact rather than external irradiation from shoreline sediments.

Hoffman et al. (1998) was concerned that exposure to ^{90}Sr from consuming whole fish (including the bones), and not just fish fillets may have resulted in the risks to certain groups of Columbia River users being underestimated in the HEDR Project. In this study, we accounted for the consumption of whole fish by Native Americans. However, our research did not support the assumption that whole fish are consumed year round in large quantities. A distinct seasonal pattern was observed whereby the fish harvested in late summer were the primary source for whole fish consumption. These fish were dried, ground, and stored for consumption throughout the winter months. The initial screening identified ^{90}Sr, and to a lesser extent ^{89}Sr, as potentially significant. The three exposure scenarios did not identify them as high priority radionuclides. Strontium-90 was of most significance in the Native American scenario, where it accounted for less than 1% of the total risk. Strontium-89,90 were of negligible significance for the migrant worker and local resident scenarios. The screening analysis did not tend to support the suggestion of Hoffman et al. (1998) that ^{90}Sr should have been included in the HEDR dose calculations.

Hoffman et al. (1998) considered that for assessing exposures to ^{131}I, the dose to the thyroid for children was the appropriate endpoint as compared to the effective dose equivalent. The initial screening did not eliminate ^{131}I as it had a screening value of 1.3×10^{-4}. Of the three scenarios (local resident, migrant worker, and Native American) used to prioritize the remaining

radionuclides, ^{131}I was most significant in the local resident scenario where it accounted for less than 2% of the total risk. The dominant exposure pathway was milk ingestion, which accounted for ~30% of the total risk. Based on data in ICRP (1998), the effective dose per unit intake for ^{131}I is higher for children compared to adults, however, the same is true for the other radionuclides that were the primary contributors to risk (^{76}As, ^{65}Zn, ^{32}P, and ^{239}Np). Therefore, the higher risks to children (compared to adults) from ^{131}I would also see a proportional rise in the risk from the other radionuclides, and the relative importance of ^{131}I would likely remain the same. Additionally, if we considered the total dose from ^{131}I over all years of exposure, atmospheric sources of ^{131}I far exceeded those from the river water pathways. For example, the ^{131}I effective dose equivalent to an adult male at Richland from 1945 to 1972 was estimated to be 0.0042 Sv (Farris et al. 1994b, Appendix C). Assuming a cancer incidence risk of 6×10^{-2} Sv^{-1}, the corresponding median cancer incidence risk to this individual was 2.5×10^{-4}, which is a factor of 7 higher than the ^{131}I risk from the river pathway for the local resident at Richland. Therefore, our results indicated that for the Columbia River pathway, ^{131}I did not merit high priority should further analyses of risk be undertaken.

8. CONCLUSIONS

The initial screening was applied to the 5 radionuclides that were evaluated for the river pathway in the HEDR Project (^{32}P, ^{65}Zn, ^{76}As, ^{24}Na, and ^{239}Np) and an additional 18 radionuclides that were released to the Columbia River. The initial screening was designed to overestimate the lifetime cancer incidence risks to the most exposed individuals for each radionuclide. Using a risk criterion of 10^{-4} and accounting for uncertainty in the estimates, the initial screening indicated that ^{45}Ca, ^{51}Cr, ^{56}Mn, ^{64}Cu, ^{69m,69}Zn, ^{93}Y, and ^{122}Sb were unimportant and could be eliminated from further analysis. Subsequent analysis using three representative scenarios indicated that ^{131}I, ^{133}I, ^{90}Sr, ^{89}Sr, ^{72}Ga, ^{46}Sc, and ^{90}Y were of low priority and probably could also be dismissed. The radionuclides ^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np were identified as the primary sources of health risk from releases to the Columbia River. This supported the HEDR Project conclusions where dose calculations were made for these four radionuclides. Unlike the HEDR Project, ^{76}As was shown to be the most important radionuclide for exposures at Richland and Pasco. The HEDR Project identified ^{32}P and ^{65}Zn as the dominant radionuclides. This difference occurred, in part, because the decrease in radioactivity in fish from the time they were caught to the time they were consumed was treated differently. The HEDR Project assumed no fish were consumed until the stated holdup time, which varied between 2, 7, or 14 days depending on the type of fish. In this study we assumed fresh fish were consumed over a period of 1 or 5 days depending on the type of fish. The difference also occurred because the dietary intake risk coefficient for ^{76}As is proportionally higher than those for ^{65}Zn and ^{32}P. The HEDR Project calculated doses not cancer incidence risks. Finally, the bioconcentration factor for ^{76}As used in this study was a factor of 2.3 higher than that used in the HEDR Project.

The HEDR Project also made dose calculations for ^{24}Na, where it was shown to account for approximately 7% of the total effective dose equivalent for a maximum representative individual at Richland from 1944 to 1971. Our analysis suggested that ^{95}Zr in particular, and possibly ^{60}Co and ^{137}Cs represented comparable risks and may have warranted additional analysis. The source terms for ^{60}Co and ^{137}Cs are poorly understood and additional work outside the scope of this project would be required to develop more accurate release estimates. The release characteristics of ^{60}Co (i.e., release as discrete metallic flakes or a dissolved substance) would need to be further explored, and the background concentrations of ^{60}Co and ^{137}Cs accounted for before such estimates could be made. However, the current screening is unlikely to underestimate the risks associated with these radionuclides and we believe this should be considered before any further work is undertaken in this area.

The screening results support the HEDR Project conclusion that fish ingestion was the dominant exposure pathway for releases to the Columbia River. However, the significance of this pathway for Native American users of the river was greater than that for non-Native Americans by a factor of ten because fish consumption rates reported for Native Americans tended to be higher than the value assumed for the maximum representative individual in the HEDR Project. Our evaluation of the exposure pathways also indicated it was reasonable to assume the entire fish was consumed for some portion of the fish harvest but this did not change the importance of the different radionuclides significantly.

The screening analysis demonstrated that a number of exposure pathways were of low priority and could be dismissed. These included ingestion of contaminated sediments, external exposure from swimming, ingestion of contaminated river water during swimming, and inhalation of contaminated aerosols.

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APPENDIX A
STATEMENT OF WORK

APPENDIX A — STATEMENT OF WORK

A.1. Introduction

The Centers for Disease Control and Prevention (CDC) is sponsoring two major environmental and health impact studies relating to operation of U.S. Government facilities at the Hanford Nuclear Site, in Washington State. These studies are known as the Hanford Environmental Dose Reconstruction (HEDR) Project, and the Hanford Thyroid Disease Study (HTDS). In addition, CDC sponsors a Cooperative Agreement with the Washington Department of Health to develop and administer the Hanford Individual Dose Assessment (IDA) Project.

The HEDR Project is funded as part of a Memorandum of Understanding between the Department of Energy (DOE) and the Department of Health and Human Services (DHHS). The CDC has been assigned the role of directing the HEDR Project. The primary purpose of the HEDR Project is to reconstruct doses to offsite members of the public resulting from radionuclide releases since 1944. The HTDS is funded directly through Congress; its primary purpose is to determine if individuals exposed to radioactive Iodine (primarily 1-131) released from the Hanford facility have an increased incidence of thyroid disease. The Hanford IDA Project will allow individuals exposed to Hanford radiation releases to estimate their individual radiation doses.

CDC and the Agency for Toxic Substances and Disease Registry (ATSDR) have established the Hanford Health Effects Subcommittee (HHES), a Federal advisory committee, whose members provide advice to CDC on community concerns about CDC's activities in their community. Contractors for the HEDR Project must work with the Subcommittee.

A.2. Task Description

The HEDR Project developed the Columbia River Dosimetry Code (Farris et al., 1994) to calculate radiation doses for hypothetical individual users of the Columbia River at various locations on the river. Initially, the HEDR Project considered all radionuclides released from the Hanford Nuclear Site between 1944 and 1972. --Ultimately, doses were calculated for five radionuclides: Sodium-24, Phosphorus-32, Zinc-65, Arsenic-76, and Neptunium-239. The water concentrations for these radionuclides that were used in the dose calculations were provided by the CHARIMA computer code (Walters et al., 1994).

The five radionuclides listed above for which dose calculations were made were selected by the Technical Steering Panel of the HEDR Project from the initial list of released radionuclides on the basis of a series of scoping or screening calculations (Napier, 1993). The radionuclide exposure pathways considered in the dose calculations were also selected on the basis of scoping calculations. Hoffman et al. (1997) suggest that Iodine-131, Cobalt-60, and Strontium-90 should also be considered in a Hanford IDA process for the Columbia River. The objective of this task is to perform screening calculations that can be used to evaluate this recommendation.

A.3. Responsibilities of the Contractor

All plans and reports will be submitted to CDC as draft reports for review and approval. The contractor shall be responsible for the deliverables listed below. Specifically, the contractor shall perform the following:

1. Review all of the available HEDR Project documents related to the published Columbia River dose calculations, and select the best available information relating to the quantities of each of the eight radionuclides listed above that were released to the Columbia River between 1944 and 1972. The contractor shall NOT develop any new information on estimates of the radionuclide releases to the Columbia River without the approval of the Project officer.

2. Review risk-based screening limits which might be used by CDC as a decision criteria for choosing radionuclides for further consideration in the development of an individual dose assessment code for the Columbia River pathway.

3. Develop a screening methodology that accounts for all potential pathways of exposure for each of the eight radionuclides listed above. Organ-specific health risk and not just radiation dose should be the end point of the screening calculations. All mathematical models and parameter values' selected for use in the methodology should be carefully justified and thoroughly referenced.

4. After the developed screening methodology has been approved by the Project Officer, perform screening calculations for the eight radionuclides referenced above. Screening calculations for a limited number of additional radionuclides may be proposed, but no screening calculations will be performed for any additional radionuclides without the concurrence of the Project Officer.

5. As a result of these screening calculations, formulate for CDC's consideration recommendations with regard to the inclusion of further radionuclides and pathways in future Columbia River individual dose calculations.

6. During the performance of this task, contractor staff will work with the health agencies of the States of Washington, Oregon, and Idaho, the Hanford Health Effects Subcommittee, the Agency for Toxic Substances and Disease Registry, Native American tribes and the public to insure full public participation in the decision making process associated with the performance of these screening calculations. This includes:

    a. Attending up to six public meetings in the northwest United States to explain the status of the work, review all documents and major decisions, and respond to questions.

    b. Publication of one fact sheet at the end of the task to explain the objectives of the task and the significance of the findings.

In addition, the contractor shall provide appropriate representation at periodic contract status meetings and/or meetings with other Government contractors as may be determined appropriate by the Project Officer.

The contractor shall also deliver to the Project Officer periodic letter status reports, as described in Item 11. Letter status reports shall be brief two-to-three page documents summarizing activities and verifying in detail all expenditures.

A.4. References

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APPENDIX B
ANNOTATED BIBLIOGRAPHY OF SELECTED REPORTS RELATED TO THE HEDR PROJECT

APPENDIX B — ANNOTATED BIBLIOGRAPHY OF SELECTED REPORTS RELATED TO THE HEDR PROJECT

Napier, B.A. 1991. *Selection of Dominant Radionuclides for Phase I of the Hanford Environmental Dose Reconstruction Project.* PNL-7231 HEDR UC-707, Pacific Northwest Laboratory, Richland, Washington. July.

This report documented the selection of the dominant radionuclides (those that may have resulted in the largest portion of the received doses) in the source term for atmospheric releases (1944–1947) and surface water releases (1964–1966). Because the early releases from Hanford operations were largely continuous and each radionuclide retained the same relative fractional contribution to the total released activity, radionuclides were ranked based on a unit source term release.

Actual measurements of radionuclide concentrations in river water were used to determine the dominant radionuclides. Appendix E provided measurements. Contributions from groundwater migration to the river were assumed to be implicit in the measured values for surface water, therefore no additional calculations were performed for groundwater releases.

A range of potential exposure pathway conditions and individual exposure mechanisms were investigated. Potential variability in the source term (reactor power levels and fuel conditions) was addressed because monitoring data for a number of years was reviewed. The selection of dominant radionuclides was made based on those frequently occurring in the resulting lists. The computer code GENII was used to make the calculations. Appendix C provided parameter inputs and results.

The exposure pathways considered for a maximally exposed individual were: drinking contaminated water, recreation in or near contaminated water, consumption of fish, irrigation with contaminated river water and consumption of contaminated produce, exposure to soils contaminated by the water, inhalation of resuspended dusts from such soils. Three exposure scenarios referred to as variations, were considered to account for lesser-exposed individuals. The variations were: exposure from drinking water only; exposure from shoreline and river recreational activities; exposure from Columbia River fish ingestion, where this was the main dietary source. Consumption rates for this last variation were taken from Hunn and Bruneau (1989). The reference for this publication was Hunn, E.S., and C.L. Bruneau. 1989. *Estimations of Traditional Native American Diets in the Columbia Plateau.* PNL-SA-17296, Pacific Northwest Laboratory, Richland, Washington. The report concluded that inclusion of the following five radionuclides in the dose calculations was essential: ^{32}P, ^{239}Np, ^{65}Zn, ^{76}As, and ^{64}Cu, with the following four radionuclides highly desirable: ^{56}Mn, ^{24}Na, ^{46}Sc, and ^{51}Cr. All intermediate calculations were presented in the appendices to the document. It should be noted, however, that a later report (Napier 1993), which is summarized below, was used to identify the radionuclides for which detailed dose calculations for releases to the Columbia River were made in the HEDR Project.

Pacific Northwest Laboratory. 1991. *Columbia River Pathway Report: Phase I of the Hanford Environmental Dose Reconstruction Project.* PNL-7411 HEDR Rev 1, Pacific Northwest Laboratory, Richland, Washington.

This document outlined Phase I of the HEDR Project, including the Phase I screening calculations. For Phase I, the years 1964–1966 were analyzed because of the wealth of environmental data, independent measurements, relatively high radionuclide concentrations in river water, and the Richland population having been recently exposed to contamination via groundwater. Phase I still looked at the eight radionuclides identified as important in the initial screening—^{32}P, ^{65}Zn, ^{76}As, ^{239}Np, ^{56}Mn, ^{51}Cr, and ^{64}Cu—because they were estimated to deliver more than 80% of the total dose to a maximally exposed individual. A simple routing model, using only effluent measurement and river discharge as inputs, used radioactive decay and mixing to estimate concentrations at downstream locations.

This document contained the routing equation used to calculate downstream concentrations, assuming

- Flow and transport could be represented as steady-state on a monthly basis
- Effluent discharge rates were constant each month
- Radionuclides were completely mixed in a cross section of the river at any location between Priest Rapids Dam and McNary Dam
- Effluent spent a short time in retention basins (~4 hours)
- Radionuclide sources and sinks were neglected (e.g., no sediment buildup).

The highest doses were estimated for individuals who consumed large quantities of fish and who drank untreated river water.

Napier, B.A. and A.J. Brothers. 1992. *Recommendations to the Technical Steering Panel Regarding Approach for Estimating Individual Radiation Doses Resulting from Releases of Radionuclides to the Columbia River. Volume 1: Recommendations*. PNWD-1977 HEDR Vol.1. Battelle Pacific Northwest Laboratories, Richland, Washington, July.

This document included information regarding the decision process used to evaluate what work and level of effort should be undertaken throughout the remainder of the HEDR Project related to the Columbia River Pathway. The following criteria were weighed as they impacted the study: minimizing cost, maximizing utility of derived information, being as complete as possible, minimizing the uncertainty of the results, and maintaining consistency with the Technical Steering Panel (TSP) guidance dose level of 100 mrem y^{-1}. When this dose criterion was exceeded, the TSP recommended that some additional effort go into characterizing the dose.

Napier, B.A. 1993. *Determination of Key Radionuclides and Parameters Related to Dose from the Columbia River Pathway*. BN-SA3768 HEDR, Battelle Pacific Northwest National Laboratories, Richland, Washington.

Incomplete source term information for 19 radionuclides for 1959–1970 was used for the scoping calculations. Effective doses for “maximum” and “average” individuals were calculated based on 200 realizations for external exposures via swimming and boating; ingestion via drinking water, and fish consumption. The year 1961 was identified as the peak dose year for the period studied. Five radionuclides, ^{24}Na, ^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np, were identified for further study in HEDR. The following radionuclides were eliminated from further analysis because only a few percent of the total dose came from them: ^{45}Ca, ^{46}Sc, ^{56}Mn, ^{51}Cr, ^{69}Zn, ^{69m}Zn, ^{89}Sr, and ^{90}Sr.

Appendix A contains incomplete individual reactor source terms (Ci d^{-1}) for 1959–1971 by month for 19 radionuclides. There were many gaps in the data. Appendix C contained the release estimates from all eight reactors (Ci d^{-1}) by month for the same radionuclides (with the same gaps in the data), river flow rate (cfs), and estimated travel time (d). Exposure factors and doses were provided.

Heeb, C.M. and D.J. Bates. 1994. *Radionuclide Releases to the Columbia River from Hanford Operations, 1944–1971*. PNWD-2223 HEDR UC-000. Battelle Pacific Northwest National Laboratories, Richland, Washington. May.

The curie quantities of 11 radionuclides and gross nonvolatile beta activity discharged to the Columbia River were estimated on a monthly basis for the period 1944–1971. This covered the entire operating history of the eight Hanford single-pass reactors. Uncertainties in the estimates were determined. All the release estimates were made based on either activity concentration measurements made during the time period of the release or on inferred values resulting from a statistical analysis of data from other time periods. One hundred Monte Carlo realizations of the Columbia River releases were made using the computer code STRRM to generate release distributions. Scoping calculations were repeated to confirm that the five radionuclides used in the detailed HEDR dose calculations were the most important ones. Appendix B provided a tabulation of minimum, median, maximum monthly release estimates for ^{24}Na, ^{32}P, ^{65}Zn, ^{76}As, ^{239}Np, ^{131}I, ^{90}Y, ^{72}Ga, ^{51}Cr, ^{56}Mn, and ^{46}Sc.

Walters, W.H., M.C. Richmond, and B.G. Gilmore. 1994. *Reconstruction of radionuclide concentrations in the Columbia River from Hanford, Washington to Portland Oregon, January 1950–January 1971*. PNWD2225 HEDR, Battelle Pacific Northwest National Laboratories, Richland, Washington. May.

Monthly average water concentrations were reconstructed at 12 locations along the Columbia River downstream of the Hanford Site for ^{24}Na, ^{32}P, ^{65}Zn, ^{76}As, and ^{239}Np based on the recommendations in Napier (1993). The calculated concentrations are presented in Appendix A. The ^{51}Cr concentrations were also computed for model validation purposes (not for dose estimates: low contribution to dose).

A 21-year period from January 1950 through January 1971 was evaluated for the Columbia River from Priest Rapids Dam near Hanford to just downstream of the Willamette River confluence at Portland, Oregon. The TSP approved this period of study because

- The period of highest releases was from 1955–1965 when production was at a maximum.
- Five years were added to each end of this time period to ensure adequate temporal coverage.
- The last of the single-pass production reactors was shut down in January 1971.

The report described how WSU-CHARIMA, a 1-D finite difference model that simulates unsteady flow hydraulics and nonuniform sediment transport in open channel systems was used

to compute water concentrations. The CHARIMA model (Holly et al. 1993[g]) was obtained from Iowa State University and modified by Battelle Pacific Northwest Laboratories and Washington State University to include radioactive decay in the transport equation, and the version was named WSU-CHARIMA. Model testing indicated that correction for sediment uptake and release was not feasible. This omission was considered to have a negligible impact except for the Portland location where concentrations for ^{65}Zn were overestimated. The Portland location was also influenced by tidal-effects.

The relatively short-lived radionuclides ^{24}Na, ^{76}As, and ^{239}Np were sensitive to downstream travel time. Transport velocities were greatly reduced after dams were constructed below the Snake River. The water concentrations of these three radionuclides at the downstream locations were much lower than they would have been under open channel conditions. Because of the longer half-lives of ^{32}P and ^{65}Zn, dam construction did not affect the downstream concentrations to any significant extent.

Farris, W.T., B.A. Napier, J.C. Simpson, S.F. Snyder, and D.B. Shipler. 1994. *Columbia River Pathway Dosimetry Report, 1944–1992*. PNWD2227 HEDR, Battelle Pacific Northwest National Laboratories, Richland, Washington.

This report contained overview information on the technical approach, model development, final bioconcentration factor data, and transmission factors (the fraction of radionuclides that pass through the treatment process). It documented the simple equations used in the Columbia River Dosimetry code to calculate radionuclide concentrations and doses for each pathway, and listed the scenario parameters used in the HEDR Project exposure scenarios.

Hunn, E. no date. *Estimations of Traditional Native American Diets in the Columbia River Plateau*. PNL-SA-17296 HEDR.

This was a draft report prepared for the HEDR Project that provided weekly per-capita consumption levels by season for adult male Native Americans within a 10-county target area. Traditional and nontraditional food categories for three tribal groups (River Yakima, Nez Perce, and Colville) were presented. The food categories were exposed vegetables; other vegetables; grains; fruits/berries; wild bird eggs; game; wild birds; anadromous fish (salmon, steelhead trout, and lamprey eels); other fish (suckers, trout, and whitefish); shellfish; blacktree moss (an exposed vegetable); and water.

Hoffman F.O., A.I. Apostoaei, J.S. Hammonds, K.M. Thiessen, B.G. Blaylock, and B.A. Thomas. 1998. *Estimation of Health Risks Based on Revised Estimates of HEDR Doses for Maximum Representative Individuals Consuming Fish and Waterfowl from the Columbia*

[g] Holly, F.M., J.C. Yang, P. Schwarz, J. Schaefer, S.H. Hsu, and R. Einhellig. 1993. *CHARIMA—Numerical Simulation of Unsteady Water and Sediment Movement in Multiple Connected Networks of Mobile-Bed Channels.* IIHR Report No. 343, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, IW.

River: An Evaluation of HEDR Reports on the Columbia River. SENES, Oak Ridge, Inc., Oak Ridge, Tennessee.

This report reviewed the HEDR Project dose estimates and presented revised estimates of the doses from ingestion of fish and waterfowl based on modified estimates of bioconcentration factors (BCFs) for fish and waterfowl and on expanded organ-specific dosimetry. Estimates of relative risk and lifetime risk were made from the revised dose estimates. The HEDR reports were reviewed and the following possible sources of bias in the HEDR dose calculations were identified:

- Scoping studies – by looking at annual average dose for only 3 years, Hoffman et al. indicated that it is possible to overlook some pathways that might contribute more significantly after radionuclide concentrations have built up (e.g., irrigation pathway and external exposure to shoreline sediments). Scoping studies also may have ruled out radionuclides because of the methodology (e.g., ^{90}Sr in fish bones and ^{60}Co in sediments).
- Bioconcentration factors – the methodology used to create BCFs distributions was flawed because only natural variability was addressed; the uncertainty about a measured mean was not addressed. Hoffman et al. suggested that it is better to use the available data and take the arithmetic mean to produce a median value about which a distribution is determined using available scientific knowledge. Also, BCFs based on fish fillets rather than on the entire organism would tend to underestimate the doses for certain radionuclides (^{90}Sr)
- In the HEDR Project the BCF for salmon was estimated to be the same as that for a second-order predator fish. This overestimated the dose from salmon ingestion.
- In the HEDR Project the holdup times between fish harvest and consumption were calculated assuming a combination of fresh fish consumption and frozen or dried fish consumption. This underestimated the doses for individuals who consumed fresh fish only.
- The ingestion rates (annual and seasonal) for fish and waterfowl for a maximum representative individual in the HEDR Project could underestimate the intake for individuals whose primary source of food was the Columbia River.
- Target organs were not correctly identified in the HEDR Project. A more recent publication of ICRP dose conversion factors across a wide range of organs makes this easier.
- Uncertainty may not have been evaluated properly.
- There was no age specific evaluation of dose in the HEDR Project.

Most of the recommendations revolved around the calculation of dose and not the source term and environmental transport calculations.

APPENDIX C
COLUMBIA RIVER EXPOSURE SCENARIO ACTIVITY CATEGORIES

APPENDIX C — COLUMBIA RIVER EXPOSURE SCENARIO ACTIVITY CATEGORIES

This list identifies general activity categories that may result in distinctive exposures to Columbia River borne contaminants. For each category, at least one source is mentioned that attributes the activity to the Native peoples of the Columbia River Plateau. A more extensive bibliography follows.

C.1. Ingestion

- Drinking water: untreated river water, treated river water
- Fresh salmon and steelhead, lamprey (mostly skin), smelt (mostly skin, but also organs), shad (Columbia River Inter-Tribal Fish Commission 1994; Hewes 1998: 623-624)
  - Organs, bones, eggs, head, skin, fillet
  - Fried, baked, broiled, or roasted
- Air-dried salmon and steelhead, lamprey, smelt, shad (Columbia River Inter-Tribal Fish Commission 1994)
  - Organs, bones, eggs, head, skin, fillet
- Smoked salmon and steelhead - fillets cooked by the fire or whole fish wrapped in leaves or mud and cooked in the coals (Wallulatum 1977: 187)
- Salmon pemmican, or “sugared salmon” (soaked in steelhead oil and set on tule mats to dry and drain excess oil) (Stern 1998: 643)
- Fresh resident fish - omnivorous (bullhead, catfish, suckers, whitefish, chiselmouth, carp, sturgeon), first-order predators (trout, whitefish, walleye, squawfish), second-order predators (e.g., sucker) (Columbia River Inter-Tribal Fish Commission 1994)
  - Organs, bones, eggs, head, skin, fillet
  - Baked or broiled
- Air dried resident fish - bottom feeders, first-order predators, second-order predators (Columbia River Inter-Tribal Fish Commission 1994)
  - Organs, bones, eggs, head, skin, fillet
- Salmon oil also reported as antidote for poisoning from Indian hellebore, water hemlock (*Cicuta douglassii*), death camas (*Zigadenus venenosus*) and baneberry (*Actaea arguta*) (Hunn et al. 1998: 535).
- Waterfowl - e.g., puddle ducks (Hoffman et al. 1998)
- Watercress (*Rorippa nasturtium-aquaticum*) and other vegetation (Hunn et al. 1998: 527)
- Acorns of garry oak (*Quercus garryana*) were also of some significance in the Columbia Gorge area, where they were baked underground after leaching in “blue” mud (Hunn et al. 1998: 530)

- Camas bulbs, cooked in a pit (wood burned under rocks, with wet willow branches followed by clumps of wet alfalfa and rye grasses, followed by wet sacks of bulbs, covered by dirt) (Hunn et al. 1998: 529).
- Seeds of yellow pond-lily (*Nuphar polysepalum*) known among the Klamath as “wokas” (Hunn et al. 1998: 530-531).
- Teas (Labrador tea – *Ledum groenlandicum*; mint –*Mentha arvensis*; wild bergamot – *Monarda fistulosa*; wild rose stems and flowers). Mint, wild bergamot and some

wormwoods (*Artemisia* spp.) were also used as preservatives to repel flies and other insects from meat, fish or berries being dried or stored. (Hunn et al. 1998: 535)

- Basket and mat-weaving (oral contact to wet reed tips while weaving) – woven for mats (for berry-drying and fish draining) and bags of various types; tule stems (*Scirpus lacustris*), cattail leaves (*Typha latifolia*) and stems of common reed grass (*Phragmites australis*). Stem fiber of Indian hemp (*Apocynum cannabium*) was used for cordage – fishnets, woven bags, capes – and also for a "time ball" of twine used to record key events in a person's life (Uebelacker and Wilson 1984).
- Cattail bags lined with salmon skin were used to store dried fish flesh that had been pounded into a powdered meal (up to 45 kg per bag) (Hunn et al. 1998: 540).

> *The oil that our people used to prepare the sugared salmon came from steelhead. Red salmon was air dried and eaten dry for lunches because the other methods of preparing fresh salmon used a lot of wood which was very difficult to get along the river. Large wooden troughs were needed with many heated rocks to bring water to a boil. Salmon fillets were put on sticks and cooked by the fire, and sometimes fish were wrapped in leaves or mud and cooked in the coals.* (Wallulatum 1977: 187).

C.2. Inhalation

- Aerosolized vapors from dip-net platforms near water falls (Hewes 1998: 623-624)
- Smoke from campfires with fuel wood from the river's edge
- Sweat lodge (river water vaporizes when applied to hot rocks in well-insulated enclosure) (Harris and Harper 1997: 794)
- Sweat lodge – aromatic plants such as juniper, wormwoods and yarrow inhaled as vapor as treatment for respiratory ailments or fever (Hunn et al. 1998: 535).

C.3. Bioavailability/Dermal Absorption

- Wading, Swimming – especially for setting fishing nets (Hunn et al. 1998, Hewes 1998)
- Boating – especially for fishing (Hunn et al. 1998, Hewes 1998)
- Dip-net platforms near water falls (Hunn et al. 1998, Hewes 1998)
- Sweat lodge (river water vaporizes when applied to hot rocks in well-insulated enclosure) (Harris and Harper 1997: 794); external washes of plant solutions as treatments for arthritis, rheumatism and muscular pains reported in Hunn et al. (1998: 535).
- Fish belly fat is rendered and used as a base for body paint (Harris and Harper 1997: 794; Hunn et al. 1998: 534)
- Basket-making (cuts on hands from sharp edges while weaving) (Harris and Harper 1997: 794).

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APPENDIX D
INPUT FILE FORMATS AND USER INSTRUCTIONS FOR THE RVRDSP CODE

APPENDIX D — INPUT FILE FORMATS AND USER INSTRUCTIONS FOR THE RVRDSP CODE

Concentrations in river water and sediments and lifetime cancer incidence risk calculations were performed within the code, RVRDSP that was written specifically for this project. The code is written in FORTRAN 77 and compiled using the Lahey EM32 on a personal computer with the Microsoft Windows 98 operating system. The program operates within the DOS command prompt. The code has also been compiled on a Linux workstation using the Lahey LF-95 Express compiler. Execution of the code is performed on the command line using the command argument

[*path*] RVRDSP [*filename*]

where *path* is the full or relative path to the executable (RVRDSP.EXE) and *filename* is the name of the input file. The filename argument is optional and if no filename is provided, the code will look for the default input file name called RVRDSP.PAR. If the input file name is not provided and the default input file is not found in the working directory, the code will abort.

Construction of the main input file is described in Table D-1. All input files are free-form ASCII, which may be created in any standard text editor. Each card represents one or more lines of input. Comments may be inserted between cards by placing a dollar sign ($) in the first column. Suggested default values are identified in parentheses if applicable in Table D-1.

At least two other files are required by the code. The first file (Table D-2) contains the river flow rate, width, and, depth as a function of time. The number of other files that are required depends on the number of individual sources in the simulation. Each source requires a separate file that describes the effluent release rate as a function of time (Table D-3). The names of the flow rate file and source file are specified in the main input file on cards 3 and 9 respectively. A third file containing exposure factors used in the risk calculation (Table D-4) is optional.

The variables jmax, jstart, and eps in the main input file are used with the Simpson's rule integration routine. The routine evaluates the integral for a variable number of points and monitors the accuracy of the solution. The accuracy is checked by computing the integral using 2^n number of middle points plus the two end points and then adding 2^{n+1} number of middle points and comparing the result with the previous evaluation. The variable jmax defines the maximum number of iterations allowed before the integration routine is terminated. On the first iteration, the crudest approximation to the integral is performed by evaluating the function at the upper and lower limits. On each successive iteration, the number of middle points (points between the upper and lower limits of integration) evaluated are increased by a factor of 2 starting with one middle point added during the second iteration. The number of additional middle points is given by 2^{n-2} where n = the iteration number. The routine evaluates the integral for at least jstart number iterations before the n-1 solution is checked for convergence with the n^{th} solution. For example, if the variable jstart is set equal to 6, then 6 iterations are performed before convergence checking occurs. The number of middle points added on the 6th iteration is $2^{6-2} = 16$. Convergence is checked by calculating the eps value and comparing it to the user input eps value. The eps variable is given by

$$EPS = \frac{\left|\Theta_p - \Theta_c\right|}{\Theta_c} \quad \text{(D-1)}$$

where

Θ_p = previous evaluation of the integral
Θ_c = current evaluation of the integral.

If the calculated eps is less than the user input eps, then the routine is terminated and the current evaluation of the integral is returned. If the calculated eps is greater than the user input eps, then 2^{n-2+1} number of middle points are added and a new value of the integral is calculated and checked. If convergence is not achieved in jmax number of iterations, then the routine is terminated and the current value of the integral is returned. A message warns the user of non-convergence and the current eps value is also printed. An adequate solution does not necessarily require convergence to be met and depends on the values of the integration variables jmax, jstart, and eps. Unacceptable solutions are usually detected by observing the concentration verses time output. If there are perturbations in the concentration versus time curve that are not accounted for by the source release model, then the eps value should be set lower and jmax increased.

Table D-1. Parameter Definition File for the RVRDSP Program

Card	Code variable	Type/format	Units	Description
1	Title	CHAR/A80		Title of run
2	Fileout	CHAR/A60		Output file name
3	Fileflow	CHAR/A60	$m^3\ s^{-1}$	File containing river flow rate as a function of time
4	Jstart	INT/*		Number of iterations to perform in the Simpson's rule integration before convergence is checked (6)
4	jmax	INT/*		Maximum number of iterations to perform in the Simpson's rule integration (12)
4	eps	REAL/*		Convergence criteria for Simpson's rule integration
5	nsrc	INT/*		Number of sources (maximum = 10)
5	nrec	INT/*		Number of receptors (maximum = 1000)
5	ntimes	INT/*		Number of output time periods (maximum = 50)
5	idisp	INT/*		Flag variable (0) = use fixed dispersivity values; (1) = calculate dispersivity values based on width, depth, and flow rate
5	ised	INT/*		Flag variable (0) = do not calculate activity in accumulating sediment; (1) = calculate activity in accumulating sediment
5	irisk	INT/*		Flag variable (0) = do not calculate risk; (1) calculate risk. NOTE if irisk=1 then an exposure factor file is needed.
NOTE: Card 6a is read only if IDISP = 1				
6a	slope	REAL/*	$m\ m^{-1}$	Average channel slope
6a	Fyakima	REAL/*	$m^3\ s^{-1}$	Annual average flow rate of the Yakima River
6a	Fsnake	REAL/*	$m^3\ s^{-1}$	Annual average flow rate in the Snake River
6a	beta	REAL/*		Unitless coefficient used to calculate transverse dispersivity (0.6)
NOTE: Card 6b is read only if IDISP = 0				

Table D-1. Parameter Definition File for the RVRDSP Program

Card	Code variable	Type/format	Units	Description
6b	Ex	REAL/*	$m^2\ s^{-1}$	Longitudinal dispersivity
6b	Ey	REAL/*	$m^2\ s^{-1}$	Transverse dispersivity
6b	Fyakima	REAL/*	$m^3\ s^{-1}$	Annual average flow rate of the Yakima River (105)
6b	Fsnake	REAL/*	$m^3\ s^{-1}$	Annual average flow rate in the Snake River (1530)
7	thalf	REAL/*	days	Radionuclide half-life
7	rho	REAL/*	$g\ cm^{-3}$	Bulk density of bed sediments (1.2)
7	vd	REAL/*	$m\ d^{-1}$	Deposition velocity of suspended sediments (0.07)
7	yshore	REAL/*	m	Distance from channel centerline to the near shore where exposure to shoreline sediments are computed. A negative value indicates the distance to the far shoreline
NOTE: Card 8 is read ntimes number of times. The time is the number of days from January 1, 1944				
8	t1(*i*)	REAL/*	days	Beginning time of simulation for time period *i*
8	t2(*i*)	REAL/*	days	Ending time of simulation for time period *i*
8	tp(*i*)	REAL/*	days	Print time step of simulation for time period *i*
NOTE: Card 9 is read nsrc number of times				
9	Xa(i)	REAL/*	m	Downstream distance (as measured from River Mile 385) for the *ith* source
9	Ya(i)	REAL/*	m	Transverse distance from near shore for the *ith* source
9	filesrc(*i*)	CHAR/A60	$Ci\ d^{-1}$	Source file names for the *ith* source.
NOTE: Card 10 is read nrec number of times				
10	xdist(*i*)	REAL/*	m	Downstream distance (as measured from River Mile 385) for the *ith* receptor
10	ydist(i)	REAL/*	m	Transverse distance from near shore for the *ith* receptor. A negative value indicates the distance to the far shoreline.
10	Tk(i)	REAL/*	m	Bed sediment thickness for the *ith* receptor
10	Sc(i)	REAL/*	$g\ m^{-3}$	Suspended sediment load at the location for the *ith* receptor
10	kd(i)	REAL/*	$mL\ g^{-1}$	Sorption coefficient at the location for the *ith* receptor
NOTE: Card 11 is read only if irisk = 1				
11	filerisk	CHAR/*		Exposure factors/risk coefficients file

Table D-2. Description of the Flow Rate, Width, and Depth Input File

Line number	Code variable	Description
1	Junk	Column header (discarded)
2 to $n+1$[a]	F(*i*,1)	Days from January 1, 1944 for the i^{th} record
2 to $n+1$[a]	F(*i*,2)	Flow rate ($m^3\ s^{-1}$) for the i^{th} record
2 to $n+1$[a]	F(*i*,3)	River width (m) for the i^{th} record
2 to $n+1$[a]	F(*i*,4)	River depth (m) for the i^{th} record

[a] *n* is the number of time, flow rate, width, and depth records. A minimum of two records is needed to operate the code.

Table D-3. Description of the Source Term Input File

Line number	Code variable	Description
1	Junk	Column header (discarded)
2 to $n+1$[a]	Q(j, i, 1)	Days from January 1, 1944 for the i^{th} record and j^{th} source.
2 to $n+1$[a]	Q(j, i, 2)	Release rate for the i^{th} record and j^{th} source (Ci d^{-1}).

[a] n is the number of time, and release rate records. A minimum of two records is needed to operate the code.

Table D-4. Description of the Exposure Factor File

Line number	Code variable	Units	Description
1	junk		Column header (discarded)
2	ef(1,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the drinking water pathway, for *jth* month (j=1, January; j=12, December)
3	ef(2,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the fish ingestion pathway, for *jth* month (j=1, January; j=12, December)
4	ef(3,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the swimming immersion pathway, for *jth* month (j=1, January; j=12, December)
5	ef(4,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the swimming ingestion pathway, for *jth* month (j=1, January; j=12, December)
6	ef(5,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the waterfowl pathway, for *jth* month (j=1, January; j=12, December)
7	ef(6,j)	$m^2\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the sediment external pathway, for *jth* month (j=1, January; j=12, December)
8	ef(7,j)	$m^2\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the sediment dermal contact pathway, for *jth* month (j=1, January; j=12, December)
9	ef(8,j)	$m^2\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the sediment ingestion contact pathway, for *jth* month (j=1, January; j=12, December)
10	ef(9,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the aerosol pathway, for *jth* month (j=1, January; j=12, December)[a]
11	ef(10,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the produce ingestion pathway, for *jth* month (j=1, January; j=12, December)
12	ef(11,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the meat ingestion pathway, for *jth* month (j=1, January; j=12, December)
13	ef(12,j)	$m^3\ d^{-1}\ Ci^{-1}$	Exposure factors/risk coefficients for the milk ingestion pathway, for *jth* month (j=1, January; j=12, December)

[a] The aerosol pathway includes inhalation of aerosols generated at a waterfall or rapids, and inhalation of steam generated during a sweat bath

APPENDIX E
CODE VERIFICATION

APPENDIX E — CODE VERIFICATION

Code verification is defined here as confirmation that the model has been written and implemented in the computer code correctly. To do this, quantities output from the RVRDSP code (such as water concentrations) are compared with like quantities calculated using other codes or analytical expressions. This appendix contains ten benchmark problems (numbered from 2 through 12 excluding 3), which compare river water concentrations and activity in sediments with 1) output from other similar models, 2) analytical solutions for steady-state releases, 3) and hand calculations performed in the spreadsheet "benchmark.xls". Benchmark 1 and 3 were performed with an earlier version of RVRDSP and are not shown. Analytical expressions for steady-state releases are developed first followed by presentation of the benchmark problems, and results. Results are not presented in formal tables, rather, were cut and pasted from the spreadsheet "benchmark.xls". This spreadsheet was used to gather results, perform hand calculations, and calculate percent differences.

E.1 DERIVATION OF ANALYTICAL EQUATIONS FOR STEADY-STATE RELEASES

The concentration equation in RVRDSP for an instantaneous release at $t = 0$ is given by (Equation 4-2 in Chapter 4)

$$C(x,y,t) = \frac{1}{\sqrt{4\pi E_x t}DW}\exp\left[-\frac{(x-ut)^2}{4E_x t}-\lambda t\right]\left[1+2\sum_{n=1}^{\infty}\exp\left(-\frac{n^2\pi^2 E_y t}{W^2}\right)\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right] \quad \text{(E-1)}$$

where

D	=	effective river depth (m)
W	=	effective river width (m)
x	=	downstream distance from source (m)
y	=	transverse distance from near shoreline (m)
y_s	=	transverse distance of source from near shoreline (m)
$C(x,y,t)$	=	dissolved phase radionuclide concentration in the river water (Ci m^{-3})
E_x	=	longitudinal turbulent dispersion coefficient (m^2 s^{-1})
E_y	=	transverse turbulent dispersion coefficient (m^2 s^{-1})
u	=	river flow velocity (m s^{-1})
λ	=	decay rate constant (s^{-1}).

Equation E-1 differs from Equation 4-2 in Chapter 4 in that retardation is not included. Retardation will be considered later in this section. Equation E-1 gives the concentration for a unit release quantity. The concentration for a unit constant release rate can be found by integrating Equation E-1 with respect to time. Each term in the infinite series in Equation E-1 has the time dependent form of

$$\frac{1}{\sqrt{t}}\exp\left(-\left(a_n^2 t + b_n^2/t\right)\right) \quad \text{with} \quad a_n > 0,\ b_n > 0 \tag{E-2}$$

where

$$a_n^2 = \frac{u^2}{4E_x} + \lambda \qquad \text{if } n = 0 \tag{E-3}$$

$$a_n^2 = \frac{u^2}{4E_x} + \lambda + \frac{n^2\pi^2 E_y}{W^2} \qquad \text{if } n > 0$$

$$b_n^2 = \frac{x^2}{4E_x} \qquad \text{if } n \geq 0$$

Define the function, $I_n(t)$ as

$$\begin{aligned} I_n(t) &= \int_0^t \frac{1}{\sqrt{s}}\exp\left(-\left(a_n^2 s + b_n^2\, s^{-1}\right)\right)ds \\ &= \frac{\sqrt{\pi}}{2a}e^{-2ab}\left[2 - \text{erfc}\left(a\sqrt{t} - b/\sqrt{t}\right) - \exp\left(-\left(a\sqrt{t} - b/\sqrt{t}\right)^2\right)\text{dwsnc}\left(a\sqrt{t} + b/\sqrt{t}\right)\right] \end{aligned} \tag{E-4}$$

where,

$$a > 0, b > 0 \text{ and}$$

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty \exp\left(-s^2\right)ds \tag{E-5}$$

is the complementary error function and dwsnc is the complementary form of Dawson's integral defined by

$$\text{dwsnc}(x) = \exp\left(x^2\right)\text{erfc}(x) \tag{E-6}$$

Equation E-4 implies that if $t \to \infty$, then the solution reduces to

$$\lim_{t\to\infty} I_n(t) = \int_0^\infty \frac{1}{\sqrt{s}}\exp\left(-\left(a_n^2 s + b_n^2 s^{-1}\right)\right)ds\,\frac{\sqrt{\pi}}{a_n}e^{-2a_n b_n} \tag{E-7}$$

The time-dependent terms in Equation (E-1) can be rearranged into the form given in Equation E-2 as follows

$$C(x,y,t)=$$

$$\frac{1}{\sqrt{4\pi E_x t}DW}\exp\left[-\frac{\left(x^2-2xut+u^2t^2\right)}{4E_x t}-\lambda t\right]\left[1+2\sum_{n=1}^{\infty}\exp\left(-\frac{n^2\pi^2E_y t}{W^2}\right)\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right]$$

$$=\frac{1}{\sqrt{4\pi E_x t}DW}\exp\left[-\frac{x^2}{4E_x t}+\frac{2xu}{4Ex}-\frac{u^2t}{4E_x}-\lambda t\right]\left[1+2\sum_{n=1}^{\infty}\exp\left(-\frac{n^2\pi^2E_y t}{W^2}\right)\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right]$$

$$=\frac{\exp\left(xu/\left(2E_x\right)\right)}{\sqrt{4\pi E_x t}DW}\exp\left[-\left(\frac{x^2}{4E_x t}+\frac{u^2t}{4E_x}+\lambda t\right)\right]\left[1+2\sum_{n=1}^{\infty}\exp\left(-\frac{n^2\pi^2E_y t}{W^2}\right)\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right]$$

$$=\frac{\exp\left(xu/\left(2E_x\right)\right)}{\sqrt{4\pi E_x}DW}\times\frac{1}{\sqrt{t}}\times$$

$$\left(\exp\left[-\left(\frac{x^2}{4E_x t}+\frac{u^2t}{4E_x}+\lambda t\right)\right]+2\sum_{n=1}^{\infty}\exp\left(-\left(\frac{n^2\pi^2E_y t}{W^2}+\frac{u^2t}{4E_x}+\lambda t+\frac{x^2}{4E_x t}\right)\right)\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right) \tag{E-8}$$

Now substitute the definitions given in Equation E-3:

$$C(x,y,t)=\frac{\exp\left(xu/\left(2E_x\right)\right)}{\sqrt{4\pi E_x}DW}\times$$
$$\left(\frac{1}{\sqrt{t}}\exp\left[-\left(a_o^2t+b_0^2t^{-1}\right)\right]+2\sum_{n=1}^{\infty}\frac{1}{\sqrt{t}}\exp\left[-\left(a_n^2t+b_n^2t^{-1}\right)\right]\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right) \tag{E-9}$$

Substitute s for t in Equation E-9, integrate from 0 to t, and make the substitution of $I_n(t)$ from Equation E-4:

$$\int_0^t C(x,y,s)ds=\frac{\exp\left(xu/\left(2E_x\right)\right)}{\sqrt{4\pi E_x}DW}\left[I_0(t)+2\sum_{n=1}^{\infty}I_n(t)\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right] \tag{E-10}$$

Now let $t\to\infty$ and use Equation E-7

$$\int_0^{\infty} C(x,y,s)ds=\frac{\exp\left(xu/\left(2E_x\right)\right)}{\sqrt{4\pi E_x}DW}\left[\frac{\sqrt{\pi}}{a_o}e^{-2a_0b_0}+2\sum_{n=1}^{\infty}\frac{\sqrt{\pi}}{a_n}e^{-2a_nb_n}\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right]$$
$$=\frac{\exp\left(xu/\left(2E_x\right)\right)}{2\sqrt{E_x}DW}\left[\frac{1}{a_o}e^{-2a_0b_0}+2\sum_{n=1}^{\infty}\frac{1}{a_n}e^{-2a_nb_n}\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right] \tag{E-11}$$

Equation E-11 was coded into a FORTRAN program (and also a Visual Basic module in the Excel spreadsheet, "benchmark.xls") and tested with another steady-state analytical solution published by the National Council on Radiation Protection and Measurements (NCRP 1996) for

the limiting case of $y = 0$, and $y_s=0$, and the influence of the far shore is minimal. This equation is given by

$$C(x,0) = \frac{Q}{\pi D\sqrt{E_x E_y}} \exp\left[\frac{u\,x}{2\,E_x} - \frac{\lambda\,x}{U}\right] K_o\left[\frac{u\,x}{2\,E_x}\right] \quad \text{(E-12)}$$

where Q = a constant release rate (Ci s^{-1}) and K_0 is the modified Bessel function of the second kind of zero order. The other terms are as defined previously. Values for $K_0(x)$ were obtained using a routine provided in *Numerical Recipes* (Press et al., 1992). Equation E-12 is only applicable to relatively short transport distances where influence from the far shore is minimal. In the special case where complete lateral mixing has been achieved, the concentration as a function of downstream distance is given by

$$C(x) = \frac{Q}{W\,D\,u} \exp\left(-\frac{\lambda\,x}{u}\right) \quad \text{(E-13)}$$

Equation E-13 is equation 3.27 in NCRP (1996) multiplied by a decay term. The term, x/u in the exponential is simply the mean travel time to the receptor. The distance to achieve complete lateral mixing (L_y) is given by Equation 3.15 in NCRP (1996):

$$L_y = 0.18\frac{u\,W^2}{E_y}. \quad \text{(E-14)}$$

E.1.2 Retardation Effects

The governing transport equation with retardation is given by (Equation 4-1 in Chapter 4)

$$R_d\frac{\partial C}{\partial t} = E_x\frac{\partial^2 C}{\partial x^2} + E_y\frac{\partial^2 C}{\partial y^2} - u\frac{\partial C}{\partial x} - R_d\lambda C \quad \text{(E-15)}$$

where

R_d = the retardation factor (unitless).

Assuming a spatially and temporally constant value of R_d and initial and boundary conditions of

- $C = 0$, at $t = 0$ for all values of x and y.
- $\partial C/\partial y = 0$, at $y = 0$, $y = W$ (width of river channel)

for a uniform and steady velocity and constant channel width, the solution to Equation E-15 for the dissolved phase concentration in river water is (Equation 4-2 in Chapter 4):

$$C(x,y,t)=\frac{1}{\sqrt{4\pi E_x t/R_d}\,DW\,R_d}\exp\left[-\frac{(x-ut/R_d)^2}{4E_x t/R_d}-\lambda t\right]$$
$$\left[1+2\sum_{n=1}^{\infty}\exp\left(-\frac{n^2\pi^2 E_y t/R_d}{W^2}\right)\cos\left(n\pi\frac{ys}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right] \quad \text{(E-16)}$$

Integration from t = 0 to infinity is performed as illustrated in Equations E-4 through E-11, with the definitions of a and b as shown below.

$$a_n^2=\frac{(u/R_d)^2}{4E_x/R_d}+\lambda \quad =\frac{1}{R_d}\left(\frac{u^2}{4E_x}+\lambda R_d\right) \qquad \text{if } n=0 \quad \text{(E-17)}$$

$$a_n^2=\frac{(u/R_d)^2}{4E_x/R_d}+\lambda+\frac{n^2\pi^2 E_y/R_d}{W^2}=\frac{1}{R_d}\left(\frac{u^2}{4E_x}+\lambda R_d+\frac{n^2\pi^2 E_y}{W^2}\right) \qquad \text{if } n>0$$

$$b_n^2=\frac{x^2}{4\,E_x/R_d}=R_d\left(\frac{x^2}{4E_x}\right) \qquad \text{if } n\geq 0$$

The R_d cancels out of the term, $(x\ u)/(2E_x)$. The final integrated equation (for t$\rightarrow\infty$) with retardation is given by

$$\int_0^{\infty}C(x,y,s)\,ds=$$
$$\frac{\exp(xu/(2E_x))}{2R_d\sqrt{E_x/R_d}\,DW}\left[\frac{e^{-2a_0b_0}}{\sqrt{\frac{1}{R_d}}\sqrt{\frac{u^2}{4E_x}+\lambda R_d}}+2\sum_{n=1}^{\infty}\frac{e^{-2a_nb_n}}{\sqrt{\frac{1}{R_d}}\sqrt{\frac{u^2}{4E_x}+\lambda R_d+\frac{n^2\pi E_x}{W^2}}}\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right]$$
$$=\frac{\exp(xu/(2E_x))}{2\sqrt{E_x}\,DW}\left[\frac{e^{-2a_0b_0}}{\sqrt{\frac{u^2}{4E_x}+\lambda R_d}}+2\sum_{n=1}^{\infty}\frac{e^{-2a_nb_n}}{\sqrt{\frac{u^2}{4E_x}+\lambda R_d+\frac{n^2\pi E_x}{W^2}}}\cos\left(n\pi\frac{y_s}{W}\right)\cos\left(n\pi\frac{y}{W}\right)\right] \quad \text{(E-18)}$$

Note that the R_d factored out of a and b in Equation E-17 cancels out in their product leaving only the term, λR_d in a_o and a_n. Therefore, when the value of λ is insignificant relative to $u^2/4E_x$ and $n^2\pi E_x/W^2$, then retardation has negligible effect on the steady-state concentration.

The number of terms computed in the infinite series is not limited and the series is truncated when

$$abs(\beta_{n-1}-\beta_n)\leq \varepsilon\,\beta_n \quad \text{(E-19)}$$

where β_n = the value of the series for n terms, β_{n-1} = the value of the series for n–1 terms, and ε = a convergence criteria value hardwired into the code at 1×10^{-16}.

Comparisons were made between concentrations calculated from Equations E-12, E-13, and E-18 and version 1.1 of RVRDSP dated 07/29/02. The results of the benchmark comparisons are expressed as the percent difference (%d) as given by

$$\%d = \frac{C_a - C_r}{C_a} \times 100 \qquad \text{(E-20)}$$

where C_a = the concentration calculated by analytical solutions or other codes, and C_r = the concentration calculated by RVRDSP. Results are cut and pasted directly from the Excel spreadsheet, “benchmark.xls”. Unless otherwise noted, the retardation factor is always 1.0.

E.2 BENCHMARK PROBLEM RESULTS

Benchmark 2: Sample Problem Described on Page 2.56 and Figure 2.17 of Codell et al. (1982)

Input Data

Data from CODELL's sample problem					Convert to RVRDSP units	
Release Rates					Release Rates	
Time (s)	Rel (Ci/s)				Time (d)	Rel (Ci/d)
0	0.8				0	69120
1.1	1.1				1.27315E-05	95040
1.9	5.5				2.19907E-05	475200
3	6.4				3.47222E-05	552960
7.1	3.1				8.21759E-05	267840
13	1.1				1.50463E-04	95040
14	0				1.62037E-04	0
11	1.77796	(cutoff time)			1.27315E-04	153615.7
Depth (ft)	25				Depth (m)	7.620
Width (ft)	500				Width (m)	152.400
U (ft/s)	1				F (m**3/s)	353.9606
T1/2 (s)	5.00E+03				T1/2 (d)	0.057870
Ex (ft2/s)	11.5				Ex (m2/s)	1.068385
Ey (ft2/s)	0.45				Ey (m2/s)	0.041806
Lambda (1/s)	1.39E-04					
X dist (ft)	7000	C (Ci/ft**3)			X dist (m)	2133.600
t (s)	5000	2.76E-13			t (d)	0.05787
t (s)	7000	5.93E-06			t (d)	0.081019
t (s)	10000	9.23E-15			t (d)	0.115741
t (s)	12000	3.99E-26			t (d)	0.138889

Release File, Benchmark 2

```
Benchmark of Codell's Sample Problem NUREG 0868
0     69120
1.27315E-05 95040
2.19907E-05 475200
3.47222E-05 552960
8.21759E-05 267840
1.27315E-04 153615.744
```

Flow Rate File, Benchmark 2

```
Time  flow rate (m**3/s)
0.0     353.9605824    152.4 7.62
1.0e10  353.9605824    152.4 7.62
```

Results

	file=bnchmrk2.out	
	(Version date 072901)	
RIVLAK	RVRDSP	% Difference
(Ci/m**3)	(Ci/m**3)	
9.757E-12	9.788E-12	-0.308%
2.095E-04	2.101E-04	-0.283%
3.260E-13	3.269E-13	-0.259%
1.409E-24	1.413E-24	-0.270%

Comments

The RIVLAK code contains errors in the linear interpolation routine that return a value of zero for the initial release at time = 0. Therefore, it is not surprising that concentrations calculated with RVRDSP are greater than those calculated by RIVLAK.

Benchmark 4: Sample Problem Simulating a 39.217 Ci Instantaneous Release

Input Data

Parameter		Units
ex=0.8		m2/s
ey=0.2		m2/s
u=0.05		m/s
w=300		m
d=3		m
q=39.217		Ci
x=70000		m
y=0		m
ys=0		m
lambda=5.625e-7		1/s

Release File for Benchmark 4

```
Benchmark of Analytical solution in KERNAL.EXE for a 39.217 Ci release
0           392170
1.0E-04     392170
```

Results

			file=bnchmrk4	
Time (s)	Time (d)	Analytical (Ci/m**3)	RVRDSP (Ver date 072902) (Ci/m**3)	% Difference Ver 072902
1209600	14	4.291E-16	4.290E-16	0.011%
1296000	15	8.581E-09	8.581E-09	0.006%
1382400	16	4.508E-06	4.509E-06	0.000%
1468800	17	4.003E-07	4.003E-07	-0.003%
1555200	18	2.554E-11	2.555E-11	-0.006%
1641600	19	3.674E-18	3.675E-18	-0.010%
1728000	20	2.972E-27	2.973E-27	-0.012%

Comments

This benchmark problem is "made up" and was used to test the numerical integration portion of the code by simulating an instantaneous release by using a constant release over a relatively short period of time. The analytical solution for an instantaneous release represented by Equation E-2 was coded in the FORTRAN code, KERNEL.EXE. Version 1.1 (07/29/02) of RVRDSP produces results that are within ±0.012% of the analytical solution.

Benchmark 5: Comparison with NCRP Equation 3.27 for the Case of Complete Lateral Mixing

Input Data

Parameter	Value	Units
Thalf	86400	s
u	1	m/s
D	3	m
W	30	m
Ex	30	m^2/s
Ey	10	m^2/s
lambda	8.02254E-06	1/s
Flow Rate	90	m^3/s
Q	1.15741E-05	Ci/s
Ly	16.2	m

Release Rate File (Note: This release rate file is used for Benchmark 5–12)

```
Benchmark of Analytical solution for constant unit release (d and Ci/d)
0          1.0
5.0E-02    1.0
1e10       1.0
```

Flow Rate File (Note: This flow rate file is used for Benchmark 5–8)

```
Time (d) flow rate (m**3/s) width depth
0.0     90.00     30.0   3.00
1.0e10  90.00     30.0   3.00
```

Results

x (m)	NCRP Eq 3.27 Modified with decay term (Ci/m**3)	RVRDSP (Version 072902) (Ci/m**3)	NCRP and RVRDSP 072902	Equation E-18 Analytical Solution (Ci/m**3)	% Difference Eq E-18 and RVRDSP 072902
200	1.284E-07	1.283E-07	0.050%	1.283E-07	0.008%
300	1.283E-07	1.282E-07	0.048%	1.282E-07	0.000%
400	1.282E-07	1.281E-07	0.046%	1.281E-07	0.000%
500	1.281E-07	1.280E-07	0.052%	1.280E-07	0.000%
600	1.280E-07	1.279E-07	0.049%	1.279E-07	0.000%
700	1.279E-07	1.278E-07	0.047%	1.278E-07	0.000%
800	1.278E-07	1.277E-07	0.045%	1.277E-07	0.000%
900	1.277E-07	1.276E-07	0.051%	1.276E-07	0.000%
1000	1.276E-07	1.275E-07	0.050%	1.275E-07	0.000%
2000	1.266E-07	1.265E-07	0.050%	1.265E-07	0.000%
4000	1.245E-07	1.245E-07	0.048%	1.245E-07	0.000%
6000	1.226E-07	1.225E-07	0.047%	1.225E-07	0.000%
8000	1.206E-07	1.206E-07	0.047%	1.206E-07	0.000%
10000	1.187E-07	1.186E-07	0.048%	1.186E-07	0.000%

Comments

For the parameters used in this problem, there was no significant difference between the results from RVRDSP Version 1.1. Differences between the NCRP analytical solution and RVRDSP were generally less than 0.05%. The same difference was noted between the analytically integrated solution (Equation E-18) and the NCRP Equations.

Benchmark 6: Comparison with NCRP Equation 3.24 and Analytical Solution for the Case of Incomplete Lateral Mixing

Input Data

Parameter	Value	Units
Thalf	86400	s
u	1	m/s
D	3	m
W	300	m
Ex	50	m^2/s
Ey	0.1	m^2/s
lambda	8.02254E-06	1/s
Flow Rate	900	m^3/s
Q	1.15741E-05	Ci/s
y	0	m
ys	0	m
Ly	162000	m

Results

x (m)	NCRP Eq 3.24 (Ci/m**3)	RVRDSP (Version date 072902) (Ci/m**3)	% Difference from NCRP	Equation E-18 Analytical Solution (Ci/m**3)	% Difference from E-18	travel time (d)
50	8.371E-07	8.364E-07	0.082%	8.364E-07	0.000%	5.7870E-04
100	6.284E-07	6.278E-07	0.085%	6.278E-07	0.000%	1.1574E-03
200	4.617E-07	4.613E-07	0.087%	4.613E-07	0.000%	2.3148E-03
300	3.825E-07	3.822E-07	0.087%	3.822E-07	0.000%	3.4722E-03
400	3.337E-07	3.334E-07	0.088%	3.334E-07	0.000%	4.6296E-03
500	2.998E-07	2.995E-07	0.088%	2.995E-07	0.000%	5.7870E-03
600	2.744E-07	2.742E-07	0.091%	2.742E-07	0.000%	6.9444E-03
700	2.545E-07	2.543E-07	0.090%	2.543E-07	0.000%	8.1019E-03
800	2.384E-07	2.382E-07	0.088%	2.382E-07	0.000%	9.2593E-03
900	2.249E-07	2.247E-07	0.088%	2.247E-07	0.000%	1.0417E-02
1000	2.135E-07	2.133E-07	0.091%	2.133E-07	0.000%	1.1574E-02
2000	1.506E-07	1.505E-07	0.092%	1.505E-07	0.000%	2.3148E-02
3000	1.222E-07	1.221E-07	0.091%	1.221E-07	0.000%	3.4722E-02
4000	1.051E-07	1.050E-07	0.090%	1.050E-07	0.000%	4.6296E-02
5000	9.333E-08	9.325E-08	0.090%	9.325E-08	0.000%	5.7870E-02
6000	8.455E-08	8.448E-08	0.089%	8.448E-08	0.000%	6.9444E-02
7000	7.768E-08	7.761E-08	0.090%	7.761E-08	0.000%	8.1019E-02
8000	7.210E-08	7.203E-08	0.089%	7.203E-08	0.000%	9.2593E-02
9000	6.744E-08	6.738E-08	0.089%	6.738E-08	0.000%	1.0417E-01
10000	6.348E-08	6.342E-08	0.090%	6.342E-08	0.000%	1.1574E-01

Comments

This benchmark problem tests the code for incomplete lateral mixing. Version date 072902 of RVRDSP produces values that are within 0.09% of the NCRP Equation 3.24 solution and within 0.000% of Equation E-18. Downstream travel time estimates are also reported.

Benchmark 7: Comparison with Analytical Solution for Incomplete Lateral Mixing and Source to Receptor Distance of 20.921 km

Input Data

Parameter	Value	Units
Thalf	86400	s
u	1	m/s
D	3	m
W	300	m
Ex	50	m^2/s
Ey	0.1	m^2/s
lambda	8.02254E-06	1/s
Flow Rate	900	m^3/s

Q	1.15741E-05	Ci/s
Ys	0	m

Results

x (m)	y - measured from near shore(m)	RVRDSP (Version date 072902) (Ci/m**3)	Equation E-18 Analytical Solution (Ci/m**3)	% difference E-18	y distance measured from far shore (m)	RVRDSP (Version date 072902) using distance from far shore (Ci/m**3)
20921	0	4.020E-08	4.020E-08	0.000%	300	4.020E-08
20921	20	3.832E-08	3.832E-08	0.000%	280	3.832E-08
20921	40	3.319E-08	3.319E-08	0.000%	260	3.319E-08
20921	60	2.612E-08	2.612E-08	0.000%	240	2.612E-08
20921	80	1.869E-08	1.869E-08	0.000%	220	1.869E-08
20921	100	1.216E-08	1.216E-08	0.000%	200	1.216E-08
20921	120	7.204E-09	7.204E-09	0.000%	180	7.204E-09
20921	140	3.886E-09	3.886E-09	0.000%	160	3.886E-09
20921	160	1.910E-09	1.910E-09	0.000%	140	1.910E-09
20921	180	8.565E-10	8.565E-10	0.000%	120	8.565E-10
20921	200	3.508E-10	3.508E-10	0.000%	100	3.508E-10
20921	220	1.313E-10	1.313E-10	0.000%	80	1.313E-10
20921	240	4.502E-11	4.502E-11	0.000%	60	4.502E-11
20921	260	1.420E-11	1.420E-11	0.000%	40	1.420E-11
20921	280	4.339E-12	4.339E-12	0.000%	20	4.339E-12
20921	299	2.165E-12	2.165E-12	0.000%	1	2.165E-12

Comments

Concentrations across the plume are within 0.000% of the analytical solution. Concentrations derived from the transverse distance as measured from the far shore were also computed and are identical to those computed for the transverse distance measured from the near shore.

Benchmark 8: Comparison with Analytical Solution for Incomplete Lateral Mixing and Source to Receptor Distance of 38.624 km

Input Data

Parameter	Value	Units
Thalf	86400	s
u	1	m/s
D	3	m
W	300	m
Ex	50	m^2/s
Ey	0.4	m^2/s
lambda	8.02254E-06	1/s
Flow Rate	900	m^3/s
Q	1.16E-05	Ci/s

Ys	0	m

Results

x (m)	y (m)	RVRDSP (Version date 072902) (Ci/m**3)	Equation E-18 Analytical Solution (Ci/m**3)	% difference E-18
38624	0	1.292E-08	1.292E-08	0.000%
38624	20	1.284E-08	1.284E-08	0.000%
38624	40	1.261E-08	1.261E-08	0.000%
38624	60	1.224E-08	1.224E-08	0.000%
38624	80	1.174E-08	1.174E-08	0.000%
38624	100	1.115E-08	1.115E-08	0.000%
38624	120	1.048E-08	1.048E-08	0.000%
38624	140	9.767E-09	9.768E-09	0.001%
38624	160	9.043E-09	9.043E-09	0.000%
38624	180	8.338E-09	8.338E-09	0.001%
38624	200	7.683E-09	7.683E-09	0.000%
38624	220	7.105E-09	7.105E-09	0.000%
38624	240	6.630E-09	6.630E-09	0.000%
38624	260	6.275E-09	6.275E-09	0.000%
38624	280	6.057E-09	6.057E-09	0.000%
38624	299	5.983E-09	5.983E-09	0.000%

Comments

Version 1.1 of RVRDSP produces results that are within 0.001% of the analytical solution.

Benchmark 9: Comparison with Analytical Solution for Incomplete Lateral Mixing and Source to Receptor Distance of 64.764 km and Verification of u, E_x, and E_y

Input Data

Parameter	Value	Units	RVRDSP
Thalf	86400	s	
u	1.3734E+00	m/s	1.3734E+00
D	7.34	m	
W	496	m	
Ex	5.1329E+03	m^2/s	5.1329E+03
Ey	5.9666E-01	m^2/s	5.9666E-01
lambda	8.02254E-06	1/s	
Flow Rate	5000	m^3/s	
Q	1.15741E-05	Ci/s	
Ys	0	m	
u*	1.3548E-01		
slope	2.5500E-04		

Flow Rate File (Note: This file is used in Benchmarks 9–12)

```
Time (d) flow rate (m**3/s)
0.0    5000.00     496.0   7.34
1.0e10 5000.00     496.0   7.34
```

Results

x (m)	y (m)	RVRDSP (Version date 072902) (Ci/m**3)	Equation E-18 Analytical Solution (Ci/m**3)	% difference E-18
62764	0	2.651E-09	2.651E-09	0.000%
62764	20	2.641E-09	2.641E-09	0.000%
62764	40	2.610E-09	2.610E-09	0.000%
62764	60	2.558E-09	2.558E-09	0.000%
62764	80	2.488E-09	2.488E-09	0.000%
62764	100	2.402E-09	2.402E-09	0.000%
62764	120	2.301E-09	2.301E-09	0.000%
62764	140	2.187E-09	2.187E-09	0.000%
62764	160	2.065E-09	2.065E-09	0.000%
62764	180	1.936E-09	1.936E-09	0.000%
62764	200	1.803E-09	1.803E-09	0.000%
62764	220	1.669E-09	1.669E-09	0.000%
62764	240	1.536E-09	1.536E-09	0.000%
62764	260	1.406E-09	1.406E-09	0.000%
62764	280	1.282E-09	1.282E-09	0.000%
62764	299	1.171E-09	1.171E-09	0.000%

Comments

This benchmark problem uses values that are representative of conditions in the Columbia River. The computation of u, E_x, and E_y are checked with hand calculations. Differences between the RVRDSP and the analytical solution are ≤0.000%.

Benchmark 10 and 11: Comparison with Analytical Solution for Incomplete Lateral Mixing and Verification of other Model Output for a 62.764 m Receptor with Retardation

Input Data

Parameter	Value	Units	RVRDSP
Thalf	0.08333	d	
u	1.3734E+00	m/s	1.3734E+00
D	7.34	m	
W	496	m	
Ex	5.1329E+03	m^2/s	5.1329E+03
Ey	5.9666E-01	m^2/s	5.9666E-01

lambda	9.6274E-05	1/s	9.6270E-05
Flow Rate	5000	m^3/s	
Q	1.15741E-05	Ci/s	
Ys	0	m	
u*	1.3548E-01	m/s	
slope	2.5500E-04		
Tb	1.0000E-03	m	
Sc	1.0000E+01	g/m**3	
Kd	1.0000E-03	m**3/g	
rho	1.2000E+06	g/m**3	
Rd	1.1635E+00	unitless	1.1635E+00
yshore	2.0000E+02	m	
ytemp	4.8000E+01		
vd	0.07	m/d	

Benchmark 10 Results

x (m)	y (m)	C in RVRDSP (Version date 072902) (Ci/m**3)	Equation E-18 Analytical Solution (Ci/m**3)	% difference E-18	Ca in RVRDSP (Version date 072902) (Ci/m**3)	Ca calculated (Ci/m**3)	% difference
62764	0	5.212E-11	5.212E-11	0.000%	5.161E-11	5.1607E-11	0.000%
62764	20	5.183E-11	5.183E-11	0.001%	5.132E-11	5.1315E-11	0.000%
62764	48	5.045E-11	5.045E-11	-0.001%	4.995E-11	4.9950E-11	0.000%
62764	60	4.953E-11	4.953E-11	0.000%	4.904E-11	4.9044E-11	-0.001%
62764	80	4.762E-11	4.762E-11	0.000%	4.715E-11	4.7145E-11	0.001%
62764	100	4.527E-11	4.527E-11	0.000%	4.482E-11	4.4821E-11	0.000%
62764	120	4.257E-11	4.257E-11	0.000%	4.215E-11	4.2147E-11	0.001%
62764	140	3.960E-11	3.960E-11	0.000%	3.921E-11	3.9209E-11	0.000%
62764	160	3.645E-11	3.645E-11	0.000%	3.609E-11	3.6092E-11	0.000%
62764	180	3.321E-11	3.321E-11	0.000%	3.288E-11	3.2882E-11	0.000%
62764	200	2.996E-11	2.996E-11	0.001%	2.966E-11	2.9659E-11	-0.001%
62764	220	2.676E-11	2.676E-11	0.001%	2.649E-11	2.6493E-11	0.002%
62764	240	2.368E-11	2.368E-11	-0.002%	2.345E-11	2.3447E-11	0.000%
62764	260	2.078E-11	2.078E-11	0.000%	2.057E-11	2.0569E-11	0.002%
62764	280	1.808E-11	1.808E-11	0.002%	1.790E-11	1.7898E-11	0.002%
62764	299	1.573E-11	1.573E-11	0.002%	1.558E-11	1.5577E-11	-0.003%

Benchmark 10 Results (continued)

Ct in RVRDSP (Version date 072902) (Ci/m**3)	Ct calculated (Ci/m**3)	% difference	Cs in RVRDSP (Version date 072902) (Ci/g)	Cs calculated (Ci/g)	% difference
6.065E-11	6.064E-11	-0.001%	5.16E-14	5.1607E-14	0.000%
6.030E-11	6.030E-11	-0.001%	5.13E-14	5.1315E-14	0.000%
5.870E-11	5.870E-11	-0.001%	5.00E-14	4.9950E-14	0.001%
5.763E-11	5.763E-11	0.001%	4.90E-14	4.9044E-14	-0.001%
5.540E-11	5.540E-11	-0.001%	4.71E-14	4.7146E-14	0.001%
5.267E-11	5.267E-11	0.000%	4.48E-14	4.4821E-14	0.000%
4.953E-11	4.953E-11	0.001%	4.21E-14	4.2148E-14	0.001%
4.608E-11	4.608E-11	0.000%	3.92E-14	3.9209E-14	0.000%
4.241E-11	4.241E-11	-0.001%	3.61E-14	3.6092E-14	0.000%
3.864E-11	3.864E-11	-0.001%	3.29E-14	3.2882E-14	0.001%
3.485E-11	3.485E-11	-0.001%	2.97E-14	2.9658E-14	-0.002%
3.113E-11	3.113E-11	0.000%	2.65E-14	2.6493E-14	0.000%
2.755E-11	2.755E-11	0.001%	2.34E-14	2.3448E-14	0.002%
2.417E-11	2.417E-11	-0.002%	2.06E-14	2.0569E-14	0.001%
2.103E-11	2.103E-11	-0.001%	1.79E-14	1.7898E-14	0.000%
1.830E-11	1.830E-11	0.002%	1.56E-14	1.5576E-14	-0.005%

Benchmark 11 Results

t (d)	Msed in RVRDSP (Ver 072902) (g/m**2)	Msed (hand calculation) (g/m**2)	% difference	Qsed in RVRDSP (Ver date 072902) (Ci/m**2)	Analytical Solution (Ci/m**2)	% difference
1	7.000E-01	7.0000E-01	0.000%	4.200E-15	4.2025E-15	0.059%
11	7.700E+00	7.7000E+00	0.000%	4.204E-15	4.2035E-15	0.000%
21	1.470E+01	1.4700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
31	2.170E+01	2.1700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
41	2.870E+01	2.8700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
51	3.570E+01	3.5700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
61	4.270E+01	4.2700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
71	4.970E+01	4.9700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
81	5.670E+01	5.6700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
91	6.370E+01	6.3700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
101	7.070E+01	7.0700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
111	7.770E+01	7.7700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
121	8.470E+01	8.4700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
131	9.170E+01	9.1700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
141	9.870E+01	9.8700E+01	0.000%	4.204E-15	4.2035E-15	0.000%
151	1.057E+02	1.0570E+02	0.000%	4.204E-15	4.2035E-15	0.000%
161	1.127E+02	1.1270E+02	0.000%	4.204E-15	4.2035E-15	0.000%

171	1.197E+02	1.1970E+02	0.000%	4.204E-15	4.2035E-15	0.000%
181	1.267E+02	1.2670E+02	0.000%	4.204E-15	4.2035E-15	0.000%
191	1.337E+02	1.3370E+02	0.000%	4.204E-15	4.2035E-15	0.000%
201	1.407E+02	1.4070E+02	0.000%	4.204E-15	4.2035E-15	0.000%
211	1.477E+02	1.4770E+02	0.000%	4.204E-15	4.2035E-15	0.000%
221	1.547E+02	1.5470E+02	0.000%	4.204E-15	4.2035E-15	0.000%
231	1.617E+02	1.6170E+02	0.000%	4.204E-15	4.2035E-15	0.000%
241	1.687E+02	1.6870E+02	0.000%	4.204E-15	4.2035E-15	0.000%
251	1.757E+02	1.7570E+02	0.000%	4.204E-15	4.2035E-15	0.000%
261	1.827E+02	1.8270E+02	0.000%	4.204E-15	4.2035E-15	0.000%
271	1.897E+02	1.8970E+02	0.000%	4.204E-15	4.2035E-15	0.000%
281	1.967E+02	1.9670E+02	0.000%	4.204E-15	4.2035E-15	0.000%
291	2.037E+02	2.0370E+02	0.000%	4.204E-15	4.2035E-15	0.000%

Comments

Minor differences between RVRDSP and the analytical solution (Equation E-18) exist but results are typically within ±0.001%. The analytical solution computations reported here and in Benchmark 12 were computed in the Visual Basic Module (function ssr) in the "benchmark.xls" spreadsheet. There is virtually no difference between the hand-calculated Cs, Msed, and Qsed values and those calculated in RVRDSP.

Benchmark 12: Comparison with Analytical Solution for Incomplete Lateral Mixing and Verification of Other Model Output for a 100 m Receptor with Retardation

Input Data

Parameter	Value	Units	RVRDSP
Thalf	0.08333	d	
u	1.3734E+00	m/s	1.3734E+00
D	7.34	m	
W	496	m	
Ex	5.1329E+03	m^2/s	5.1329E+03
Ey	5.9666E-01	m^2/s	5.9666E-01
lambda	9.6274E-05	1/s	9.6270E-05
Flow Rate	5000	m^3/s	
Q	1.15741E-05	Ci/s	
Ys	0	m	
u*	1.3548E-01		
slope	2.5500E-04		
Tb	1.0000E-03	m	
Sc	1.0000E+01	g/m**3	
Kd	1.0000E-03	m**3/g	
rho	1.2000E+06	g/m**3	
Rd	1.1635E+00	unitless	1.1635E+00

ys	2.0000E+02	m	
ytemp	4.8000E+01		
vd	0.07	m/d	

Results

x (m)	y (m)	C in RVRDSP (Version date 072902) (Ci/m**3)	Equation E-18 Analytical Solution (Ci/m**3)	% difference E-18	Ca in RVRDSP (Version date 072902) (Ci/m**3)	Ca calculated (Ci/m**3)	% difference
100	0	3.706E-08	3.706E-08	0.006%	3.669E-08	3.669E-08	0.006%
100	20	1.087E-08	1.087E-08	0.003%	1.076E-08	1.076E-08	-0.003%
100	48	4.557E-09	4.557E-09	-0.006%	4.512E-09	4.512E-09	-0.004%
100	60	3.317E-09	3.317E-09	0.001%	3.285E-09	3.284E-09	0.000%
100	80	2.020E-09	2.020E-09	-0.003%	2.000E-09	2.000E-09	-0.003%
100	100	1.262E-09	1.262E-09	-0.002%	1.250E-09	1.250E-09	-0.002%
100	120	8.026E-10	8.026E-10	0.003%	7.946E-10	7.947E-10	0.002%
100	140	5.165E-10	5.165E-10	0.002%	5.114E-10	5.114E-10	0.002%
100	160	3.353E-10	3.353E-10	-0.002%	3.320E-10	3.320E-10	-0.002%
100	180	2.193E-10	2.192E-10	-0.004%	2.171E-10	2.171E-10	-0.005%
100	200	1.442E-10	1.441E-10	-0.005%	1.427E-10	1.427E-10	-0.003%
100	220	9.520E-11	9.521E-11	0.004%	9.426E-11	9.426E-11	0.005%
100	240	6.311E-11	6.312E-11	0.011%	6.249E-11	6.249E-11	0.011%
100	260	4.197E-11	4.197E-11	0.001%	4.156E-11	4.156E-11	0.000%
100	280	2.799E-11	2.799E-11	-0.021%	2.772E-11	2.771E-11	-0.022%
100	299	1.910E-11	1.909E-11	-0.023%	1.891E-11	1.890E-11	-0.023%

Results (continued)

Ct in RVRDSP (Version date 072902) (Ci/m**3)	Ct calculated (Ci/m**3)	% difference	Cs in RVRDSP (Version date 072902) (Ci/g)	Cs calculated (Ci/g)	% difference
4.312E-08	4.312E-08	0.007%	3.669E-11	3.669E-11	0.000%
1.265E-08	1.265E-08	0.004%	1.076E-11	1.076E-11	-0.006%
5.302E-09	5.302E-09	-0.004%	4.512E-12	4.512E-12	0.002%
3.860E-09	3.860E-09	0.000%	3.285E-12	3.284E-12	-0.001%
2.350E-09	2.350E-09	-0.002%	2.000E-12	2.000E-12	0.000%
1.469E-09	1.469E-09	-0.003%	1.250E-12	1.250E-12	0.000%
9.338E-10	9.338E-10	0.003%	7.946E-13	7.946E-13	-0.001%
6.009E-10	6.009E-10	0.002%	5.114E-13	5.113E-13	-0.001%
3.902E-10	3.902E-10	-0.001%	3.320E-13	3.320E-13	0.000%
2.551E-10	2.551E-10	-0.002%	2.171E-13	2.171E-13	0.000%
1.677E-10	1.677E-10	-0.001%	1.427E-13	1.427E-13	0.002%
1.108E-10	1.108E-10	0.009%	9.426E-14	9.426E-14	0.000%
7.343E-11	7.344E-11	0.011%	6.249E-14	6.249E-14	0.000%

4.884E-11	4.884E-11	0.002%	4.156E-14	4.156E-14	-0.001%
3.257E-11	3.256E-11	-0.019%	2.772E-14	2.772E-14	-0.001%
2.222E-11	2.221E-11	-0.023%	1.891E-14	1.891E-14	0.000%

Comments

Minor differences between RVRDSP and the analytical solution (Equation E-18) exist at the 100m distance, but the differences are no greater than 0.023%. Some difference could be expected at this distance, because the RVRDSP code uses an alternate expression for the cross-channel mixing term.

Verification of Risk Calculation

This benchmark problem compares the carcinogenic risk output from RVRDSP with those calculated in the "Risk Calculation" worksheet in the spreadsheet, "benchmark.xls". Risks are calculated with RVRDSP Version 1.1 dated 072902 and risk factors from the draft report for Zn-65 at the 300 Area. The actual values of risks do not reflect the most recent changes to the exposure methodology, but are only intended to provide a check on the calculations. Daily concentrations are output, pasted in the spreadsheet, and multiplied by the appropriate exposure factor for each of the 13 pathways of exposure to yield the risk for that day. These calculations also provide a check of the Perl script, "getrc.pl". This script takes the exposure factors calculated in the spreadsheets for each scenario, converts the units from L Bq^{-1} d^{-1} to m^3 Ci^{-1} d^{-1} (or from m^2 Bq^{-1} d^{-1} to m^2 Ci^{-1} d^{-1} for sediment pathways), and writes separate exposure factor files for each nuclide. The cumulative risk beginning in 1944 and ending June 30, 1946 for each of the 13 pathways are output on a daily basis. Each daily value is not reproduced in this appendix because of the large number of values (912), but is listed electronically in the spreadsheet. The total risk by pathway is presented in the table below for the end of the simulation (June 30, 1944). The risk factors presented in the tables below are for the month of June. Note that for the waterfowl pathway, the exposure factor is zero indicating no ingestion for that month.

Comparison of Risks Calculated in the Excel Spreadsheet "benchmark.xls" and those Calculated in RVRDSP Version 1.1 Dated 072902

Pathway 1: Drinking Water			Pathway 2: Fish Ingestion			Pathway 3: Swimming Immersion		
Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP
6.62E-10	2.7E-06	2.7E-06	3.52E-08	1.1E-04	1.1E-04	2.10E-11	1.6E-08	1.6E-08

Pathway 4: Swimming Ingestion			Pathway 5: Waterfowl Ingestion			Pathway 6: Sediment External		
Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (m**2/d-Bq)	Excel Calculated	RVRDSP
2.21E-11	1.7E-08	1.7E-08	0.00E+00	8.5E-06	8.5E-06	9.44E-13	1.8E-07	1.8E-07

Pathway 7: Sediment Dermal			Pathway 8: Sediment Ingestion			Pathway 9: Aerosol inhalation		
Risk Factor (m**2/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (m**2/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP
2.75E-13	2.9E-08	2.9E-08	6.92E-15	7.3E-10	7.3E-10	1.00E-11	4.3E-08	4.3E-08

Pathway 10: Boating			Pathway 11: Produce			Pathway 12: Meat		
Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP	Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP
1.50E-11	6.4E-08	6.4E-08	1.28E-09	5.5E-06	5.5E-06	1.45E-09	6.2E-06	6.2E-06

Pathway 13: Milk			Total	
Risk Factor (L/d-Bq)	Excel Calculated	RVRDSP	Excel Calculated	RVRDSP
4.20E-10	1.8E-06	1.8E-06	1.4E-04	1.4E-04

E.3 REFERENCES

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APPENDIX F
RADIONUCLIDE AND PATHWAY-SPECIFIC SCREENING RISKS AND RIVER WATER CONCENTRATIONS

APPENDIX F — RADIONUCLIDE AND PATHWAY-SPECIFIC SCREENING RISKS AND RIVER WATER CONCENTRATIONS

This appendix contains the radionuclide and pathway-specific screening risks for the initial screening calculations at the Ringold and Richland locations (Tables F-1, F-2), and screening risks for the three exposure scenarios (Tables F-3 through F-8) at Pasco and Richland. Tables F-9 and 10 contain monthly-average aqueous-phase radionuclide river water concentrations at Richland. The risks are expressed in terms of the incremental lifetime cancer incidence risk for exposure from 1945 to 1972. There are two receptor locations for each exposure scenario. Nuclides are listed in rows, and pathways of exposure in columns. The exposure pathways are (in order of appearance):

- Direct ingestion of contaminated river water (Direct Ing)
- Ingestion of contaminated fish (Fish Ing)
- Immersion in contaminated river water (Swim-Imm)
- Ingestion of contaminated river water during swimming (Swim-Ing)
- Ingestion of contaminated waterfowl (Waterfowl)
- External exposure to contaminated sediments (Sed-Ext)
- Exposure to contaminated sediments through dermal contact (Sed-Dermal)
- Ingestion of contaminated sediments (Sed-Ing)
- Inhalation of contaminated aerosols (Aerosol)
- External exposure while boating (Boating)
- Ingestion of produce irrigated with contaminated river water (Produce-Ing)
- Ingestion of meat from cattle drinking contaminated river water and consuming feed that was irrigated with contaminated river water (Meat-Ing)
- Ingestion of milk from cows drinking contaminated river water and consuming feed that was irrigated with contaminated river water (Milk-Ing)

Table F-1. Screening Risk Values for the Initial Screening at Ringold

Nuclide	Direct-Ing	Fish-Ing	Swim-Imm	Swim-Ing	Waterfowl	Sed-Ext	Sed-Dermal	Sed-Ing	Aerosol	Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total	% of Total
^{24}Na	3.60E-05	6.20E-05	2.00E-05	3.40E-07	0.00E+00	1.30E-07	0.00E+00	8.40E-12	1.40E-06	5.00E-05	6.70E-07	3.00E-05	2.60E-06	2.03E-04	0.87%
^{32}P	1.30E-05	1.80E-03	7.40E-10	8.60E-08	5.60E-04	1.50E-10	6.30E-08	2.10E-11	6.70E-07	2.60E-09	1.70E-08	1.10E-05	1.20E-05	2.40E-03	10.31%
^{45}Ca	1.70E-07	9.90E-06	1.10E-12	1.20E-09	0.00E+00	3.00E-13	3.20E-08	5.00E-12	2.50E-08	4.00E-12	1.90E-11	8.10E-09	3.20E-07	1.05E-05	0.04%
^{46}Sc	4.60E-06	1.20E-04	2.00E-07	3.90E-08	0.00E+00	2.10E-06	4.40E-06	1.50E-09	5.20E-07	5.60E-07	1.20E-09	2.10E-07	7.00E-06	1.40E-04	0.60%
^{51}Cr	8.20E-06	1.40E-05	1.80E-07	7.10E-08	0.00E+00	1.50E-07	0.00E+00	2.00E-10	2.00E-07	5.10E-07	6.70E-09	5.10E-06	9.90E-06	3.83E-05	0.16%
^{56}Mn	1.60E-05	2.70E-07	7.30E-06	2.70E-07	0.00E+00	4.60E-08	0.00E+00	8.90E-12	1.70E-07	1.00E-05	3.60E-06	1.60E-07	2.20E-07	3.80E-05	0.16%
^{60}Co	2.00E-06	2.20E-04	3.40E-08	1.40E-08	0.00E+00	8.80E-06	1.40E-05	1.30E-08	3.10E-07	1.20E-07	2.00E-11	1.90E-06	4.70E-06	2.52E-04	1.08%
^{64}Cu	2.30E-05	1.50E-05	8.00E-07	1.80E-07	0.00E+00	2.20E-09	0.00E+00	1.50E-12	3.70E-07	2.50E-06	8.50E-07	2.60E-06	1.60E-06	4.69E-05	0.20%
^{65}Zn	3.40E-05	1.50E-03	2.30E-07	2.90E-07	1.30E-04	1.70E-05	2.50E-06	7.60E-08	5.30E-07	6.50E-07	2.90E-09	7.70E-05	6.80E-05	1.83E-03	7.87%
^{69m}Zn	5.30E-06	2.00E-05	1.80E-07	5.70E-08	3.90E-07	3.20E-08	0.00E+00	3.50E-11	9.70E-08	4.20E-07	2.70E-07	6.10E-06	3.90E-07	3.32E-05	0.14%
^{72}Ga	4.90E-05	7.80E-05	4.60E-06	5.70E-07	0.00E+00	3.60E-07	0.00E+00	2.00E-10	4.60E-07	9.70E-06	2.00E-06	1.70E-07	3.70E-06	1.49E-04	0.64%
^{76}As	1.00E-04	1.40E-02	5.50E-07	7.80E-07	0.00E+00	1.70E-08	0.00E+00	7.80E-11	1.00E-06	1.80E-06	1.90E-06	2.50E-05	1.40E-05	1.41E-02	60.84%
^{89}Sr	3.50E-07	2.30E-05	1.60E-11	3.00E-09	2.00E-07	4.90E-12	2.70E-09	1.40E-12	1.70E-08	4.30E-11	1.50E-10	7.90E-08	5.20E-07	2.42E-05	0.10%
^{90}Sr	6.80E-07	1.30E-04	1.30E-11	5.80E-09	5.40E-07	1.80E-10	5.00E-08	1.10E-10	2.60E-08	3.60E-11	1.20E-12	4.40E-07	5.10E-06	1.37E-04	0.59%
^{90}Y	4.00E-05	2.90E-05	2.20E-09	3.60E-07	0.00E+00	1.90E-09	5.40E-07	3.90E-10	3.80E-07	5.80E-09	3.40E-07	1.10E-06	1.20E-05	8.37E-05	0.36%
^{93}Y	1.80E-05	1.30E-06	4.10E-08	1.90E-07	0.00E+00	2.10E-09	0.00E+00	3.20E-11	1.30E-07	9.60E-08	9.60E-07	4.00E-07	1.00E-06	2.21E-05	0.10%
^{95}Zr	4.10E-06	3.30E-04	7.80E-08	3.10E-08	0.00E+00	2.10E-06	1.20E-05	3.00E-09	3.80E-07	2.50E-07	1.30E-09	9.40E-11	6.10E-06	3.55E-04	1.53%
^{122}Sb	6.50E-06	1.50E-05	2.90E-08	4.60E-08	0.00E+00	3.10E-09	0.00E+00	1.50E-11	6.20E-08	1.00E-07	4.80E-08	8.70E-08	2.00E-06	2.39E-05	0.10%
^{131}I	8.20E-06	4.30E-05	7.70E-09	6.10E-08	0.00E+00	5.00E-10	6.00E-09	2.50E-11	5.90E-08	2.50E-08	4.30E-08	1.10E-05	1.10E-05	7.34E-05	0.32%
^{133}I	2.70E-05	6.50E-06	1.40E-07	2.20E-07	0.00E+00	9.50E-10	7.80E-09	4.60E-12	8.40E-08	4.10E-07	6.30E-07	1.20E-05	2.80E-06	4.98E-05	0.21%
^{137}Cs	8.30E-07	2.20E-04	2.20E-09	7.20E-09	1.70E-05	9.80E-07	8.00E-06	9.80E-09	5.10E-08	6.10E-09	1.50E-12	1.30E-06	4.60E-06	2.53E-04	1.09%
^{239}Np	1.70E-04	2.70E-03	6.70E-07	1.30E-06	0.00E+00	2.20E-07	1.20E-05	1.80E-09	1.80E-06	2.10E-06	1.70E-06	2.50E-06	5.20E-05	2.94E-03	12.66%
Total	5.7E-04	2.1E-02	3.5E-05	4.9E-06	7.1E-04	3.2E-05	5.4E-05	1.1E-07	8.7E-06	7.9E-05	1.3E-05	1.9E-04	2.2E-04	2.32E-02	100%
% of Total	2.44%	91.78%	0.15%	0.02%	3.05%	0.14%	0.23%	0.00%	0.04%	0.34%	0.06%	0.81%	0.95%	100%	

Table F-2. Screening Risk Values for the Initial Screening at Richland

Nuclide	Direct-Ing	Fish-Ing	Imm	Swim-Ing	Waterfowl	Sed-Ext	Dermal	Sed-Ing	Aerosol	Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total	% of Total
^{24}Na	5.60E-05	9.70E-05	3.20E-05	5.60E-07	0.00E+00	2.10E-07	0.00E+00	1.40E-11	2.10E-06	7.70E-05	1.10E-06	4.60E-05	4.00E-06	3.16E-04	0.81%
^{32}P	2.30E-05	3.20E-03	1.40E-09	1.60E-07	1.00E-03	3.00E-10	1.20E-07	4.10E-11	1.20E-06	4.60E-09	3.10E-08	2.00E-05	2.10E-05	4.27E-03	10.94%
^{45}Ca	3.00E-07	1.80E-05	2.10E-12	2.20E-09	0.00E+00	5.90E-13	6.20E-08	9.70E-12	4.50E-08	7.20E-12	3.60E-11	1.50E-08	5.80E-07	1.90E-05	0.05%
^{46}Sc	8.30E-06	2.20E-04	3.70E-07	7.30E-08	0.00E+00	4.10E-06	8.50E-06	2.90E-09	9.30E-07	1.00E-06	2.20E-09	3.70E-07	1.30E-05	2.57E-04	0.66%
^{51}Cr	1.50E-05	2.50E-05	3.40E-07	1.30E-07	0.00E+00	2.80E-07	0.00E+00	3.90E-10	3.60E-07	9.20E-07	1.20E-08	9.30E-06	1.80E-05	6.93E-05	0.18%
^{56}Mn	1.30E-05	2.30E-07	6.90E-06	2.60E-07	0.00E+00	4.30E-08	0.00E+00	8.80E-12	1.40E-07	8.30E-06	3.20E-06	1.30E-07	1.80E-07	3.24E-05	0.08%
^{60}Co	3.50E-06	4.00E-04	6.30E-08	2.60E-08	0.00E+00	1.70E-05	2.70E-05	2.50E-08	5.70E-07	2.10E-07	3.70E-11	3.50E-06	8.50E-06	4.60E-04	1.18%
^{64}Cu	3.30E-05	2.20E-05	1.30E-06	2.80E-07	0.00E+00	3.50E-09	0.00E+00	2.50E-12	5.40E-07	3.60E-06	1.30E-06	3.70E-06	2.30E-06	6.80E-05	0.17%
^{65}Zn	6.10E-05	2.70E-03	4.30E-07	5.50E-07	2.40E-04	3.30E-05	4.70E-06	1.50E-07	9.50E-07	1.20E-06	5.30E-09	1.40E-04	1.20E-04	3.30E-03	8.47%
^{69m}Zn	7.00E-06	2.80E-05	2.70E-07	8.40E-08	4.90E-07	4.70E-08	0.00E+00	5.40E-11	1.30E-07	5.60E-07	3.90E-07	8.00E-06	5.10E-07	4.55E-05	0.12%
^{72}Ga	6.80E-05	1.10E-04	7.00E-06	8.70E-07	0.00E+00	5.50E-07	0.00E+00	3.10E-10	6.30E-07	1.30E-05	3.00E-06	2.30E-07	5.10E-06	2.08E-04	0.53%
^{76}As	1.70E-04	2.30E-02	9.30E-07	1.30E-06	0.00E+00	3.00E-08	0.00E+00	1.40E-10	1.60E-06	2.80E-06	3.20E-06	4.00E-05	2.30E-05	2.32E-02	59.61%
^{89}Sr	6.40E-07	4.10E-05	2.90E-11	5.70E-09	3.70E-07	9.60E-12	5.10E-09	2.70E-12	3.10E-08	7.80E-11	2.80E-10	1.40E-07	9.40E-07	4.31E-05	0.11%
^{90}Sr	1.20E-06	2.30E-04	2.40E-11	1.10E-08	9.70E-07	3.50E-10	9.40E-08	2.00E-10	4.70E-08	6.60E-11	2.30E-12	7.90E-07	9.30E-06	2.42E-04	0.62%
^{90}Y	6.90E-05	5.10E-05	3.90E-09	6.50E-07	0.00E+00	3.50E-09	1.00E-06	7.30E-10	6.60E-07	1.00E-08	6.10E-07	1.90E-06	2.10E-05	1.46E-04	0.37%
^{93}Y	2.40E-05	1.80E-06	6.00E-08	2.70E-07	0.00E+00	3.10E-09	0.00E+00	4.80E-11	1.80E-07	1.30E-07	1.30E-06	5.30E-07	1.30E-06	2.96E-05	0.08%
^{95}Zr	7.00E-06	5.70E-04	1.40E-07	5.60E-08	0.00E+00	3.80E-06	2.20E-05	5.70E-09	6.60E-07	4.30E-07	2.30E-09	1.60E-10	1.10E-05	6.15E-04	1.58%
^{122}Sb	1.10E-05	2.70E-05	5.30E-08	8.30E-08	0.00E+00	5.70E-09	0.00E+00	2.80E-11	1.10E-07	1.70E-07	8.50E-08	1.50E-07	3.40E-06	4.21E-05	0.11%
^{131}I	1.50E-05	7.80E-05	1.40E-08	1.10E-07	0.00E+00	9.60E-10	1.20E-08	4.90E-11	1.10E-07	4.50E-08	7.90E-08	2.00E-05	2.00E-05	1.33E-04	0.34%
^{133}I	4.20E-05	1.10E-05	2.30E-07	3.60E-07	0.00E+00	1.60E-09	1.40E-08	8.00E-12	1.30E-07	6.50E-07	1.00E-06	1.90E-05	4.50E-06	7.89E-05	0.20%
^{137}Cs	1.50E-06	4.10E-04	4.10E-09	1.40E-08	3.00E-05	1.90E-06	1.50E-05	1.90E-08	9.30E-08	1.10E-08	2.70E-12	2.40E-06	8.40E-06	4.69E-04	1.20%
^{239}Np	2.80E-04	4.50E-03	1.20E-06	2.30E-06	0.00E+00	4.00E-07	2.10E-05	3.30E-09	2.90E-06	3.40E-06	2.90E-06	4.10E-06	8.50E-05	4.90E-03	12.58%
Total	9.1E-04	3.6E-02	5.1E-05	8.2E-06	1.3E-03	6.1E-05	1.0E-04	2.1E-07	1.4E-05	1.1E-04	1.8E-05	3.2E-04	3.8E-04	3.90E-02	100%
% of Total	2.33%	91.67%	0.13%	0.02%	3.26%	0.16%	0.26%	0.00%	0.04%	0.29%	0.05%	0.82%	0.98%	100%	

Table F-3. Screening Risk Values for the Native American Scenario at Pasco

Nuclide	Direct-Ing	Fish-Ing	Swim-Imm	Swim-Ing	Waterfowl	Sed-Ext	Sed-Dermal	Sed-Ing	Aerosol	Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total
^{24}Na	4.00E-05	3.20E-05	1.80E-05	3.00E-07	0.00E+00	1.00E-07	0.00E+00	1.00E-11	1.50E-06	2.80E-05	5.30E-07	0.00E+00	0.00E+00	1.20E-04
^{32}P	2.00E-05	1.20E-03	8.90E-10	1.00E-07	2.70E-04	1.80E-10	9.80E-08	3.30E-11	1.10E-06	2.00E-09	2.70E-06	0.00E+00	0.00E+00	1.49E-03
^{45}Ca	2.70E-07	7.10E-06	1.40E-12	1.40E-09	0.00E+00	3.50E-13	4.80E-08	7.60E-12	4.00E-08	3.20E-12	7.50E-08	0.00E+00	0.00E+00	7.53E-06
^{46}Sc	7.40E-06	8.90E-05	2.40E-07	4.70E-08	0.00E+00	2.50E-06	6.60E-06	2.30E-09	8.30E-07	4.50E-07	2.10E-06	0.00E+00	0.00E+00	1.09E-04
^{51}Cr	1.30E-05	1.00E-05	2.20E-07	8.60E-08	0.00E+00	1.70E-07	0.00E+00	3.10E-10	3.20E-07	4.10E-07	3.00E-06	0.00E+00	0.00E+00	2.72E-05
^{56}Mn	4.30E-06	4.00E-08	1.90E-06	7.10E-08	0.00E+00	1.00E-08	0.00E+00	3.20E-12	4.70E-08	1.40E-06	1.80E-08	0.00E+00	0.00E+00	7.79E-06
^{60}Co	3.20E-06	1.60E-04	4.10E-08	1.70E-08	0.00E+00	1.00E-05	2.10E-05	1.90E-08	5.10E-07	9.60E-08	1.10E-06	0.00E+00	0.00E+00	1.96E-04
^{64}Cu	2.30E-05	6.80E-06	6.70E-07	1.50E-07	0.00E+00	1.60E-09	0.00E+00	1.70E-12	3.70E-07	1.20E-06	2.50E-07	0.00E+00	0.00E+00	3.24E-05
^{65}Zn	5.50E-05	1.10E-03	2.80E-07	3.60E-07	6.60E-05	2.00E-05	3.70E-06	1.10E-07	8.50E-07	5.30E-07	1.90E-05	0.00E+00	0.00E+00	1.27E-03
^{69,69m}Zn	4.40E-06	8.30E-06	1.40E-07	4.20E-08	9.20E-08	2.00E-08	0.00E+00	3.50E-11	8.10E-08	1.80E-07	6.60E-08	0.00E+00	0.00E+00	1.33E-05
^{72}Ga	4.50E-05	3.50E-05	3.60E-06	4.50E-07	0.00E+00	2.50E-07	0.00E+00	2.10E-10	4.30E-07	4.40E-06	7.60E-07	0.00E+00	0.00E+00	8.99E-05
^{76}As	1.30E-04	7.80E-03	5.40E-07	7.70E-07	0.00E+00	1.60E-08	0.00E+00	1.00E-10	1.30E-06	1.10E-06	2.90E-06	0.00E+00	0.00E+00	7.94E-03
^{89}Sr	5.80E-07	1.80E-05	1.90E-11	3.70E-09	1.00E-07	5.70E-12	4.00E-09	2.10E-12	2.70E-08	3.50E-11	1.50E-07	0.00E+00	0.00E+00	1.89E-05
^{90}Sr	1.10E-06	9.90E-05	1.60E-11	7.10E-09	2.70E-07	2.10E-10	7.30E-08	1.60E-10	4.20E-08	3.00E-11	1.50E-06	0.00E+00	0.00E+00	1.02E-04
^{90}Y	5.80E-05	1.90E-05	2.40E-09	4.00E-07	0.00E+00	2.00E-09	7.90E-07	5.70E-10	5.60E-07	4.20E-09	3.20E-06	0.00E+00	0.00E+00	8.20E-05
^{93}Y	1.50E-05	5.00E-07	2.80E-08	1.30E-07	0.00E+00	1.30E-09	0.00E+00	3.00E-11	1.10E-07	3.90E-08	1.60E-07	0.00E+00	0.00E+00	1.60E-05
^{95}Zr	6.30E-06	2.30E-04	9.10E-08	3.70E-08	0.00E+00	2.30E-06	1.70E-05	4.40E-09	5.90E-07	1.90E-07	1.60E-06	0.00E+00	0.00E+00	2.58E-04
^{122}Sb	9.50E-06	1.00E-05	3.30E-08	5.20E-08	0.00E+00	3.30E-09	0.00E+00	2.20E-11	9.10E-08	7.30E-08	4.20E-07	0.00E+00	0.00E+00	2.02E-05
^{131}I	1.30E-05	3.00E-05	9.20E-09	7.30E-08	0.00E+00	5.60E-10	9.20E-09	3.90E-11	9.40E-08	2.00E-08	3.00E-06	0.00E+00	0.00E+00	4.62E-05
^{133}I	3.20E-05	3.60E-06	1.30E-07	2.10E-07	0.00E+00	8.40E-10	9.70E-09	5.70E-12	1.00E-07	2.50E-07	6.10E-07	0.00E+00	0.00E+00	3.69E-05
^{137}Cs	1.40E-06	1.60E-04	2.60E-09	8.80E-09	8.30E-06	1.10E-06	1.20E-05	1.40E-08	8.30E-08	5.00E-09	1.30E-06	0.00E+00	0.00E+00	1.84E-04
^{239}Np	2.30E-04	1.60E-03	7.20E-07	1.40E-06	0.00E+00	2.20E-07	1.60E-05	2.50E-09	2.40E-06	1.40E-06	1.20E-05	0.00E+00	0.00E+00	1.86E-03
Total	7.1E-04	1.3E-02	2.7E-05	4.7E-06	3.4E-04	3.7E-05	7.7E-05	1.5E-07	1.1E-05	4.0E-05	5.6E-05	0.0E+00	0.0E+00	1.39E-02
% of Total	5.11%	90.59%	0.19%	0.03%	2.48%	0.26%	0.56%	0.00%	0.08%	0.29%	0.41%	0.00%	0.00%	100%

Table F-4. Screening Risk Values for the Native American Scenario at Richland

Nuclide	Direct-Ing	Fish-Ing	Swim-Imm	Swim-Ing	Waterfowl	Sed-Ext	Sed-Dermal	Sed-Ing	Aerosol	Produce-Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total
^{24}Na	5.60E-05	4.30E-05	2.30E-05	4.00E-07	0.00E+00	1.40E-07	0.00E+00	1.30E-11	2.10E-06	3.80E-05	7.20E-07	0.00E+00	0.00E+00	1.63E-04
^{32}P	2.30E-05	1.40E-03	9.90E-10	1.20E-07	3.10E-04	2.00E-10	1.10E-07	3.70E-11	1.20E-06	2.30E-09	3.10E-06	0.00E+00	0.00E+00	1.74E-03
^{45}Ca	3.00E-07	7.90E-06	1.50E-12	1.60E-09	0.00E+00	3.90E-13	5.30E-08	8.50E-12	4.50E-08	3.60E-12	8.30E-08	0.00E+00	0.00E+00	8.38E-06
^{46}Sc	8.30E-06	9.80E-05	2.60E-07	5.20E-08	0.00E+00	2.70E-06	7.30E-06	2.50E-09	9.30E-07	5.00E-07	2.30E-06	0.00E+00	0.00E+00	1.20E-04
^{51}Cr	1.50E-05	1.10E-05	2.40E-07	9.50E-08	0.00E+00	1.90E-07	0.00E+00	3.40E-10	3.60E-07	4.60E-07	3.30E-06	0.00E+00	0.00E+00	3.06E-05
^{56}Mn	1.30E-05	1.10E-07	5.00E-06	1.80E-07	0.00E+00	2.80E-08	0.00E+00	8.50E-12	1.40E-07	4.10E-06	4.60E-08	0.00E+00	0.00E+00	2.26E-05
^{60}Co	3.50E-06	1.80E-04	4.50E-08	1.80E-08	0.00E+00	1.10E-05	2.30E-05	2.10E-08	5.70E-07	1.10E-07	1.20E-06	0.00E+00	0.00E+00	2.19E-04
^{64}Cu	3.30E-05	9.60E-06	9.10E-07	2.00E-07	0.00E+00	2.30E-09	0.00E+00	2.30E-12	5.40E-07	1.80E-06	3.50E-07	0.00E+00	0.00E+00	4.64E-05
^{65}Zn	6.10E-05	1.20E-03	3.00E-07	3.90E-07	7.30E-05	2.20E-05	4.10E-06	1.20E-07	9.50E-07	5.80E-07	2.10E-05	0.00E+00	0.00E+00	1.38E-03
^{69,69m}Zn	7.00E-06	1.30E-05	1.90E-07	6.00E-08	1.50E-07	3.10E-08	0.00E+00	5.10E-11	1.30E-07	2.80E-07	1.00E-07	0.00E+00	0.00E+00	2.09E-05
^{72}Ga	6.80E-05	5.00E-05	5.00E-06	6.20E-07	0.00E+00	3.60E-07	0.00E+00	2.90E-10	6.30E-07	6.60E-06	1.10E-06	0.00E+00	0.00E+00	1.32E-04
^{76}As	1.70E-04	9.80E-03	6.70E-07	9.50E-07	0.00E+00	2.00E-08	0.00E+00	1.20E-10	1.60E-06	1.40E-06	3.70E-06	0.00E+00	0.00E+00	9.98E-03
^{89}Sr	6.40E-07	2.00E-05	2.10E-11	4.10E-09	1.10E-07	6.40E-12	4.50E-09	2.30E-12	3.10E-08	3.90E-11	1.70E-07	0.00E+00	0.00E+00	2.10E-05
^{90}Sr	1.20E-06	1.10E-04	1.70E-11	7.80E-09	3.00E-07	2.30E-10	8.00E-08	1.70E-10	4.70E-08	3.30E-11	1.60E-06	0.00E+00	0.00E+00	1.13E-04
^{90}Y	6.90E-05	2.20E-05	2.80E-09	4.60E-07	0.00E+00	2.30E-09	9.20E-07	6.70E-10	6.60E-07	5.00E-09	3.80E-06	0.00E+00	0.00E+00	9.69E-05
^{93}Y	2.40E-05	7.80E-07	4.20E-08	1.90E-07	0.00E+00	2.00E-09	0.00E+00	4.50E-11	1.80E-07	6.30E-08	2.50E-07	0.00E+00	0.00E+00	2.55E-05
^{95}Zr	7.00E-06	2.50E-04	1.00E-07	4.00E-08	0.00E+00	2.60E-06	1.90E-05	4.90E-09	6.60E-07	2.20E-07	1.70E-06	0.00E+00	0.00E+00	2.81E-04
^{122}Sb	1.10E-05	1.20E-05	3.80E-08	6.00E-08	0.00E+00	3.80E-09	0.00E+00	2.50E-11	1.10E-07	8.60E-08	4.90E-07	0.00E+00	0.00E+00	2.38E-05
^{131}I	1.50E-05	3.40E-05	1.00E-08	8.10E-08	0.00E+00	6.40E-10	1.00E-08	4.30E-11	1.10E-07	2.20E-08	3.40E-06	0.00E+00	0.00E+00	5.26E-05
^{133}I	4.20E-05	4.60E-06	1.70E-07	2.60E-07	0.00E+00	1.10E-09	1.20E-08	7.20E-12	1.30E-07	3.20E-07	7.90E-07	0.00E+00	0.00E+00	4.83E-05
^{137}Cs	1.50E-06	1.70E-04	2.90E-09	9.70E-09	9.30E-06	1.20E-06	1.30E-05	1.60E-08	9.30E-08	5.50E-09	1.50E-06	0.00E+00	0.00E+00	1.97E-04
^{239}Np	2.80E-04	2.00E-03	8.50E-07	1.70E-06	0.00E+00	2.70E-07	1.90E-05	2.90E-09	2.90E-06	1.70E-06	1.40E-05	0.00E+00	0.00E+00	2.32E-03
Total	9.1E-04	1.5E-02	3.7E-05	5.9E-06	3.9E-04	4.1E-05	8.7E-05	1.7E-07	1.4E-05	5.6E-05	6.5E-05	0.0E+00	0.0E+00	1.70E-02
% of Total	5.34%	90.57%	0.22%	0.03%	2.31%	0.24%	0.51%	0.00%	0.08%	0.33%	0.38%	0.00%	0.00%	100%

Table F-5. Screening Risk Values for the Migrant Worker Scenario at Pasco

Nuclide	Direct-Ing	Fish-Ing	Swim-Imm	Swim-Ing	Waterfowl	Sed-Ext	Sed-Dermal	Sed-Ing	Aerosol	Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total
^{24}Na	2.00E-05	4.00E-06	1.80E-05	3.00E-07	0.00E+00	1.50E-08	0.00E+00	1.10E-11	3.00E-13	0.00E+00	7.90E-07	8.20E-06	2.00E-05	7.13E-05
^{32}P	8.30E-06	8.40E-05	8.90E-10	1.00E-07	0.00E+00	2.50E-11	1.10E-07	3.70E-11	1.70E-13	0.00E+00	2.80E-08	2.00E-06	3.90E-06	9.84E-05
^{45}Ca	1.10E-07	7.10E-07	1.40E-12	1.40E-09	0.00E+00	5.40E-14	5.50E-08	8.80E-12	6.40E-15	0.00E+00	3.30E-11	1.10E-09	7.80E-09	8.85E-07
^{46}Sc	3.40E-06	9.90E-06	2.40E-07	4.70E-08	0.00E+00	3.60E-07	7.70E-06	2.70E-09	1.50E-13	0.00E+00	2.00E-09	3.50E-08	5.10E-09	2.17E-05
^{51}Cr	6.20E-06	1.20E-06	2.20E-07	8.60E-08	0.00E+00	2.50E-08	0.00E+00	3.50E-10	5.80E-14	0.00E+00	1.10E-08	9.60E-07	3.10E-07	9.01E-06
^{56}Mn	3.60E-06	5.60E-09	1.90E-06	7.10E-08	0.00E+00	2.20E-09	0.00E+00	3.30E-12	1.50E-14	0.00E+00	1.20E-06	2.90E-08	4.00E-08	6.85E-06
^{60}Co	1.30E-06	1.50E-05	4.10E-08	1.70E-08	0.00E+00	1.50E-06	2.40E-05	2.20E-08	8.10E-14	0.00E+00	3.30E-11	2.00E-07	6.40E-08	4.21E-05
^{64}Cu	1.10E-05	8.20E-07	6.70E-07	1.50E-07	0.00E+00	2.30E-10	0.00E+00	1.80E-12	6.70E-14	0.00E+00	9.20E-07	6.30E-07	6.00E-07	1.48E-05
^{65}Zn	2.50E-05	1.00E-04	2.80E-07	3.60E-07	0.00E+00	3.00E-06	4.30E-06	1.30E-07	1.50E-13	0.00E+00	4.80E-09	1.20E-05	5.80E-06	1.51E-04
^{69,69m}Zn	2.50E-06	1.10E-06	1.40E-07	4.20E-08	0.00E+00	3.40E-09	0.00E+00	3.70E-11	1.80E-14	0.00E+00	2.60E-07	1.60E-06	7.40E-07	6.39E-06
^{72}Ga	2.60E-05	4.80E-06	3.60E-06	4.50E-07	0.00E+00	4.40E-08	0.00E+00	2.20E-10	9.70E-14	0.00E+00	2.10E-06	4.70E-08	7.40E-09	3.70E-05
^{76}As	5.70E-05	9.50E-04	5.40E-07	7.70E-07	0.00E+00	2.20E-09	0.00E+00	1.10E-10	2.20E-13	0.00E+00	2.50E-06	6.50E-06	1.50E-07	1.02E-03
^{89}Sr	2.60E-07	3.90E-07	1.90E-11	3.70E-09	0.00E+00	8.70E-13	4.60E-09	2.40E-12	4.90E-15	0.00E+00	2.60E-10	1.30E-08	1.30E-08	6.85E-07
^{90}Sr	5.10E-07	1.00E-06	1.60E-11	7.10E-09	0.00E+00	3.10E-11	8.50E-08	1.80E-10	7.50E-15	0.00E+00	2.00E-12	2.20E-08	2.20E-08	1.65E-06
^{90}Y	2.70E-05	2.40E-06	2.40E-09	4.00E-07	0.00E+00	2.70E-10	8.70E-07	6.30E-10	1.00E-13	0.00E+00	5.20E-07	3.00E-07	4.30E-08	3.15E-05
^{93}Y	8.00E-06	6.60E-08	2.80E-08	1.30E-07	0.00E+00	2.00E-10	0.00E+00	3.20E-11	2.30E-14	0.00E+00	8.60E-07	9.90E-08	1.40E-08	9.20E-06
^{95}Zr	2.70E-06	2.40E-05	9.10E-08	3.70E-08	0.00E+00	3.50E-07	2.00E-05	5.10E-09	9.70E-14	0.00E+00	2.10E-09	1.40E-11	4.10E-11	4.72E-05
^{122}Sb	4.00E-06	1.20E-06	3.30E-08	5.20E-08	0.00E+00	4.30E-10	0.00E+00	2.40E-11	1.50E-14	0.00E+00	7.30E-08	2.10E-08	1.00E-08	5.39E-06
^{131}I	5.70E-06	3.70E-06	9.20E-09	7.30E-08	0.00E+00	7.60E-11	1.00E-08	4.40E-11	1.60E-14	0.00E+00	7.00E-08	2.40E-06	2.90E-06	1.49E-05
^{133}I	1.50E-05	4.60E-07	1.30E-07	2.10E-07	0.00E+00	1.20E-10	1.10E-08	6.30E-12	1.80E-14	0.00E+00	8.00E-07	3.30E-06	3.90E-06	2.38E-05
^{137}Cs	6.20E-07	7.70E-06	2.60E-09	8.80E-09	0.00E+00	1.70E-07	1.40E-05	1.70E-08	1.50E-14	0.00E+00	2.40E-12	1.40E-07	1.30E-07	2.28E-05
^{239}Np	1.00E-04	2.00E-04	7.20E-07	1.40E-06	0.00E+00	3.20E-08	1.80E-05	2.80E-09	4.20E-13	0.00E+00	2.40E-06	6.30E-07	3.00E-08	3.23E-04
Total	3.3E-04	1.4E-03	2.7E-05	4.7E-06	0.0E+00	5.5E-06	8.9E-05	1.8E-07	2.0E-12	0.0E+00	1.3E-05	3.9E-05	3.9E-05	1.96E-03
% of Total	16.77%	72.17%	1.36%	0.24%	0.00%	0.28%	4.55%	0.01%	0.00%	0.00%	0.64%	2.00%	1.98%	100%

Table F-6. Screening Risk Values for the Migrant Worker Scenario at Richland

Nuclide	Direct-Ing	Fish-Ing	Swim-Imm	Swim-Ing	Waterfowl	Sed-Ext	Sed-Dermal	Sed-Ing	Aerosol	Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total
^{24}Na	2.70E-05	5.40E-06	2.30E-05	4.00E-07	0.00E+00	2.00E-08	0.00E+00	1.40E-11	4.00E-13	0.00E+00	1.10E-06	1.10E-05	2.60E-05	9.39E-05
^{32}P	9.20E-06	9.30E-05	9.90E-10	1.20E-07	0.00E+00	2.80E-11	1.20E-07	4.10E-11	1.90E-13	0.00E+00	3.10E-08	2.30E-06	4.40E-06	1.09E-04
^{45}Ca	1.20E-07	7.80E-07	1.50E-12	1.60E-09	0.00E+00	6.00E-14	6.20E-08	9.70E-12	7.10E-15	0.00E+00	3.60E-11	1.20E-09	8.70E-09	9.74E-07
^{46}Sc	3.80E-06	1.10E-05	2.60E-07	5.20E-08	0.00E+00	4.00E-07	8.50E-06	2.90E-09	1.70E-13	0.00E+00	2.20E-09	3.90E-08	5.60E-09	2.41E-05
^{51}Cr	6.90E-06	1.40E-06	2.40E-07	9.50E-08	0.00E+00	2.80E-08	0.00E+00	3.90E-10	6.50E-14	0.00E+00	1.20E-08	1.10E-06	3.40E-07	1.01E-05
^{56}Mn	9.90E-06	1.50E-08	5.00E-06	1.80E-07	0.00E+00	6.00E-09	0.00E+00	8.80E-12	4.20E-14	0.00E+00	3.20E-06	7.90E-08	1.10E-07	1.85E-05
^{60}Co	1.40E-06	1.70E-05	4.50E-08	1.80E-08	0.00E+00	1.70E-06	2.70E-05	2.50E-08	9.00E-14	0.00E+00	3.70E-11	2.20E-07	7.10E-08	4.75E-05
^{64}Cu	1.50E-05	1.20E-06	9.10E-07	2.00E-07	0.00E+00	3.20E-10	0.00E+00	2.50E-12	9.40E-14	0.00E+00	1.30E-06	8.80E-07	8.30E-07	2.03E-05
^{65}Zn	2.80E-05	1.10E-04	3.00E-07	3.90E-07	0.00E+00	3.30E-06	4.70E-06	1.50E-07	1.70E-13	0.00E+00	5.30E-09	1.30E-05	6.40E-06	1.66E-04
^{69,69m}Zn	3.80E-06	1.60E-06	1.90E-07	6.00E-08	0.00E+00	4.90E-09	0.00E+00	5.40E-11	2.70E-14	0.00E+00	3.90E-07	2.30E-06	1.10E-06	9.44E-06
^{72}Ga	3.80E-05	6.90E-06	5.00E-06	6.20E-07	0.00E+00	6.20E-08	0.00E+00	3.10E-10	1.40E-13	0.00E+00	3.00E-06	6.70E-08	1.10E-08	5.37E-05
^{76}As	7.20E-05	1.20E-03	6.70E-07	9.50E-07	0.00E+00	2.70E-09	0.00E+00	1.40E-10	2.70E-13	0.00E+00	3.20E-06	8.10E-06	1.90E-07	1.29E-03
^{89}Sr	2.90E-07	4.30E-07	2.10E-11	4.10E-09	0.00E+00	9.70E-13	5.10E-09	2.70E-12	5.40E-15	0.00E+00	2.80E-10	1.50E-08	1.40E-08	7.59E-07
^{90}Sr	5.60E-07	1.10E-06	1.70E-11	7.80E-09	0.00E+00	3.40E-11	9.40E-08	2.00E-10	8.30E-15	0.00E+00	2.30E-12	2.50E-08	2.40E-08	1.81E-06
^{90}Y	3.20E-05	2.80E-06	2.80E-09	4.60E-07	0.00E+00	3.20E-10	1.00E-06	7.30E-10	1.20E-13	0.00E+00	6.10E-07	3.50E-07	5.10E-08	3.73E-05
^{93}Y	1.20E-05	1.00E-07	4.20E-08	1.90E-07	0.00E+00	3.00E-10	0.00E+00	4.80E-11	3.50E-14	0.00E+00	1.30E-06	1.50E-07	2.20E-08	1.38E-05
^{95}Zr	3.00E-06	2.70E-05	1.00E-07	4.00E-08	0.00E+00	3.90E-07	2.20E-05	5.70E-09	1.10E-13	0.00E+00	2.30E-09	1.60E-11	4.50E-11	5.25E-05
^{122}Sb	4.60E-06	1.40E-06	3.80E-08	6.00E-08	0.00E+00	5.00E-10	0.00E+00	2.80E-11	1.70E-14	0.00E+00	8.50E-08	2.50E-08	1.20E-08	6.22E-06
^{131}I	6.40E-06	4.20E-06	1.00E-08	8.10E-08	0.00E+00	8.50E-11	1.20E-08	4.90E-11	1.80E-14	0.00E+00	7.90E-08	2.70E-06	3.20E-06	1.67E-05
^{133}I	1.90E-05	5.90E-07	1.70E-07	2.60E-07	0.00E+00	1.50E-10	1.40E-08	8.00E-12	2.40E-14	0.00E+00	1.00E-06	4.30E-06	5.10E-06	3.04E-05
^{137}Cs	6.90E-07	8.50E-06	2.90E-09	9.70E-09	0.00E+00	1.80E-07	1.50E-05	1.90E-08	1.60E-14	0.00E+00	2.70E-12	1.50E-07	1.50E-07	2.47E-05
^{239}Np	1.20E-04	2.40E-04	8.50E-07	1.70E-06	0.00E+00	3.80E-08	2.10E-05	3.30E-09	5.00E-13	0.00E+00	2.90E-06	7.50E-07	3.60E-08	3.87E-04
Total	4.1E-04	1.7E-03	3.7E-05	5.9E-06	0.0E+00	6.1E-06	1.0E-04	2.1E-07	2.5E-12	0.0E+00	1.8E-05	4.8E-05	4.8E-05	2.41E-03
% of Total	17.16%	71.95%	1.53%	0.24%	0.00%	0.25%	4.13%	0.01%	0.00%	0.00%	0.76%	1.97%	1.99%	100%

Table F-7. Screening Risk Values for the Local Resident Scenario at Pasco

Nuclide	Direct-Ing	Fish-Ing	Swim-Imm	Swim-Ing	Waterfowl	Sed-Ext	Sed-Dermal	Sed-Ing	Aerosol	Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total
^{24}Na	2.00E-05	1.60E-06	4.60E-06	8.00E-08	0.00E+00	6.30E-09	0.00E+00	4.50E-12	0.00E+00	4.60E-06	4.50E-07	1.60E-05	3.90E-05	8.63E-05
^{32}P	1.00E-05	1.60E-04	2.00E-10	2.30E-08	1.30E-04	7.80E-12	1.70E-08	1.20E-11	0.00E+00	2.00E-10	2.30E-06	9.00E-06	1.60E-05	3.27E-04
^{45}Ca	1.40E-07	1.00E-06	3.10E-13	3.10E-10	0.00E+00	2.30E-14	1.20E-08	3.70E-12	0.00E+00	3.10E-13	6.30E-08	6.50E-09	4.30E-08	1.26E-06
^{46}Sc	3.70E-06	1.40E-05	5.40E-08	1.10E-08	0.00E+00	1.50E-07	1.50E-06	1.10E-09	0.00E+00	5.40E-08	1.70E-06	1.70E-07	2.20E-08	2.14E-05
^{51}Cr	6.70E-06	1.60E-06	5.00E-08	1.90E-08	0.00E+00	9.60E-09	0.00E+00	1.30E-10	0.00E+00	5.00E-08	2.50E-06	4.10E-06	1.20E-06	1.62E-05
^{56}Mn	2.20E-06	1.20E-09	6.50E-07	2.40E-08	0.00E+00	1.30E-09	0.00E+00	1.90E-12	0.00E+00	6.50E-07	1.50E-08	2.30E-08	3.30E-08	3.60E-06
^{60}Co	1.60E-06	2.20E-05	9.10E-09	3.70E-09	0.00E+00	6.40E-07	5.20E-06	9.70E-09	0.00E+00	9.10E-09	9.20E-07	1.60E-06	4.40E-07	3.24E-05
^{64}Cu	1.20E-05	3.10E-07	1.70E-07	3.70E-08	0.00E+00	8.50E-11	0.00E+00	6.70E-13	0.00E+00	1.70E-07	2.00E-07	1.30E-06	1.20E-06	1.54E-05
^{65}Zn	2.70E-05	1.50E-04	6.40E-08	8.20E-08	3.10E-05	1.30E-06	9.10E-07	5.60E-08	0.00E+00	6.40E-08	1.60E-05	6.20E-05	2.70E-05	3.15E-04
$^{69,69m}Zn$	2.20E-06	3.90E-07	3.80E-08	1.20E-08	4.40E-08	1.50E-09	0.00E+00	1.70E-11	0.00E+00	3.80E-08	5.50E-08	2.50E-06	1.20E-06	6.48E-06
^{72}Ga	2.30E-05	1.70E-06	9.90E-07	1.20E-07	0.00E+00	2.00E-08	0.00E+00	1.00E-10	0.00E+00	9.90E-07	6.30E-07	7.60E-08	1.20E-08	2.75E-05
^{76}As	6.60E-05	5.50E-04	1.30E-07	1.80E-07	0.00E+00	7.60E-10	0.00E+00	3.90E-11	0.00E+00	1.30E-07	2.40E-06	1.60E-05	3.70E-07	6.35E-04
^{89}Sr	2.90E-07	5.20E-07	4.10E-12	8.00E-10	4.80E-08	3.40E-13	9.00E-10	9.50E-13	0.00E+00	4.10E-12	1.20E-07	6.40E-08	5.60E-08	1.10E-06
^{90}Sr	5.60E-07	1.40E-06	3.40E-12	1.50E-09	1.30E-07	1.30E-11	1.80E-08	7.90E-11	0.00E+00	3.40E-12	1.20E-06	3.60E-07	2.90E-07	3.96E-06
^{90}Y	2.90E-05	2.10E-06	5.40E-10	9.00E-08	0.00E+00	1.00E-10	1.60E-07	2.30E-10	0.00E+00	5.40E-10	2.70E-06	7.90E-07	1.10E-07	3.50E-05
^{93}Y	7.40E-06	2.10E-08	7.50E-09	3.40E-08	0.00E+00	8.90E-11	0.00E+00	1.40E-11	0.00E+00	7.50E-09	1.30E-07	1.60E-07	2.30E-08	7.78E-06
^{95}Zr	3.20E-06	3.40E-05	2.10E-08	8.40E-09	0.00E+00	1.40E-07	4.00E-06	2.00E-09	0.00E+00	2.10E-08	1.30E-06	7.20E-11	1.90E-10	4.27E-05
^{122}Sb	4.70E-06	1.10E-06	7.50E-09	1.20E-08	0.00E+00	1.40E-10	0.00E+00	7.80E-12	0.00E+00	7.50E-09	3.50E-07	6.30E-08	2.90E-08	6.27E-06
^{131}I	6.50E-06	4.50E-06	2.00E-09	1.60E-08	0.00E+00	2.70E-11	1.80E-09	1.50E-11	0.00E+00	2.00E-09	2.50E-06	8.80E-06	9.90E-06	3.22E-05
^{133}I	1.60E-05	2.20E-07	3.30E-08	5.10E-08	0.00E+00	4.70E-11	2.20E-09	2.60E-12	0.00E+00	3.30E-08	5.10E-07	7.20E-06	8.50E-06	3.25E-05
^{137}Cs	6.80E-07	2.10E-05	5.80E-10	1.90E-09	4.00E-06	7.10E-08	2.90E-06	7.20E-09	0.00E+00	5.80E-10	1.10E-06	1.10E-06	9.10E-07	3.18E-05
^{239}Np	1.20E-04	1.70E-04	1.70E-07	3.40E-07	0.00E+00	1.20E-08	3.30E-06	1.00E-09	0.00E+00	1.70E-07	1.00E-05	1.70E-06	8.00E-08	3.06E-04
Total	3.6E-04	1.1E-03	7.0E-06	1.1E-06	1.7E-04	2.4E-06	1.8E-05	7.8E-08	0.0E+00	7.0E-06	4.7E-05	1.3E-04	1.1E-04	1.99E-03
% of Total	18.26%	57.22%	0.35%	0.06%	8.31%	0.12%	0.91%	0.00%	0.00%	0.35%	2.37%	6.69%	5.35%	100%

Table F-8. Screening Risk Values for the Local Resident Scenario at Richland

Nuclide	Direct-Ing	Fish-Ing	Swim-Imm	Swim-Ing	Waterfowl	Sed-Ext	Sed-Dermal	Sed-Ing	Aerosol	Boating	Produce-Ing	Meat-Ing	Milk-Ing	Total
^{24}Na	2.80E-05	2.20E-06	6.00E-06	1.00E-07	0.00E+00	8.20E-09	0.00E+00	5.80E-12	0.00E+00	6.00E-06	6.10E-07	2.30E-05	5.40E-05	1.20E-04
^{32}P	1.10E-05	1.80E-04	2.20E-10	2.60E-08	1.50E-04	8.60E-12	1.90E-08	1.30E-11	0.00E+00	2.20E-10	2.60E-06	1.00E-05	1.80E-05	3.72E-04
^{45}Ca	1.50E-07	1.20E-06	3.40E-13	3.40E-10	0.00E+00	2.50E-14	1.30E-08	4.10E-12	0.00E+00	3.40E-13	6.90E-08	7.30E-09	4.70E-08	1.49E-06
^{46}Sc	4.10E-06	1.50E-05	5.90E-08	1.20E-08	0.00E+00	1.60E-07	1.70E-06	1.20E-09	0.00E+00	5.90E-08	1.90E-06	1.90E-07	2.50E-08	2.32E-05
^{51}Cr	7.50E-06	1.80E-06	5.50E-08	2.10E-08	0.00E+00	1.10E-08	0.00E+00	1.50E-10	0.00E+00	5.50E-08	2.80E-06	4.60E-06	1.40E-06	1.82E-05
^{56}Mn	6.30E-06	3.30E-09	1.60E-06	5.80E-08	0.00E+00	3.10E-09	0.00E+00	4.50E-12	0.00E+00	1.60E-06	3.90E-08	6.70E-08	9.60E-08	9.77E-06
^{60}Co	1.80E-06	2.50E-05	1.00E-08	4.00E-09	0.00E+00	7.10E-07	5.80E-06	1.10E-08	0.00E+00	1.00E-08	1.00E-06	1.80E-06	4.90E-07	3.66E-05
^{64}Cu	1.70E-05	4.40E-07	2.20E-07	4.90E-08	0.00E+00	1.10E-10	0.00E+00	8.90E-13	0.00E+00	2.20E-07	2.90E-07	1.80E-06	1.80E-06	2.18E-05
^{65}Zn	3.00E-05	1.70E-04	7.00E-08	9.00E-08	3.50E-05	1.40E-06	1.00E-06	6.20E-08	0.00E+00	7.00E-08	1.70E-05	6.90E-05	3.00E-05	3.54E-04
^{69,69m}Zn	3.50E-06	6.00E-07	5.30E-08	1.60E-08	7.20E-08	2.10E-09	0.00E+00	2.30E-11	0.00E+00	5.30E-08	8.30E-08	4.00E-06	1.90E-06	1.03E-05
^{72}Ga	3.40E-05	2.50E-06	1.30E-06	1.60E-07	0.00E+00	2.70E-08	0.00E+00	1.40E-10	0.00E+00	1.30E-06	9.10E-07	1.10E-07	1.80E-08	4.03E-05
^{76}As	8.40E-05	7.00E-04	1.60E-07	2.20E-07	0.00E+00	9.20E-10	0.00E+00	4.80E-11	0.00E+00	1.60E-07	3.10E-06	2.00E-05	4.70E-07	8.08E-04
^{89}Sr	3.20E-07	5.80E-07	4.50E-12	8.70E-10	5.40E-08	3.80E-13	1.00E-09	1.00E-12	0.00E+00	4.50E-12	1.40E-07	7.20E-08	6.20E-08	1.23E-06
^{90}Sr	6.20E-07	1.60E-06	3.70E-12	1.70E-09	1.40E-07	1.50E-11	2.00E-08	8.70E-11	0.00E+00	3.70E-12	1.40E-06	4.00E-07	3.30E-07	4.51E-06
^{90}Y	3.50E-05	2.50E-06	6.20E-10	1.00E-07	0.00E+00	1.20E-10	1.80E-07	2.70E-10	0.00E+00	6.20E-10	3.10E-06	9.40E-07	1.30E-07	4.20E-05
^{93}Y	1.20E-05	3.30E-08	1.10E-08	4.90E-08	0.00E+00	1.30E-10	0.00E+00	2.00E-11	0.00E+00	1.10E-08	2.10E-07	2.70E-07	3.80E-08	1.26E-05
^{95}Zr	3.50E-06	3.80E-05	2.30E-08	9.20E-09	0.00E+00	1.50E-07	4.40E-06	2.30E-09	0.00E+00	2.30E-08	1.40E-06	8.10E-11	2.10E-10	4.75E-05
^{122}Sb	5.60E-06	1.30E-06	8.50E-09	1.30E-08	0.00E+00	1.60E-10	0.00E+00	8.90E-12	0.00E+00	8.50E-09	4.10E-07	7.40E-08	3.50E-08	7.45E-06
^{131}I	7.40E-06	5.10E-06	2.30E-09	1.80E-08	0.00E+00	3.00E-11	2.00E-09	1.70E-11	0.00E+00	2.30E-09	2.80E-06	1.00E-05	1.10E-05	3.63E-05
^{133}I	2.10E-05	2.90E-07	4.00E-08	6.30E-08	0.00E+00	5.80E-11	2.70E-09	3.20E-12	0.00E+00	4.00E-08	6.60E-07	9.50E-06	1.10E-05	4.26E-05
^{137}Cs	7.60E-07	2.30E-05	6.30E-10	2.10E-09	4.40E-06	7.90E-08	3.20E-06	8.00E-09	0.00E+00	6.30E-10	1.20E-06	1.20E-06	1.00E-06	3.49E-05
^{239}Np	1.40E-04	2.10E-04	2.00E-07	3.90E-07	0.00E+00	1.40E-08	3.90E-06	1.20E-09	0.00E+00	2.00E-07	1.20E-05	2.10E-06	9.60E-08	3.69E-04
Total	4.5E-04	1.4E-03	9.8E-06	1.4E-06	1.9E-04	2.6E-06	2.0E-05	8.6E-08	0.0E+00	9.8E-06	5.4E-05	1.6E-04	1.3E-04	2.41E-03
% of Total	18.80%	57.24%	0.41%	0.06%	7.86%	0.11%	0.84%	0.00%	0.00%	0.41%	2.23%	6.59%	5.47%	100%

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, $^{69,69m}Zn$, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	$^{69,69m}Zn$	^{72}Ga
Jan-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Feb-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mar-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Apr-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
May-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jun-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jul-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Aug-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sep-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Oct-44	5.63E-10	1.30E-08	6.38E-10	3.84E-09	2.48E-07	2.99E-09	1.15E-09	2.08E-07	4.47E-08	1.89E-08	5.79E-08
Nov-44	8.46E-10	1.78E-08	8.80E-10	4.08E-09	3.53E-07	3.12E-09	1.61E-09	2.58E-07	5.63E-08	1.91E-08	7.99E-08
Dec-44	1.44E-08	2.88E-08	1.42E-09	8.30E-09	5.88E-07	3.60E-09	2.60E-09	4.08E-07	9.66E-08	3.10E-08	1.15E-07
Jan-45	3.85E-08	4.86E-08	2.41E-09	1.92E-08	1.01E-06	5.01E-09	4.38E-09	6.76E-07	1.58E-07	4.85E-08	1.84E-07
Feb-45	5.23E-08	4.72E-08	2.34E-09	2.92E-08	1.06E-06	2.94E-09	4.29E-09	6.53E-07	1.64E-07	4.95E-08	2.04E-07
Mar-45	9.24E-08	1.03E-07	5.05E-09	8.39E-08	1.46E-06	2.82E-08	9.19E-09	1.74E-06	3.59E-07	1.53E-07	5.08E-07
Apr-45	1.18E-07	8.44E-08	4.14E-09	7.34E-08	1.37E-06	1.26E-08	7.59E-09	1.52E-06	2.96E-07	1.44E-07	4.88E-07
May-45	6.23E-08	2.41E-08	1.16E-09	2.32E-08	3.85E-07	3.55E-08	2.12E-09	6.77E-07	9.29E-08	1.06E-07	3.26E-07
Jun-45	5.86E-08	1.13E-08	5.41E-10	1.04E-08	2.26E-07	2.27E-08	9.89E-10	3.70E-07	5.22E-08	7.65E-08	2.34E-07
Jul-45	6.53E-08	1.94E-08	9.30E-10	1.94E-08	4.05E-07	4.38E-08	1.70E-09	5.66E-07	8.35E-08	1.02E-07	3.14E-07
Aug-45	8.84E-08	3.93E-08	1.90E-09	4.11E-08	5.00E-07	2.80E-08	3.48E-09	9.28E-07	1.33E-07	1.11E-07	3.97E-07
Sep-45	6.51E-08	5.48E-08	2.67E-09	6.00E-08	5.53E-07	1.66E-08	4.89E-09	1.11E-06	2.01E-07	1.26E-07	4.39E-07
Oct-45	1.29E-07	8.25E-08	4.05E-09	8.85E-08	9.66E-07	1.17E-08	7.41E-09	1.44E-06	2.99E-07	1.36E-07	4.95E-07
Nov-45	1.13E-07	8.49E-08	4.17E-09	6.81E-08	1.21E-06	1.06E-08	7.63E-09	1.47E-06	2.82E-07	1.27E-07	4.40E-07
Dec-45	1.11E-07	7.47E-08	3.67E-09	6.87E-08	1.13E-06	1.71E-08	6.74E-09	1.33E-06	2.72E-07	1.25E-07	4.05E-07
Jan-46	7.35E-08	7.57E-08	3.72E-09	6.06E-08	1.31E-06	7.65E-08	6.79E-09	1.34E-06	2.79E-07	1.31E-07	4.57E-07
Feb-46	7.87E-08	8.95E-08	4.40E-09	6.48E-08	1.34E-06	7.05E-08	8.05E-09	1.51E-06	3.15E-07	1.34E-07	4.78E-07
Mar-46	9.15E-08	7.01E-08	3.42E-09	5.71E-08	8.76E-07	6.43E-08	6.27E-09	1.38E-06	2.52E-07	1.46E-07	4.99E-07
Apr-46	4.98E-08	2.28E-08	1.10E-09	2.21E-08	2.81E-07	2.56E-09	2.02E-09	5.94E-07	9.40E-08	9.17E-08	2.72E-07
May-46	2.19E-08	7.45E-09	3.56E-10	7.39E-09	8.28E-08	3.16E-08	6.51E-10	2.53E-07	3.44E-08	5.29E-08	1.73E-07
Jun-46	2.75E-08	5.09E-09	2.43E-10	6.45E-09	5.50E-08	4.12E-08	4.44E-10	1.81E-07	2.77E-08	4.56E-08	1.45E-07
Jul-46	3.67E-08	9.24E-09	4.42E-10	1.02E-08	1.34E-07	1.98E-08	8.08E-10	3.00E-07	4.25E-08	6.07E-08	1.99E-07
Aug-46	4.31E-08	1.84E-08	8.86E-10	2.02E-08	2.59E-07	8.05E-09	1.62E-09	5.00E-07	7.62E-08	8.02E-08	2.83E-07
Sep-46	5.85E-08	2.86E-08	1.39E-09	3.40E-08	4.02E-07	3.68E-09	2.53E-09	6.76E-07	1.15E-07	9.42E-08	3.15E-07
Oct-46	6.06E-08	4.78E-08	2.33E-09	5.05E-08	6.20E-07	3.27E-10	4.26E-09	9.74E-07	1.66E-07	9.93E-08	3.61E-07
Nov-46	5.58E-08	4.88E-08	2.39E-09	4.58E-08	5.78E-07	2.21E-08	4.38E-09	9.01E-07	1.90E-07	9.37E-08	3.39E-07
Dec-46	7.73E-08	4.23E-08	2.06E-09	4.01E-08	5.32E-07	3.43E-08	3.77E-09	8.98E-07	1.68E-07	1.11E-07	3.75E-07
Jan-47	4.68E-08	4.81E-08	2.35E-09	4.32E-08	4.31E-07	2.74E-08	4.30E-09	9.66E-07	1.79E-07	1.05E-07	3.42E-07
Feb-47	4.08E-08	4.07E-08	1.98E-09	3.42E-08	4.56E-07	2.78E-08	3.63E-09	8.59E-07	1.47E-07	9.51E-08	3.15E-07
Mar-47	6.92E-08	3.82E-08	1.85E-09	3.52E-08	3.90E-07	4.67E-08	3.39E-09	8.61E-07	1.42E-07	1.06E-07	3.49E-07
Apr-47	4.75E-08	2.26E-08	1.09E-09	2.00E-08	2.77E-07	2.37E-09	2.00E-09	5.88E-07	8.98E-08	8.75E-08	2.65E-07
May-47	2.69E-08	7.74E-09	3.70E-10	8.29E-09	9.55E-08	4.27E-08	6.76E-10	2.62E-07	3.74E-08	5.69E-08	1.78E-07
Jun-47	2.74E-08	5.51E-09	2.63E-10	7.07E-09	8.81E-08	4.01E-08	4.81E-10	1.91E-07	2.86E-08	4.52E-08	1.60E-07

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, ^{69,69m}Zn, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	^{69,69m}Zn	^{72}Ga
Jul-47	3.58E-08	1.16E-08	5.57E-10	1.19E-08	1.59E-07	2.46E-08	1.02E-09	3.68E-07	4.71E-08	6.42E-08	2.19E-07
Aug-47	3.80E-08	1.78E-08	8.62E-10	1.88E-08	5.55E-08	7.82E-09	1.58E-09	4.68E-07	6.85E-08	6.82E-08	2.51E-07
Sep-47	5.33E-08	3.02E-08	1.47E-09	3.31E-08	1.00E-07	2.87E-09	2.68E-09	6.85E-07	1.17E-07	8.76E-08	3.11E-07
Oct-47	5.65E-08	2.64E-08	1.28E-09	2.79E-08	6.73E-08	4.40E-09	2.34E-09	6.46E-07	1.03E-07	9.01E-08	3.14E-07
Nov-47	4.36E-08	2.43E-08	1.18E-09	2.47E-08	3.04E-07	3.77E-09	2.15E-09	5.80E-07	9.63E-08	8.00E-08	2.59E-07
Dec-47	6.68E-08	3.49E-08	1.70E-09	3.59E-08	3.98E-07	1.54E-09	3.11E-09	7.42E-07	1.41E-07	9.19E-08	3.29E-07
Jan-48	6.23E-08	3.44E-08	1.68E-09	3.45E-08	4.67E-07	6.78E-10	3.07E-09	7.37E-07	1.40E-07	9.33E-08	3.09E-07
Feb-48	4.78E-08	2.98E-08	1.45E-09	2.83E-08	3.81E-07	4.68E-10	2.67E-09	6.31E-07	1.16E-07	7.50E-08	2.53E-07
Mar-48	7.57E-08	4.39E-08	2.14E-09	4.13E-08	5.56E-07	1.19E-09	3.91E-09	8.95E-07	1.57E-07	9.41E-08	3.48E-07
Apr-48	6.81E-08	2.58E-08	1.25E-09	2.92E-08	3.47E-07	2.55E-09	2.30E-09	6.04E-07	1.01E-07	7.97E-08	2.83E-07
May-48	2.64E-08	7.25E-09	3.47E-10	8.10E-09	7.79E-08	3.04E-08	6.33E-10	2.45E-07	3.13E-08	4.75E-08	1.56E-07
Jun-48	1.86E-08	1.90E-09	9.06E-11	2.36E-09	3.72E-08	5.41E-08	1.66E-10	7.16E-08	1.23E-08	2.21E-08	8.79E-08
Jul-48	7.31E-08	1.45E-08	6.95E-10	1.58E-08	2.52E-07	3.64E-08	1.27E-09	4.54E-07	6.06E-08	8.27E-08	3.00E-07
Aug-48	1.00E-07	2.47E-08	1.19E-09	2.48E-08	2.58E-07	7.86E-08	2.18E-09	6.59E-07	9.16E-08	9.59E-08	3.64E-07
Sep-48	8.42E-08	3.63E-08	1.76E-09	3.33E-08	4.10E-07	4.53E-08	3.23E-09	8.27E-07	1.22E-07	9.63E-08	3.89E-07
Oct-48	1.12E-07	6.21E-08	3.03E-09	5.14E-08	1.19E-06	2.25E-08	5.54E-09	1.21E-06	2.14E-07	1.26E-07	4.91E-07
Nov-48	1.12E-07	6.51E-08	3.19E-09	6.55E-08	5.24E-07	2.35E-08	5.85E-09	1.17E-06	2.16E-07	1.07E-07	4.65E-07
Dec-48	1.65E-07	8.15E-08	4.00E-09	7.81E-08	1.36E-06	2.88E-08	7.31E-09	1.45E-06	2.88E-07	1.37E-07	5.35E-07
Jan-49	1.60E-07	7.84E-08	3.85E-09	7.19E-08	1.37E-06	2.33E-08	7.04E-09	1.39E-06	2.84E-07	1.35E-07	5.05E-07
Feb-49	1.47E-07	6.84E-08	3.36E-09	6.18E-08	1.12E-06	1.77E-08	6.16E-09	1.20E-06	2.38E-07	1.10E-07	4.37E-07
Mar-49	1.46E-07	8.59E-08	4.21E-09	7.27E-08	1.28E-06	2.82E-08	7.69E-09	1.56E-06	3.09E-07	1.53E-07	5.59E-07
Apr-49	8.55E-08	3.34E-08	1.62E-09	3.01E-08	5.34E-07	4.76E-08	2.96E-09	8.22E-07	1.23E-07	1.11E-07	3.78E-07
May-49	6.52E-08	1.15E-08	5.49E-10	1.14E-08	2.07E-07	4.37E-08	1.00E-09	3.74E-07	5.05E-08	7.38E-08	2.57E-07
Jun-49	6.51E-08	1.11E-08	5.30E-10	1.17E-08	2.26E-07	4.48E-08	9.70E-10	3.58E-07	5.02E-08	7.22E-08	2.76E-07
Jul-49	8.68E-08	2.42E-08	1.17E-09	2.83E-08	2.55E-07	7.75E-08	2.13E-09	6.58E-07	9.27E-08	1.00E-07	3.92E-07
Aug-49	1.21E-07	3.61E-08	1.75E-09	4.32E-08	4.67E-07	6.09E-08	3.20E-09	8.49E-07	1.46E-07	1.22E-07	4.55E-07
Sep-49	1.54E-07	5.35E-08	2.61E-09	5.95E-08	6.49E-07	4.20E-08	4.77E-09	1.08E-06	1.90E-07	1.17E-07	5.09E-07
Oct-49	1.30E-07	8.81E-08	4.32E-09	8.33E-08	1.22E-06	4.23E-08	7.88E-09	1.60E-06	3.05E-07	1.52E-07	6.20E-07
Nov-49	1.68E-07	1.02E-07	4.97E-09	8.00E-08	1.60E-06	7.31E-08	9.08E-09	1.91E-06	3.40E-07	1.79E-07	7.24E-07
Dec-49	1.74E-07	1.02E-07	4.98E-09	8.28E-08	2.03E-06	8.82E-08	9.10E-09	2.04E-06	3.66E-07	2.18E-07	7.49E-07
Jan-50	2.37E-07	9.67E-08	4.72E-09	7.51E-08	1.95E-06	7.75E-08	8.64E-09	1.93E-06	3.10E-07	1.84E-07	6.99E-07
Feb-50	2.07E-07	8.89E-08	4.33E-09	6.48E-08	1.68E-06	8.44E-08	7.93E-09	1.81E-06	2.84E-07	1.74E-07	6.72E-07
Mar-50	2.23E-07	8.82E-08	4.29E-09	7.03E-08	1.72E-06	9.44E-08	7.85E-09	1.91E-06	3.01E-07	2.10E-07	7.67E-07
Apr-50	1.84E-07	5.36E-08	2.60E-09	4.79E-08	1.14E-06	5.91E-08	4.75E-09	1.32E-06	1.93E-07	1.71E-07	6.13E-07
May-50	1.62E-07	2.51E-08	1.20E-09	2.33E-08	5.56E-07	1.20E-07	2.20E-09	7.66E-07	1.01E-07	1.32E-07	4.77E-07
Jun-50	6.63E-08	1.02E-08	4.86E-10	1.14E-08	2.48E-07	1.17E-07	8.89E-10	3.59E-07	4.87E-08	7.95E-08	3.22E-07
Jul-50	1.03E-07	1.25E-08	5.96E-10	1.45E-08	3.35E-07	1.38E-07	1.09E-09	4.34E-07	5.62E-08	8.98E-08	3.65E-07
Aug-50	1.37E-07	3.17E-08	1.53E-09	3.44E-08	3.59E-07	4.11E-08	2.79E-09	8.82E-07	1.14E-07	1.27E-07	5.32E-07
Sep-50	2.07E-07	5.41E-08	2.62E-09	5.83E-08	2.51E-07	6.45E-08	4.80E-09	1.25E-06	1.87E-07	1.49E-07	6.22E-07
Oct-50	3.33E-07	6.56E-08	3.19E-09	8.05E-08	6.23E-07	4.67E-08	5.85E-09	1.39E-06	2.59E-07	1.73E-07	7.69E-07
Nov-50	3.03E-07	7.75E-08	3.77E-09	7.46E-08	6.56E-07	6.77E-08	6.88E-09	1.69E-06	2.59E-07	1.86E-07	7.80E-07

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, ^{69,69m}Zn, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	^{69,69m}Zn	^{72}Ga
Dec-50	4.20E-07	8.54E-08	4.15E-09	7.33E-08	1.27E-06	3.30E-08	7.59E-09	1.86E-06	2.76E-07	1.97E-07	8.21E-07
Jan-51	3.47E-07	5.32E-08	2.59E-09	3.36E-08	9.85E-07	4.82E-08	4.75E-09	1.16E-06	1.35E-07	9.87E-08	4.13E-07
Feb-51	5.81E-07	3.88E-08	1.88E-09	2.05E-08	1.18E-06	8.29E-08	3.44E-09	9.20E-07	1.11E-07	9.42E-08	3.96E-07
Mar-51	7.14E-07	5.92E-08	2.87E-09	2.93E-08	1.26E-06	5.80E-08	5.25E-09	1.33E-06	1.53E-07	1.17E-07	5.56E-07
Apr-51	3.36E-07	2.76E-08	1.33E-09	1.98E-08	9.02E-07	6.12E-08	2.44E-09	7.08E-07	1.01E-07	9.94E-08	3.96E-07
May-51	1.73E-07	6.54E-09	3.13E-10	8.61E-09	4.24E-07	8.94E-08	5.72E-10	2.15E-07	4.51E-08	6.66E-08	2.86E-07
Jun-51	1.84E-07	1.09E-08	5.20E-10	1.20E-08	3.45E-07	8.41E-08	9.49E-10	3.63E-07	4.72E-08	7.13E-08	3.03E-07
Jul-51	1.93E-07	1.21E-08	5.80E-10	1.34E-08	2.24E-07	7.48E-08	1.06E-09	3.88E-07	6.31E-08	8.96E-08	3.99E-07
Aug-51	3.93E-07	3.22E-08	1.55E-09	2.78E-08	6.33E-07	7.67E-08	2.84E-09	8.69E-07	9.67E-08	1.02E-07	5.06E-07
Sep-51	4.97E-07	6.21E-08	3.02E-09	6.49E-08	1.31E-06	4.13E-08	5.52E-09	1.33E-06	2.24E-07	1.57E-07	7.16E-07
Oct-51	4.65E-07	5.97E-08	2.91E-09	3.21E-08	1.56E-06	5.43E-08	5.32E-09	1.31E-06	1.67E-07	1.20E-07	5.55E-07
Nov-51	6.07E-07	6.25E-08	3.04E-09	5.11E-08	1.48E-06	5.00E-08	5.57E-09	1.31E-06	2.14E-07	1.41E-07	6.31E-07
Dec-51	5.87E-07	6.79E-08	3.31E-09	3.05E-08	2.06E-06	3.54E-08	6.06E-09	1.37E-06	1.54E-07	9.51E-08	4.14E-07
Jan-52	5.00E-07	6.59E-08	3.20E-09	5.79E-08	1.16E-06	3.90E-08	5.85E-09	1.44E-06	2.29E-07	1.66E-07	6.39E-07
Feb-52	6.41E-07	9.19E-08	4.48E-09	1.33E-08	2.17E-06	3.37E-08	8.17E-09	1.92E-06	9.78E-08	6.32E-08	3.10E-07
Mar-52	7.27E-07	6.19E-08	3.01E-09	3.34E-08	1.20E-06	7.06E-08	5.52E-09	1.33E-06	1.64E-07	1.16E-07	5.10E-07
Apr-52	7.57E-07	4.48E-08	2.17E-09	1.45E-08	1.71E-06	1.16E-07	3.99E-09	1.02E-06	9.06E-08	7.06E-08	3.31E-07
May-52	3.23E-07	1.45E-08	6.97E-10	7.17E-09	5.84E-07	1.34E-07	1.27E-09	4.66E-07	4.55E-08	6.45E-08	3.30E-07
Jun-52	2.62E-07	1.31E-08	6.26E-10	4.80E-09	6.34E-07	1.05E-07	1.14E-09	4.14E-07	3.06E-08	4.26E-08	2.46E-07
Jul-52	3.49E-07	2.29E-08	1.10E-09	1.78E-08	9.32E-07	9.01E-08	2.01E-09	6.77E-07	6.28E-08	7.79E-08	3.78E-07
Aug-52	5.38E-07	3.55E-08	1.72E-09	1.37E-08	1.61E-06	6.51E-08	3.14E-09	8.66E-07	7.73E-08	6.85E-08	3.23E-07
Sep-52	1.12E-06	8.68E-08	4.23E-09	2.79E-08	2.68E-06	4.42E-08	7.73E-09	1.74E-06	1.15E-07	6.97E-08	4.39E-07
Oct-52	1.05E-06	1.89E-07	9.25E-09	6.71E-08	3.38E-06	8.00E-08	1.68E-08	3.62E-06	2.24E-07	1.23E-07	6.59E-07
Nov-52	9.40E-07	1.67E-07	8.17E-09	2.81E-08	3.33E-06	5.24E-08	1.50E-08	3.04E-06	1.84E-07	9.32E-08	4.91E-07
Dec-52	9.89E-07	2.17E-07	1.07E-08	4.20E-08	3.10E-06	4.13E-08	1.95E-08	3.58E-06	3.04E-07	1.29E-07	6.86E-07
Jan-53	1.11E-06	3.10E-07	1.52E-08	3.74E-08	2.97E-06	5.63E-08	2.78E-08	5.37E-06	2.49E-07	1.12E-07	6.34E-07
Feb-53	1.06E-06	1.78E-07	8.67E-09	3.13E-08	2.32E-06	5.81E-08	1.59E-08	3.65E-06	1.84E-07	1.19E-07	5.63E-07
Mar-53	1.55E-06	1.87E-07	9.09E-09	2.57E-08	2.42E-06	1.16E-07	1.66E-08	4.02E-06	1.69E-07	1.19E-07	5.95E-07
Apr-53	1.13E-06	1.38E-07	6.72E-09	2.58E-08	2.43E-06	2.16E-07	1.23E-08	2.93E-06	3.43E-08	2.35E-08	3.41E-07
May-53	9.80E-07	8.62E-08	4.16E-09	2.26E-08	1.57E-06	4.69E-07	7.60E-09	2.25E-06	7.16E-08	7.28E-08	5.11E-07
Jun-53	3.92E-07	2.61E-08	1.25E-09	5.96E-09	8.09E-07	4.04E-07	2.29E-09	8.47E-07	1.79E-08	2.59E-08	3.00E-07
Jul-53	4.64E-07	2.62E-08	1.26E-09	1.34E-08	1.10E-06	3.47E-07	2.30E-09	8.00E-07	5.26E-08	6.97E-08	3.76E-07
Aug-53	8.73E-07	6.71E-08	3.25E-09	2.74E-08	2.31E-06	2.97E-07	5.93E-09	1.66E-06	1.19E-07	1.10E-07	5.75E-07
Sep-53	9.07E-07	7.09E-08	3.44E-09	5.10E-08	2.38E-06	2.61E-07	6.31E-09	1.55E-06	1.52E-07	1.12E-07	6.38E-07
Oct-53	1.38E-06	1.05E-07	5.12E-09	4.87E-08	3.16E-06	2.06E-07	9.34E-09	2.20E-06	2.04E-07	1.37E-07	7.48E-07
Nov-53	1.53E-06	1.92E-07	9.37E-09	5.77E-08	3.75E-06	2.10E-07	1.71E-08	3.84E-06	1.67E-07	1.02E-07	6.93E-07
Dec-53	1.74E-06	2.52E-07	1.23E-08	4.88E-08	4.12E-06	1.96E-07	2.25E-08	4.87E-06	1.65E-07	9.41E-08	7.40E-07
Jan-54	8.54E-07	1.49E-07	7.26E-09	1.08E-07	2.52E-06	8.98E-08	1.33E-08	2.89E-06	3.77E-07	2.23E-07	9.24E-07
Feb-54	8.02E-07	1.33E-07	6.49E-09	1.02E-07	2.52E-06	7.24E-08	1.19E-08	2.55E-06	3.91E-07	2.20E-07	8.83E-07
Mar-54	1.17E-06	1.41E-07	6.89E-09	1.11E-07	2.57E-06	1.31E-07	1.26E-08	2.90E-06	3.88E-07	2.50E-07	9.95E-07
Apr-54	9.59E-07	1.42E-07	6.92E-09	1.17E-07	2.79E-06	1.05E-07	1.27E-08	2.81E-06	3.89E-07	2.33E-07	9.67E-07
May-54	4.36E-07	3.32E-08	1.60E-09	3.03E-08	6.14E-07	3.01E-07	2.92E-09	1.00E-06	1.19E-07	1.54E-07	6.18E-07

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, ^{69,69m}Zn, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	^{69,69m}Zn	^{72}Ga
Jun-54	4.36E-07	2.03E-08	9.70E-10	2.11E-08	4.06E-07	4.51E-07	1.77E-09	6.88E-07	8.80E-08	1.36E-07	5.35E-07
Jul-54	4.44E-07	2.43E-08	1.16E-09	2.89E-08	4.88E-07	4.72E-07	2.12E-09	8.13E-07	9.32E-08	1.42E-07	6.06E-07
Aug-54	6.98E-07	5.27E-08	2.54E-09	5.83E-08	1.43E-06	3.23E-07	4.63E-09	1.47E-06	1.68E-07	1.91E-07	7.97E-07
Sep-54	8.28E-07	8.49E-08	4.11E-09	8.22E-08	2.16E-06	2.26E-07	7.51E-09	2.08E-06	2.36E-07	2.13E-07	9.07E-07
Oct-54	1.04E-06	1.29E-07	6.31E-09	1.18E-07	3.24E-06	1.51E-07	1.16E-08	2.66E-06	3.75E-07	2.44E-07	1.04E-06
Nov-54	1.04E-06	1.28E-07	6.22E-09	1.09E-07	2.70E-06	1.36E-07	1.14E-08	2.62E-06	3.24E-07	2.10E-07	9.57E-07
Dec-54	1.25E-06	1.43E-07	6.99E-09	1.36E-07	3.63E-06	1.57E-07	1.28E-08	2.91E-06	3.92E-07	2.48E-07	1.11E-06
Jan-55	1.30E-06	1.34E-07	6.55E-09	1.38E-07	3.61E-06	1.79E-07	1.20E-08	2.70E-06	3.63E-07	2.24E-07	1.07E-06
Feb-55	8.14E-07	8.16E-08	3.98E-09	5.08E-08	1.90E-06	8.59E-08	7.31E-09	1.65E-06	2.17E-07	1.38E-07	6.37E-07
Mar-55	1.80E-06	1.34E-07	6.51E-09	1.25E-07	4.67E-06	3.17E-07	1.19E-08	2.90E-06	4.72E-07	3.43E-07	1.38E-06
Apr-55	1.41E-06	1.10E-07	5.37E-09	8.89E-08	4.63E-06	3.66E-07	9.85E-09	2.30E-06	3.89E-07	2.61E-07	1.19E-06
May-55	8.41E-07	1.10E-07	5.36E-09	1.03E-07	5.64E-06	4.51E-07	9.79E-09	2.35E-06	4.85E-07	3.45E-07	1.56E-06
Jun-55	3.86E-07	2.26E-08	1.08E-09	2.14E-08	1.25E-06	3.99E-07	1.98E-09	7.15E-07	1.44E-07	2.03E-07	8.76E-07
Jul-55	8.30E-07	2.00E-08	9.55E-10	1.07E-08	1.45E-06	4.96E-07	1.75E-09	6.49E-07	9.57E-08	1.40E-07	7.69E-07
Aug-55	1.11E-06	3.98E-08	1.93E-09	1.79E-08	3.30E-06	4.93E-07	3.52E-09	1.02E-06	2.13E-07	2.11E-07	9.28E-07
Sep-55	1.72E-06	7.37E-08	3.59E-09	3.79E-08	4.39E-06	2.90E-07	6.56E-09	1.52E-06	2.82E-07	1.86E-07	9.42E-07
Oct-55	1.53E-06	1.66E-07	8.14E-09	1.27E-07	4.07E-06	2.35E-07	1.48E-08	3.14E-06	5.28E-07	2.95E-07	1.45E-06
Nov-55	1.79E-06	1.55E-07	7.58E-09	1.10E-07	3.82E-06	1.46E-07	1.39E-08	3.13E-06	5.28E-07	3.35E-07	1.44E-06
Dec-55	2.31E-06	2.28E-07	1.11E-08	1.33E-07	5.23E-06	1.57E-07	2.03E-08	4.32E-06	6.98E-07	3.94E-07	1.56E-06
Jan-56	1.40E-06	1.14E-07	5.57E-09	9.58E-08	3.71E-06	1.28E-07	1.03E-08	2.20E-06	5.78E-07	3.40E-07	1.26E-06
Feb-56	1.24E-06	1.26E-07	6.15E-09	9.47E-08	3.00E-06	1.14E-07	1.12E-08	2.44E-06	5.17E-07	3.04E-07	1.23E-06
Mar-56	2.02E-06	2.66E-07	1.30E-08	1.31E-07	4.26E-06	1.65E-07	2.36E-08	5.17E-06	6.42E-07	3.82E-07	1.57E-06
Apr-56	1.02E-06	6.60E-08	3.18E-09	5.14E-08	1.46E-06	3.98E-07	5.83E-09	1.79E-06	2.45E-07	2.71E-07	1.09E-06
May-56	7.17E-07	3.15E-08	1.51E-09	2.94E-08	7.55E-07	7.05E-07	2.76E-09	9.93E-07	1.65E-07	2.32E-07	9.46E-07
Jun-56	9.13E-07	1.95E-08	9.32E-10	2.12E-08	5.59E-07	9.77E-07	1.70E-09	6.59E-07	1.17E-07	1.83E-07	8.08E-07
Jul-56	1.25E-06	2.55E-08	1.22E-09	4.02E-08	1.37E-06	7.58E-07	2.24E-09	7.49E-07	1.96E-07	2.46E-07	1.12E-06
Aug-56	1.76E-06	4.86E-08	2.35E-09	9.27E-08	3.29E-06	3.58E-07	4.31E-09	1.16E-06	3.62E-07	3.17E-07	1.52E-06
Sep-56	2.07E-06	9.06E-08	4.42E-09	1.28E-07	4.83E-06	2.34E-07	8.07E-09	1.84E-06	5.31E-07	3.43E-07	1.53E-06
Oct-56	1.91E-06	1.01E-07	4.91E-09	1.15E-07	5.93E-06	1.86E-07	8.99E-09	1.95E-06	4.40E-07	2.58E-07	1.39E-06
Nov-56	2.16E-06	1.69E-07	8.27E-09	9.67E-08	6.50E-06	1.71E-07	1.51E-08	3.26E-06	4.71E-07	2.71E-07	1.21E-06
Dec-56	2.45E-06	2.19E-07	1.07E-08	8.44E-08	6.53E-06	1.54E-07	1.95E-08	4.02E-06	4.07E-07	2.16E-07	1.17E-06
Jan-57	3.02E-06	2.42E-07	1.18E-08	1.34E-07	5.28E-06	2.06E-07	2.15E-08	4.86E-06	3.53E-07	2.23E-07	1.06E-06
Feb-57	3.17E-06	2.44E-07	1.19E-08	9.53E-08	5.57E-06	2.64E-07	2.19E-08	4.79E-06	2.71E-07	1.62E-07	1.00E-06
Mar-57	5.05E-06	3.01E-07	1.48E-08	1.15E-07	6.62E-06	5.38E-07	2.71E-08	5.20E-06	4.69E-07	2.19E-07	1.33E-06
Apr-57	3.71E-06	2.16E-07	1.05E-08	1.07E-07	6.88E-06	1.26E-06	1.93E-08	4.15E-06	3.69E-07	2.18E-07	1.03E-06
May-57	1.54E-06	4.75E-08	2.28E-09	2.38E-08	1.48E-06	3.54E-06	4.16E-09	1.46E-06	1.14E-07	1.55E-07	7.38E-07
Jun-57	1.17E-06	3.16E-08	1.51E-09	1.47E-08	9.83E-07	1.56E-06	2.77E-09	9.90E-07	8.27E-08	1.15E-07	7.23E-07
Jul-57	2.38E-06	5.73E-08	2.77E-09	5.74E-08	3.75E-06	1.09E-06	5.06E-09	1.50E-06	2.94E-07	3.03E-07	1.22E-06
Aug-57	2.60E-06	1.63E-07	7.93E-09	9.66E-08	6.17E-06	6.84E-07	1.45E-08	3.62E-06	3.78E-07	2.87E-07	1.26E-06
Sep-57	3.35E-06	2.07E-07	1.01E-08	1.34E-07	8.34E-06	3.56E-07	1.85E-08	3.85E-06	6.16E-07	3.35E-07	1.52E-06
Oct-57	4.44E-06	2.38E-07	1.16E-08	1.61E-07	1.02E-05	3.94E-07	2.13E-08	4.32E-06	7.59E-07	3.94E-07	1.56E-06

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, $^{69,69m}Zn$, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	$^{69,69m}Zn$	^{72}Ga
Nov-57	4.10E-06	2.43E-07	1.19E-08	1.52E-07	1.03E-05	4.35E-07	2.18E-08	4.39E-06	8.22E-07	4.20E-07	1.52E-06
Dec-57	3.77E-06	5.26E-07	2.58E-08	1.85E-07	9.78E-06	3.46E-07	4.69E-08	9.19E-06	8.85E-07	4.19E-07	1.54E-06
Jan-58	4.36E-06	4.45E-07	2.18E-08	1.67E-07	9.68E-06	3.71E-07	4.00E-08	7.92E-06	5.61E-07	2.76E-07	1.46E-06
Feb-58	3.32E-06	3.30E-07	1.61E-08	1.18E-07	7.41E-06	3.93E-07	2.96E-08	6.29E-06	5.59E-07	3.17E-07	1.32E-06
Mar-58	3.95E-06	2.32E-07	1.13E-08	9.44E-08	5.82E-06	6.62E-07	2.07E-08	4.93E-06	3.85E-07	2.70E-07	1.44E-06
Apr-58	2.90E-06	4.13E-07	2.01E-08	9.88E-08	5.41E-06	5.49E-07	3.66E-08	9.02E-06	5.44E-07	4.04E-07	1.19E-06
May-58	1.91E-06	1.17E-07	5.61E-09	3.69E-08	2.34E-06	1.39E-06	1.03E-08	3.40E-06	2.10E-07	2.58E-07	1.07E-06
Jun-58	1.65E-06	6.89E-08	3.30E-09	2.50E-08	1.81E-06	2.48E-06	6.04E-09	2.19E-06	7.96E-08	1.13E-07	1.03E-06
Jul-58	2.71E-06	2.08E-07	1.01E-08	5.57E-08	2.75E-06	1.33E-06	1.84E-08	5.52E-06	1.90E-07	1.99E-07	1.29E-06
Aug-58	3.91E-06	1.93E-07	9.40E-09	8.59E-08	8.25E-06	5.86E-07	1.73E-08	4.20E-06	3.57E-07	2.63E-07	3.33E-07
Sep-58	5.18E-06	2.16E-07	1.05E-08	7.38E-08	7.80E-06	9.64E-07	1.93E-08	4.07E-06	2.43E-07	1.34E-07	1.97E-06
Oct-58	5.82E-06	3.05E-07	1.49E-08	1.23E-07	8.15E-06	7.22E-07	2.72E-08	5.81E-06	7.44E-07	4.24E-07	9.74E-07
Nov-58	4.36E-06	3.19E-07	1.56E-08	1.54E-07	7.06E-06	3.57E-07	2.86E-08	5.87E-06	5.61E-07	2.93E-07	7.84E-07
Dec-58	5.72E-06	4.16E-07	2.03E-08	5.48E-08	8.08E-06	4.93E-07	3.71E-08	8.00E-06	5.66E-07	3.24E-07	6.95E-07
Jan-59	4.18E-06	3.67E-07	1.79E-08	4.51E-08	6.64E-06	3.95E-07	3.28E-08	7.43E-06	2.83E-07	1.80E-07	1.02E-06
Feb-59	3.59E-06	3.34E-07	1.62E-08	2.81E-08	5.04E-06	6.20E-07	2.97E-08	6.98E-06	3.92E-07	2.68E-07	9.19E-08
Mar-59	5.98E-06	3.36E-07	1.63E-08	4.01E-08	4.51E-06	1.05E-06	2.98E-08	7.48E-06	4.56E-07	3.51E-07	5.08E-08
Apr-59	5.51E-06	1.99E-07	9.63E-09	4.20E-08	4.16E-06	2.27E-06	1.77E-08	4.83E-06	3.17E-07	2.86E-07	1.46E-06
May-59	2.99E-06	8.22E-08	3.95E-09	1.02E-08	3.01E-06	2.26E-06	7.22E-09	2.42E-06	1.61E-07	2.03E-07	1.17E-06
Jun-59	2.33E-06	4.12E-08	1.97E-09	9.64E-09	1.65E-06	1.61E-06	3.60E-09	1.36E-06	9.45E-08	1.41E-07	7.76E-07
Jul-59	2.43E-06	5.62E-08	2.70E-09	3.55E-08	2.28E-06	1.84E-06	4.92E-09	1.77E-06	1.41E-07	1.96E-07	1.09E-06
Aug-59	5.56E-06	1.12E-07	5.44E-09	7.22E-08	3.78E-06	1.23E-06	9.95E-09	2.79E-06	2.21E-07	2.07E-07	1.50E-06
Sep-59	4.82E-06	1.27E-07	6.18E-09	5.92E-08	4.01E-06	1.00E-06	1.13E-08	3.01E-06	5.14E-07	4.42E-07	1.20E-06
Oct-59	3.92E-06	2.36E-07	1.14E-08	2.28E-08	5.46E-06	1.08E-06	2.08E-08	5.60E-06	2.11E-07	1.81E-07	1.05E-06
Nov-59	6.09E-06	3.17E-07	1.54E-08	6.57E-08	4.46E-06	8.13E-07	2.81E-08	7.27E-06	5.28E-07	4.32E-07	9.51E-07
Dec-59	7.46E-06	2.67E-07	1.30E-08	1.91E-07	7.04E-06	7.65E-07	2.38E-08	5.81E-06	8.36E-07	6.15E-07	1.50E-06
Jan-60	8.59E-06	4.38E-07	2.14E-08	4.25E-07	8.12E-06	5.67E-07	3.90E-08	8.82E-06	1.66E-06	1.05E-06	2.60E-07
Feb-60	8.51E-06	3.05E-07	1.49E-08	4.35E-08	7.98E-06	7.36E-07	2.74E-08	6.04E-06	4.90E-07	2.94E-07	1.31E-06
Mar-60	1.14E-05	4.68E-07	2.29E-08	9.77E-08	1.15E-05	1.51E-06	4.17E-08	8.92E-06	6.41E-07	3.65E-07	7.09E-07
Apr-60	6.92E-06	1.73E-07	8.34E-09	8.00E-08	5.11E-06	3.87E-06	1.53E-08	4.58E-06	4.28E-07	4.51E-07	1.28E-06
May-60	5.61E-06	1.37E-07	6.60E-09	4.65E-08	4.51E-06	2.21E-06	1.21E-08	3.82E-06	3.59E-07	4.11E-07	2.04E-06
Jun-60	2.83E-06	7.49E-08	3.59E-09	4.16E-08	3.37E-06	1.78E-06	6.57E-09	2.29E-06	2.22E-07	2.97E-07	2.61E-07
Jul-60	2.85E-06	8.34E-08	4.01E-09	5.95E-08	2.96E-06	1.82E-06	7.32E-09	2.49E-06	2.41E-07	3.10E-07	8.65E-07
Aug-60	5.94E-06	1.48E-07	7.16E-09	2.46E-08	2.82E-06	1.62E-06	1.31E-08	3.56E-06	2.05E-07	1.81E-07	1.20E-06
Sep-60	8.41E-06	2.09E-07	1.02E-08	1.78E-07	8.36E-06	1.36E-06	1.87E-08	4.15E-06	5.82E-07	3.58E-07	2.20E-06
Oct-60	6.75E-06	2.66E-07	1.30E-08	2.39E-07	1.52E-05	4.34E-07	2.38E-08	4.96E-06	5.91E-07	3.21E-07	1.71E-06
Nov-60	1.30E-05	4.39E-07	2.15E-08	2.71E-07	1.91E-05	9.48E-07	3.91E-08	8.26E-06	5.64E-07	3.10E-07	1.99E-06
Dec-60	9.33E-06	6.59E-07	3.23E-08	5.80E-08	1.30E-05	1.04E-06	5.90E-08	1.17E-05	9.93E-07	4.88E-07	1.84E-06
Jan-61	1.16E-05	7.23E-07	3.54E-08	1.38E-07	1.78E-05	1.18E-06	6.47E-08	1.32E-05	1.26E-06	6.61E-07	2.12E-06
Feb-61	5.91E-06	5.34E-07	2.60E-08	3.84E-08	6.60E-06	1.07E-06	4.76E-08	1.13E-05	5.88E-07	4.10E-07	1.55E-06
Mar-61	1.02E-05	5.63E-07	2.74E-08	3.09E-07	7.58E-06	2.45E-06	5.00E-08	1.22E-05	1.18E-06	8.67E-07	1.26E-06
Apr-61	7.04E-06	4.44E-07	2.16E-08	8.30E-08	7.03E-06	2.56E-06	3.95E-08	1.01E-05	1.23E-06	9.78E-07	1.45E-06

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, ^{69,69m}Zn, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	^{69,69m}Zn	^{72}Ga
May-61	4.24E-06	1.78E-07	8.57E-09	9.84E-09	3.07E-06	2.39E-06	1.57E-08	5.15E-06	3.10E-07	3.78E-07	1.65E-06
Jun-61	2.40E-06	6.00E-08	2.87E-09	5.25E-10	1.47E-06	1.95E-06	5.24E-09	2.06E-06	1.89E-07	3.01E-07	6.39E-07
Jul-61	3.52E-06	7.67E-08	3.69E-09	1.10E-09	2.88E-06	1.59E-06	6.76E-09	2.12E-06	1.54E-07	1.74E-07	4.94E-07
Aug-61	4.08E-06	8.21E-08	3.99E-09	6.98E-09	8.13E-06	7.58E-07	7.33E-09	1.83E-06	5.59E-07	4.34E-07	5.23E-07
Sep-61	2.77E-06	1.88E-07	9.18E-09	9.05E-09	1.51E-05	5.07E-07	1.67E-08	3.44E-06	6.67E-07	3.51E-07	3.36E-07
Oct-61	5.15E-06	2.39E-07	1.17E-08	5.69E-09	1.67E-05	4.20E-07	2.14E-08	4.33E-06	4.62E-07	2.34E-07	4.88E-07
Nov-61	5.87E-06	2.67E-07	1.31E-08	7.37E-09	1.84E-05	3.99E-07	2.40E-08	4.73E-06	6.68E-07	3.28E-07	6.59E-07
Dec-61	6.64E-06	2.58E-07	1.27E-08	8.46E-09	2.04E-05	3.02E-07	2.33E-08	4.35E-06	4.75E-07	2.07E-07	3.54E-07
Jan-62	7.00E-06	2.56E-07	1.25E-08	2.12E-08	2.96E-05	4.21E-07	2.28E-08	4.77E-06	1.00E-06	5.48E-07	2.88E-07
Feb-62	6.34E-06	2.35E-07	1.15E-08	1.51E-08	1.58E-05	4.65E-07	2.10E-08	4.49E-06	6.15E-07	3.56E-07	2.56E-07
Mar-62	9.82E-06	4.44E-07	2.18E-08	1.70E-08	2.41E-05	1.03E-06	3.97E-08	7.77E-06	9.65E-07	4.61E-07	2.21E-07
Apr-62	8.30E-06	2.24E-07	1.09E-08	1.38E-08	1.58E-05	4.42E-06	1.99E-08	5.16E-06	1.08E-06	8.82E-07	8.00E-07
May-62	4.74E-06	1.46E-07	7.01E-09	2.70E-08	1.10E-05	2.44E-06	1.28E-08	3.92E-06	3.84E-07	4.16E-07	1.17E-07
Jun-62	3.65E-06	6.74E-08	3.24E-09	4.48E-09	3.78E-06	3.97E-06	5.92E-09	2.05E-06	3.19E-07	4.21E-07	1.02E-07
Jul-62	3.57E-06	7.15E-08	3.44E-09	1.22E-08	8.35E-06	2.23E-06	6.30E-09	2.00E-06	5.42E-07	6.23E-07	3.05E-07
Aug-62	4.76E-06	1.48E-07	7.17E-09	9.99E-08	8.91E-06	1.52E-06	1.31E-08	3.55E-06	7.14E-07	6.29E-07	6.29E-07
Sep-62	6.94E-06	2.66E-07	1.30E-08	2.28E-07	2.48E-05	8.34E-07	2.38E-08	4.96E-06	1.54E-06	8.44E-07	8.92E-07
Oct-62	5.99E-06	2.07E-07	1.01E-08	9.89E-08	2.30E-05	6.27E-07	1.86E-08	3.83E-06	6.07E-07	3.22E-07	5.30E-07
Nov-62	4.30E-06	1.78E-07	8.69E-09	8.80E-08	1.49E-05	1.13E-06	1.59E-08	3.44E-06	6.31E-07	3.68E-07	6.43E-07
Dec-62	4.72E-06	1.75E-07	8.54E-09	1.25E-07	1.54E-05	8.13E-07	1.56E-08	3.60E-06	8.64E-07	5.69E-07	3.50E-07
Jan-63	4.06E-06	1.57E-07	7.67E-09	1.17E-07	5.86E-06	3.13E-07	1.41E-08	3.16E-06	4.41E-07	2.81E-07	3.11E-07
Feb-63	4.18E-06	1.31E-07	6.36E-09	8.50E-08	7.68E-06	6.61E-07	1.17E-08	2.78E-06	3.73E-07	2.60E-07	2.99E-07
Mar-63	8.02E-06	2.86E-07	1.39E-08	1.56E-07	1.09E-05	1.33E-06	2.54E-08	5.72E-06	2.70E-07	1.68E-07	3.64E-07
Apr-63	6.83E-06	2.32E-07	1.13E-08	1.00E-07	8.36E-06	1.47E-06	2.06E-08	5.16E-06	3.50E-07	2.69E-07	4.09E-07
May-63	2.82E-06	1.15E-07	5.56E-09	4.10E-08	4.42E-06	1.86E-06	1.02E-08	2.93E-06	1.61E-07	1.57E-07	3.57E-07
Jun-63	2.26E-06	6.00E-08	2.88E-09	3.32E-08	2.53E-06	2.00E-06	5.26E-09	1.83E-06	5.79E-08	7.67E-08	2.46E-07
Jul-63	2.85E-06	7.46E-08	3.59E-09	4.28E-08	4.06E-06	2.76E-06	6.56E-09	2.11E-06	6.89E-08	8.06E-08	3.52E-07
Aug-63	3.51E-06	1.07E-07	5.21E-09	6.35E-08	9.45E-06	1.50E-06	9.55E-09	2.48E-06	1.16E-07	9.43E-08	5.66E-07
Sep-63	4.64E-06	1.60E-07	7.82E-09	1.23E-07	1.18E-05	7.08E-07	1.43E-08	3.04E-06	1.41E-07	7.95E-08	6.51E-07
Oct-63	4.90E-06	2.26E-07	1.11E-08	1.41E-07	1.55E-05	6.07E-07	2.02E-08	4.15E-06	2.21E-07	1.16E-07	8.08E-07
Nov-63	5.21E-06	2.42E-07	1.19E-08	1.34E-07	1.46E-05	4.31E-07	2.17E-08	4.22E-06	2.58E-07	1.22E-07	5.61E-07
Dec-63	6.46E-06	3.11E-07	1.53E-08	1.63E-07	1.58E-05	5.69E-07	2.78E-08	5.54E-06	2.07E-07	1.02E-07	7.38E-07
Jan-64	6.33E-06	3.19E-07	1.57E-08	1.66E-07	1.46E-05	3.60E-07	2.87E-08	5.31E-06	2.77E-07	1.21E-07	4.77E-07
Feb-64	4.45E-06	2.38E-07	1.16E-08	8.93E-08	1.01E-05	5.35E-07	2.13E-08	4.75E-06	2.60E-07	1.60E-07	4.35E-07
Mar-64	5.38E-06	4.08E-07	2.00E-08	1.68E-07	1.30E-05	5.88E-07	3.65E-08	7.39E-06	3.72E-07	1.90E-07	5.57E-07
Apr-64	5.43E-06	3.03E-07	1.48E-08	1.60E-07	9.43E-06	5.39E-07	2.72E-08	5.45E-06	4.48E-07	2.30E-07	3.72E-07
May-64	3.92E-06	1.46E-07	7.06E-09	7.27E-08	5.39E-06	2.33E-06	1.29E-08	3.91E-06	2.09E-07	2.22E-07	6.58E-07
Jun-64	2.46E-06	4.16E-08	1.99E-09	2.73E-08	2.07E-06	4.18E-06	3.64E-09	1.38E-06	6.76E-08	1.02E-07	5.66E-07
Jul-64	2.30E-06	3.72E-08	1.78E-09	4.42E-08	1.69E-06	3.35E-06	3.26E-09	1.16E-06	4.24E-08	5.82E-08	5.09E-07
Aug-64	3.37E-06	6.24E-08	3.02E-09	7.72E-08	4.55E-06	1.50E-06	5.52E-09	1.54E-06	1.65E-07	1.54E-07	4.68E-07
Sep-64	4.33E-06	1.52E-07	7.42E-09	1.53E-07	8.98E-06	6.59E-07	1.35E-08	3.01E-06	2.82E-07	1.72E-07	4.45E-07

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, $^{69,69m}Zn$, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	$^{69,69m}Zn$	^{72}Ga
Oct-64	3.45E-06	1.16E-07	5.62E-09	1.18E-07	6.26E-06	8.86E-07	1.03E-08	2.50E-06	1.37E-07	9.88E-08	3.33E-07
Nov-64	5.61E-06	2.24E-07	1.09E-08	1.15E-07	1.07E-05	4.00E-07	1.99E-08	4.34E-06	2.26E-07	1.33E-07	1.03E-06
Dec-64	6.04E-06	2.37E-07	1.16E-08	1.11E-07	1.17E-05	8.55E-07	2.12E-08	4.54E-06	2.55E-07	1.47E-07	1.28E-06
Jan-65	4.25E-06	2.55E-07	1.24E-08	1.16E-07	1.10E-05	6.38E-07	2.27E-08	5.26E-06	2.74E-07	1.80E-07	4.38E-07
Feb-65	3.45E-06	1.52E-07	7.36E-09	7.54E-08	5.63E-06	8.51E-07	1.35E-08	3.39E-06	2.32E-07	1.80E-07	2.53E-07
Mar-65	4.46E-06	2.80E-07	1.36E-08	1.31E-07	7.01E-06	8.83E-07	2.48E-08	6.07E-06	3.65E-07	2.66E-07	7.40E-07
Apr-65	3.98E-06	2.29E-07	1.11E-08	9.42E-08	4.99E-06	1.49E-06	2.03E-08	5.39E-06	2.26E-07	1.92E-07	4.45E-07
May-65	2.45E-06	9.35E-08	4.49E-09	4.84E-08	2.09E-06	2.98E-06	8.22E-09	2.73E-06	1.24E-07	1.55E-07	3.46E-07
Jun-65	1.86E-06	4.26E-08	2.04E-09	3.27E-08	1.66E-06	2.87E-06	3.74E-09	1.33E-06	8.30E-08	1.15E-07	3.78E-07
Jul-65	1.47E-06	4.01E-08	1.93E-09	4.53E-08	2.00E-06	1.64E-06	3.53E-09	1.11E-06	6.09E-08	6.99E-08	3.12E-07
Aug-65	2.04E-06	7.49E-08	3.63E-09	8.09E-08	3.79E-06	9.94E-07	6.64E-09	1.73E-06	8.00E-08	6.75E-08	2.91E-07
Sep-65	2.17E-06	1.40E-07	6.84E-09	1.33E-07	6.30E-06	6.07E-07	1.25E-08	2.63E-06	1.24E-07	7.05E-08	2.63E-07
Oct-65	3.43E-06	2.44E-07	1.20E-08	2.34E-07	6.28E-06	7.04E-07	2.18E-08	4.19E-06	8.96E-08	4.22E-08	4.64E-07
Nov-65	2.87E-06	1.83E-07	8.95E-09	1.50E-07	5.80E-06	4.76E-07	1.64E-08	3.26E-06	1.07E-07	5.54E-08	3.34E-07
Dec-65	3.32E-06	1.92E-07	9.40E-09	1.56E-07	5.91E-06	4.68E-07	1.72E-08	3.53E-06	1.58E-07	8.64E-08	3.36E-07
Jan-66	3.34E-06	1.90E-07	9.32E-09	1.38E-07	6.51E-06	2.91E-07	1.71E-08	3.33E-06	1.55E-07	7.71E-08	3.23E-07
Feb-66	2.76E-06	1.13E-07	5.53E-09	1.07E-07	4.04E-06	3.14E-07	1.02E-08	2.16E-06	1.04E-07	6.08E-08	4.07E-07
Mar-66	3.52E-06	2.16E-07	1.06E-08	1.81E-07	5.61E-06	5.16E-07	1.93E-08	4.05E-06	1.93E-07	1.09E-07	1.76E-07
Apr-66	3.06E-06	1.57E-07	7.66E-09	1.08E-07	5.06E-06	4.07E-07	1.41E-08	2.90E-06	1.83E-07	1.02E-07	2.26E-07
May-66	1.96E-06	6.74E-08	3.25E-09	6.86E-08	2.40E-06	1.34E-06	5.95E-09	1.76E-06	9.95E-08	1.04E-07	2.80E-07
Jun-66	1.48E-06	3.30E-08	1.59E-09	4.03E-08	1.23E-06	1.76E-06	2.90E-09	9.74E-07	3.51E-08	4.46E-08	2.36E-07
Jul-66	5.73E-07	8.66E-09	4.17E-10	1.14E-08	2.58E-07	5.42E-07	7.72E-10	2.41E-07	1.22E-08	1.41E-08	8.96E-08
Aug-66	1.04E-06	1.37E-08	6.66E-10	1.25E-08	4.81E-07	1.34E-07	1.22E-09	2.98E-07	2.22E-08	1.68E-08	4.50E-07
Sep-66	3.48E-06	1.46E-07	7.13E-09	1.10E-07	5.02E-06	3.28E-07	1.29E-08	2.67E-06	2.08E-07	1.12E-07	1.05E-06
Oct-66	3.10E-06	1.38E-07	6.77E-09	1.08E-07	5.50E-06	3.50E-07	1.24E-08	2.39E-06	3.21E-07	1.56E-07	2.37E-07
Nov-66	2.34E-06	1.27E-07	6.21E-09	1.45E-07	5.76E-06	1.74E-07	1.14E-08	2.19E-06	2.27E-07	1.09E-07	1.45E-07
Dec-66	3.41E-06	1.38E-07	6.74E-09	1.37E-07	5.74E-06	3.93E-07	1.23E-08	2.51E-06	2.43E-07	1.31E-07	3.18E-07
Jan-67	4.02E-06	1.37E-07	6.71E-09	1.92E-07	5.59E-06	2.99E-07	1.23E-08	2.53E-06	3.15E-07	1.74E-07	6.07E-07
Feb-67	3.65E-06	1.45E-07	7.08E-09	1.39E-07	4.87E-06	2.67E-07	1.29E-08	2.68E-06	2.86E-07	1.58E-07	3.31E-07
Mar-67	3.73E-06	1.27E-07	6.22E-09	1.29E-07	3.88E-06	4.49E-07	1.14E-08	2.55E-06	3.56E-07	2.29E-07	4.16E-07
Apr-67	4.19E-06	1.98E-07	9.66E-09	1.34E-07	4.66E-06	7.98E-07	1.76E-08	3.97E-06	3.51E-07	2.27E-07	4.06E-07
May-67	2.87E-06	1.46E-07	7.07E-09	8.01E-08	3.12E-06	1.27E-06	1.29E-08	3.46E-06	1.48E-07	1.30E-07	2.94E-07
Jun-67	1.18E-06	3.91E-08	1.87E-09	3.37E-08	1.30E-06	2.55E-06	3.42E-09	1.29E-06	5.34E-08	8.03E-08	2.34E-07
Jul-67	1.60E-06	4.83E-08	2.32E-09	4.35E-08	1.53E-06	2.38E-06	4.24E-09	1.43E-06	7.92E-08	1.02E-07	2.77E-07
Aug-67	3.01E-06	1.13E-07	5.49E-09	9.93E-08	3.41E-06	1.03E-06	1.00E-08	2.59E-06	1.12E-07	9.26E-08	3.26E-07
Sep-67	3.40E-06	1.49E-07	7.28E-09	1.32E-07	3.98E-06	4.88E-07	1.34E-08	2.86E-06	1.97E-07	1.17E-07	2.71E-07
Oct-67	3.86E-06	1.64E-07	8.05E-09	1.46E-07	4.77E-06	3.70E-07	1.47E-08	2.98E-06	1.63E-07	8.62E-08	1.92E-07
Nov-67	3.56E-06	1.20E-07	5.88E-09	1.27E-07	4.40E-06	2.92E-07	1.08E-08	2.22E-06	1.66E-07	9.16E-08	8.28E-08
Dec-67	3.78E-06	1.25E-07	6.09E-09	1.00E-07	4.11E-06	3.25E-07	1.11E-08	2.48E-06	1.73E-07	1.10E-07	8.11E-08
Jan-68	3.50E-06	1.26E-07	6.14E-09	8.33E-08	3.27E-06	1.98E-07	1.13E-08	2.36E-06	1.23E-07	7.00E-08	4.83E-07
Feb-68	4.22E-06	2.14E-07	1.05E-08	4.40E-08	3.33E-06	2.45E-07	1.91E-08	3.93E-06	1.52E-07	8.29E-08	4.87E-07
Mar-68	2.76E-06	1.58E-07	7.70E-09	5.59E-08	2.56E-06	9.39E-07	1.41E-08	3.43E-06	1.54E-07	1.15E-07	4.42E-07

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, ^{69,69m}Zn, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	^{69,69m}Zn	^{72}Ga
Apr-68	2.31E-06	1.96E-07	9.53E-09	4.16E-08	1.97E-06	8.83E-07	1.74E-08	4.12E-06	1.54E-07	1.09E-07	9.21E-08
May-68	2.04E-06	1.55E-07	7.50E-09	3.97E-08	2.03E-06	9.85E-07	1.37E-08	3.56E-06	1.05E-07	8.77E-08	1.29E-07
Jun-68	7.82E-07	2.80E-08	1.35E-09	1.75E-08	5.75E-07	1.53E-06	2.47E-09	8.22E-07	3.48E-08	4.39E-08	8.39E-08
Jul-68	5.99E-07	2.77E-08	1.33E-09	2.10E-08	7.63E-07	9.34E-07	2.44E-09	7.72E-07	3.77E-08	4.38E-08	1.04E-07
Aug-68	1.59E-06	9.12E-08	4.43E-09	6.55E-08	1.89E-06	6.58E-07	8.08E-09	2.02E-06	9.34E-08	7.25E-08	1.79E-07
Sep-68	1.52E-06	1.02E-07	4.98E-09	4.58E-08	1.66E-06	5.04E-07	9.12E-09	2.07E-06	8.53E-08	5.60E-08	1.41E-07
Oct-68	1.96E-06	1.13E-07	5.50E-09	5.77E-08	2.42E-06	3.76E-07	1.01E-08	2.12E-06	8.81E-08	5.01E-08	3.15E-07
Nov-68	1.91E-06	9.18E-08	4.49E-09	6.09E-08	2.15E-06	3.05E-07	8.23E-09	1.74E-06	1.18E-07	6.81E-08	2.57E-07
Dec-68	1.71E-06	9.41E-08	4.59E-09	4.65E-08	1.93E-06	3.09E-07	8.39E-09	1.90E-06	9.09E-08	5.97E-08	3.97E-07
Jan-69	1.45E-06	7.53E-08	3.66E-09	3.92E-08	1.21E-06	1.36E-07	6.71E-09	1.61E-06	9.45E-08	6.90E-08	3.57E-07
Feb-69	1.28E-06	8.20E-08	3.98E-09	2.06E-08	9.52E-07	4.43E-07	7.27E-09	1.85E-06	9.21E-08	7.41E-08	1.87E-07
Mar-69	1.79E-06	1.36E-07	6.60E-09	8.47E-08	1.39E-06	4.63E-07	1.21E-08	2.93E-06	1.36E-07	1.01E-07	7.65E-08
Apr-69	1.31E-06	6.88E-08	3.32E-09	4.61E-08	8.01E-07	4.63E-06	6.07E-09	1.80E-06	7.23E-08	7.59E-08	1.17E-07
May-69	9.15E-07	2.71E-08	1.30E-09	3.46E-08	4.87E-07	4.04E-06	2.39E-09	7.67E-07	4.02E-08	4.78E-08	6.11E-08
Jun-69	9.00E-07	2.57E-08	1.24E-09	3.89E-08	5.40E-07	1.97E-06	2.26E-09	7.29E-07	3.14E-08	3.74E-08	1.51E-07
Jul-69	7.82E-07	3.55E-08	1.71E-09	3.31E-08	4.73E-07	1.03E-06	3.13E-09	9.42E-07	3.96E-08	4.22E-08	1.39E-07
Aug-69	1.07E-06	7.94E-08	3.86E-09	5.63E-08	9.53E-07	4.51E-07	7.06E-09	1.69E-06	8.69E-08	6.23E-08	2.28E-07
Sep-69	1.09E-06	7.93E-08	3.88E-09	6.16E-08	1.05E-06	2.63E-07	7.12E-09	1.48E-06	6.39E-08	3.56E-08	1.36E-07
Oct-69	1.06E-06	7.08E-08	3.46E-09	3.60E-08	8.51E-07	2.78E-07	6.33E-09	1.38E-06	7.33E-08	4.45E-08	1.04E-07
Nov-69	7.06E-07	3.49E-08	1.70E-09	6.43E-08	7.42E-07	1.51E-07	3.14E-09	7.01E-07	6.39E-08	4.14E-08	2.63E-08
Dec-69	1.04E-06	3.69E-08	1.80E-09	1.04E-07	9.21E-07	7.59E-08	3.28E-09	7.69E-07	8.92E-08	6.19E-08	4.30E-07
Jan-70	1.55E-06	2.69E-08	1.31E-09	7.10E-08	8.90E-07	3.55E-07	2.41E-09	5.36E-07	4.90E-08	3.10E-08	4.00E-07
Feb-70	5.72E-08	1.59E-09	7.80E-11	3.30E-09	5.57E-08	8.96E-09	1.68E-10	2.80E-08	3.59E-09	1.80E-09	1.80E-08
Mar-70	1.47E-07	5.74E-09	2.80E-10	1.03E-08	8.57E-08	4.02E-08	5.09E-10	1.14E-07	1.85E-08	1.17E-08	5.50E-08
Apr-70	4.82E-07	2.57E-08	1.25E-09	2.95E-08	2.68E-07	1.28E-07	2.27E-09	5.27E-07	5.90E-08	3.96E-08	1.59E-07
May-70	4.09E-07	7.65E-09	3.71E-10	2.12E-08	2.28E-07	1.78E-07	6.83E-10	1.79E-07	4.64E-08	4.00E-08	1.29E-07
Jun-70	3.33E-07	2.87E-09	1.38E-10	1.17E-08	1.77E-07	2.11E-07	2.54E-10	7.55E-08	2.80E-08	2.95E-08	1.01E-07
Jul-70	3.50E-07	2.80E-08	1.36E-09	5.19E-09	9.51E-07	1.84E-07	2.47E-09	6.49E-07	4.53E-08	3.80E-08	1.40E-07
Aug-70	2.61E-07	2.44E-08	1.19E-09	4.01E-09	7.87E-07	9.49E-08	2.18E-09	5.20E-07	3.99E-08	2.86E-08	8.47E-08
Sep-70	5.40E-07	5.21E-08	2.55E-09	1.27E-08	1.74E-06	1.21E-07	4.65E-09	9.76E-07	7.41E-08	4.15E-08	1.78E-07
Oct-70	5.93E-07	4.76E-08	2.33E-09	1.11E-08	1.99E-06	1.43E-07	4.26E-09	8.93E-07	9.90E-08	5.58E-08	2.04E-07
Nov-70	5.40E-07	5.21E-08	2.55E-09	1.07E-08	1.91E-06	9.81E-08	4.66E-09	9.76E-07	7.28E-08	4.05E-08	1.65E-07
Dec-70	5.25E-07	5.88E-08	2.88E-09	9.04E-09	1.57E-06	1.11E-07	5.26E-09	1.12E-06	7.21E-08	4.16E-08	1.72E-07
Jan-71	4.74E-07	5.37E-08	2.63E-09	7.34E-09	1.63E-06	9.92E-08	4.82E-09	9.76E-07	8.85E-08	4.68E-08	1.59E-07
Feb-71	1.08E-08	1.18E-09	5.77E-11	1.92E-10	3.75E-08	3.08E-09	1.34E-10	2.20E-08	3.04E-09	1.80E-09	4.94E-09
Mar-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Apr-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
May-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jun-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jul-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Aug-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F-9. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{24}Na, ^{32}P, ^{45}Ca, ^{46}Sc, ^{51}Cr, ^{56}Mn, ^{60}Co, ^{64}Cu, ^{65}Zn, $^{69,69m}Zn$, and ^{72}Ga (Ci m^{-3})

Month-Year	^{24}Na	^{32}P	^{45}Ca	^{46}Sc	^{51}Cr	^{56}Mn	^{60}Co	^{64}Cu	^{65}Zn	$^{69,69m}Zn$	^{72}Ga
Sep-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Oct-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nov-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dec-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Jan-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Feb-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mar-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Apr-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
May-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jun-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jul-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Aug-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sep-44	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.06E-07
Oct-44	3.65E-08	2.03E-10	9.06E-11	1.45E-08	8.60E-09	2.27E-08	5.15E-09	1.48E-12	3.92E-10	2.00E-10	8.39E-07
Nov-44	5.43E-08	2.60E-10	1.16E-10	1.81E-08	9.20E-09	3.38E-08	6.94E-09	2.58E-12	5.90E-10	2.60E-10	1.29E-06
Dec-44	7.81E-08	3.98E-10	1.78E-10	2.75E-08	1.34E-08	4.61E-08	1.12E-08	2.41E-11	1.25E-09	3.97E-10	2.14E-06
Jan-45	1.53E-07	7.21E-10	3.22E-10	4.93E-08	2.34E-08	7.24E-08	1.87E-08	3.08E-11	2.48E-09	7.16E-10	2.75E-06
Feb-45	1.65E-07	7.94E-10	3.55E-10	5.43E-08	2.57E-08	7.56E-08	1.82E-08	4.54E-11	2.63E-09	7.95E-10	3.33E-06
Mar-45	3.88E-07	1.24E-09	5.52E-10	8.88E-08	5.59E-08	1.42E-07	4.10E-08	1.94E-10	9.94E-09	1.23E-09	3.87E-06
Apr-45	3.34E-07	9.64E-10	4.30E-10	7.10E-08	4.90E-08	1.17E-07	3.42E-08	1.37E-10	7.77E-09	9.65E-10	3.34E-06
May-45	9.56E-08	3.24E-10	1.43E-10	2.74E-08	3.56E-08	3.61E-08	1.07E-08	1.49E-11	1.43E-09	3.21E-10	1.22E-06
Jun-45	4.65E-08	1.40E-10	6.19E-11	1.24E-08	1.96E-08	1.83E-08	5.16E-09	1.09E-10	4.09E-09	1.39E-10	6.94E-07
Jul-45	1.01E-07	2.51E-10	1.11E-10	2.15E-08	2.94E-08	2.99E-08	8.65E-09	1.12E-11	1.18E-09	2.49E-10	1.03E-06
Aug-45	2.27E-07	3.26E-10	1.45E-10	2.63E-08	2.68E-08	5.32E-08	1.68E-08	2.95E-11	3.19E-09	3.25E-10	1.77E-06
Sep-45	2.72E-07	4.49E-10	2.00E-10	3.45E-08	2.84E-08	7.78E-08	2.28E-08	7.86E-11	4.85E-09	4.48E-10	2.51E-06
Oct-45	4.24E-07	6.47E-10	2.89E-10	4.71E-08	3.10E-08	1.18E-07	3.31E-08	9.97E-11	7.29E-09	6.46E-10	3.36E-06
Nov-45	3.22E-07	1.06E-09	4.74E-10	7.70E-08	5.04E-08	1.15E-07	3.41E-08	1.31E-10	7.71E-09	1.06E-09	3.08E-06
Dec-45	2.69E-07	9.32E-10	4.16E-10	6.82E-08	4.58E-08	1.07E-07	3.01E-08	8.07E-11	1.02E-08	9.35E-10	3.23E-06
Jan-46	2.84E-07	9.45E-10	4.21E-10	6.90E-08	4.65E-08	1.17E-07	3.05E-08	8.36E-11	7.65E-09	9.41E-10	3.32E-06
Feb-46	3.15E-07	1.10E-09	4.92E-10	7.94E-08	5.01E-08	1.26E-07	3.57E-08	8.59E-11	7.44E-09	1.10E-09	3.52E-06
Mar-46	2.71E-07	6.99E-10	3.11E-10	5.31E-08	4.16E-08	9.96E-08	2.89E-08	1.13E-10	8.18E-09	6.99E-10	2.52E-06
Apr-46	9.67E-08	2.06E-10	9.15E-11	1.71E-08	1.98E-08	3.53E-08	9.97E-09	1.18E-11	2.76E-09	2.06E-10	1.16E-06
May-46	2.51E-08	1.51E-10	6.69E-11	1.35E-08	2.23E-08	1.27E-08	3.43E-09	1.32E-11	1.98E-09	1.50E-10	4.50E-07
Jun-46	1.46E-08	9.33E-11	4.12E-11	8.42E-09	1.48E-08	9.38E-09	2.36E-09	1.16E-11	1.05E-09	9.24E-11	3.64E-07
Jul-46	3.91E-08	8.18E-11	3.62E-11	7.21E-09	1.12E-08	1.58E-08	4.21E-09	1.08E-12	3.20E-10	8.12E-11	5.62E-07
Aug-46	1.08E-07	1.61E-10	7.15E-11	1.35E-08	1.66E-08	2.87E-08	8.10E-09	8.38E-12	1.23E-09	1.60E-10	9.68E-07
Sep-46	1.58E-07	3.46E-10	1.54E-10	2.78E-08	2.82E-08	4.20E-08	1.22E-08	2.95E-11	2.78E-09	3.44E-10	1.35E-06
Oct-46	2.11E-07	4.42E-10	1.97E-10	3.38E-08	2.74E-08	6.61E-08	1.98E-08	5.19E-11	4.72E-09	4.42E-10	1.88E-06
Nov-46	2.10E-07	4.60E-10	2.05E-10	3.41E-08	2.41E-08	7.15E-08	1.98E-08	5.06E-11	4.41E-09	4.60E-10	2.27E-06
Dec-46	1.84E-07	3.94E-10	1.75E-10	3.06E-08	2.65E-08	6.33E-08	1.77E-08	4.07E-11	3.91E-09	3.92E-10	1.89E-06
Jan-47	1.73E-07	3.95E-10	1.76E-10	3.01E-08	2.40E-08	6.72E-08	1.99E-08	3.11E-11	4.72E-09	3.95E-10	2.06E-06
Feb-47	1.52E-07	3.29E-10	1.46E-10	2.55E-08	2.19E-08	5.59E-08	1.70E-08	3.06E-11	4.88E-09	3.28E-10	2.01E-06
Mar-47	1.53E-07	3.13E-10	1.39E-10	2.48E-08	2.35E-08	5.71E-08	1.62E-08	3.88E-11	4.18E-09	3.11E-10	1.70E-06
Apr-47	1.00E-07	1.94E-10	8.60E-11	1.60E-08	1.85E-08	3.34E-08	9.88E-09	1.75E-11	2.30E-09	1.93E-10	1.14E-06

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
May-47	2.41E-08	7.67E-11	3.39E-11	6.83E-09	1.12E-08	1.32E-08	3.56E-09	2.02E-11	2.57E-09	7.60E-11	4.72E-07
Jun-47	2.32E-08	1.20E-10	5.30E-11	1.07E-08	1.82E-08	1.07E-08	2.54E-09	1.67E-11	1.41E-09	1.19E-10	4.09E-07
Jul-47	5.83E-08	9.11E-11	4.03E-11	7.98E-09	1.20E-08	1.69E-08	5.27E-09	3.53E-12	3.95E-10	9.06E-11	5.78E-07
Aug-47	1.16E-07	1.56E-10	6.91E-11	1.29E-08	1.51E-08	2.58E-08	7.81E-09	7.39E-12	1.33E-09	1.55E-10	9.26E-07
Sep-47	1.55E-07	6.56E-11	2.92E-11	5.27E-09	4.95E-09	4.33E-08	1.28E-08	2.59E-11	1.92E-09	6.71E-11	1.42E-06
Oct-47	1.46E-07	3.68E-11	1.64E-11	2.99E-09	3.18E-09	3.90E-08	1.14E-08	1.78E-11	2.29E-09	3.67E-11	1.14E-06
Nov-47	1.16E-07	4.08E-11	1.81E-11	3.29E-09	3.38E-09	3.43E-08	1.04E-08	2.12E-11	2.33E-09	4.06E-11	1.06E-06
Dec-47	1.48E-07	3.74E-10	1.67E-10	2.89E-08	2.51E-08	4.98E-08	1.46E-08	2.34E-11	3.49E-09	3.70E-10	1.46E-06
Jan-48	1.51E-07	4.26E-10	1.89E-10	3.30E-08	2.89E-08	5.07E-08	1.44E-08	2.94E-11	3.99E-09	4.23E-10	1.38E-06
Feb-48	1.10E-07	3.41E-10	1.52E-10	2.64E-08	2.27E-08	4.35E-08	1.25E-08	2.70E-11	2.86E-09	3.41E-10	1.39E-06
Mar-48	1.70E-07	5.19E-10	2.31E-10	3.96E-08	3.22E-08	5.94E-08	1.82E-08	5.62E-11	4.73E-09	5.16E-10	1.61E-06
Apr-48	1.09E-07	2.72E-10	1.21E-10	2.18E-08	2.16E-08	3.91E-08	1.10E-08	1.49E-11	2.41E-09	2.72E-10	1.18E-06
May-48	2.60E-08	6.44E-11	2.85E-11	5.73E-09	9.38E-09	1.14E-08	3.33E-09	5.00E-11	2.54E-09	6.38E-11	3.78E-07
Jun-48	9.31E-10	5.48E-11	2.42E-11	5.01E-09	9.49E-09	4.21E-09	8.92E-10	2.39E-11	1.45E-09	5.41E-11	2.74E-07
Jul-48	7.36E-08	1.88E-10	8.34E-11	1.64E-08	2.45E-08	2.30E-08	6.56E-09	1.80E-12	3.76E-10	1.87E-10	8.17E-07
Aug-48	1.51E-07	3.25E-10	1.44E-10	2.71E-08	3.28E-08	3.59E-08	1.08E-08	1.23E-11	1.30E-09	3.23E-10	1.20E-06
Sep-48	2.10E-07	2.56E-10	1.14E-10	2.05E-08	1.98E-08	5.03E-08	1.55E-08	1.02E-11	3.92E-09	2.57E-10	1.90E-06
Oct-48	3.10E-07	7.67E-10	3.42E-10	5.81E-08	4.56E-08	8.72E-08	2.56E-08	8.66E-11	6.61E-09	7.60E-10	2.71E-06
Nov-48	2.81E-07	4.77E-10	2.13E-10	3.55E-08	2.45E-08	9.70E-08	2.64E-08	3.81E-10	9.79E-09	4.83E-10	2.97E-06
Dec-48	3.47E-07	5.19E-10	2.31E-10	3.81E-08	2.59E-08	1.13E-07	3.29E-08	1.19E-10	6.37E-09	5.18E-10	3.25E-06
Jan-49	3.32E-07	5.29E-10	2.36E-10	3.88E-08	2.62E-08	1.13E-07	3.16E-08	2.44E-10	7.56E-09	5.28E-10	3.10E-06
Feb-49	3.04E-07	4.24E-10	1.89E-10	3.10E-08	2.06E-08	1.01E-07	2.75E-08	9.65E-11	6.51E-09	4.26E-10	3.24E-06
Mar-49	3.35E-07	5.99E-10	2.67E-10	4.41E-08	3.09E-08	1.23E-07	3.48E-08	6.61E-11	8.65E-09	5.96E-10	3.33E-06
Apr-49	1.41E-07	4.20E-10	1.87E-10	3.42E-08	3.70E-08	4.98E-08	1.44E-08	3.81E-11	3.41E-09	4.17E-10	1.63E-06
May-49	4.32E-08	1.60E-10	7.08E-11	1.41E-08	2.23E-08	1.82E-08	5.23E-09	8.37E-11	4.16E-09	1.59E-10	6.70E-07
Jun-49	5.59E-08	1.60E-10	7.08E-11	1.41E-08	2.19E-08	1.87E-08	5.05E-09	4.37E-11	4.13E-09	1.59E-10	7.00E-07
Jul-49	1.63E-07	1.86E-10	8.25E-11	1.56E-08	1.93E-08	3.59E-08	1.07E-08	1.09E-11	1.28E-09	1.85E-10	1.22E-06
Aug-49	2.25E-07	1.17E-10	5.18E-11	9.44E-09	9.55E-09	5.27E-08	1.55E-08	4.36E-11	2.90E-09	1.17E-10	1.71E-06
Sep-49	3.32E-07	1.87E-10	8.32E-11	1.43E-08	1.17E-08	7.62E-08	2.22E-08	9.58E-11	5.00E-09	1.86E-10	2.63E-06
Oct-49	4.36E-07	4.40E-10	1.96E-10	3.24E-08	2.27E-08	1.23E-07	3.57E-08	6.74E-11	8.56E-09	4.37E-10	3.78E-06
Nov-49	4.91E-07	1.10E-09	4.89E-10	8.17E-08	5.99E-08	1.47E-07	4.15E-08	1.85E-10	1.29E-08	1.09E-09	4.13E-06
Dec-49	4.49E-07	1.04E-09	4.65E-10	7.96E-08	6.34E-08	1.46E-07	4.22E-08	1.76E-10	1.47E-08	1.04E-09	3.82E-06
Jan-50	4.03E-07	9.85E-10	4.39E-10	7.52E-08	5.98E-08	1.35E-07	4.00E-08	2.14E-10	9.99E-09	9.83E-10	3.51E-06
Feb-50	3.26E-07	8.84E-10	3.94E-10	6.79E-08	5.55E-08	1.26E-07	3.69E-08	1.26E-10	1.07E-08	8.82E-10	3.59E-06
Mar-50	4.17E-07	1.10E-09	4.87E-10	8.56E-08	7.65E-08	1.30E-07	3.71E-08	8.97E-11	9.57E-09	1.09E-09	3.34E-06
Apr-50	2.32E-07	5.63E-10	2.50E-10	4.60E-08	4.92E-08	8.12E-08	2.32E-08	5.32E-11	6.40E-09	5.62E-10	2.35E-06
May-50	1.25E-07	4.24E-10	1.88E-10	3.67E-08	5.30E-08	4.01E-08	1.13E-08	5.82E-12	9.58E-10	4.20E-10	1.21E-06
Jun-50	3.47E-08	1.82E-10	8.03E-11	1.64E-08	2.85E-08	1.87E-08	4.72E-09	2.00E-10	5.67E-09	1.80E-10	6.50E-07
Jul-50	5.60E-08	2.21E-10	9.78E-11	1.98E-08	3.39E-08	2.09E-08	5.77E-09	9.89E-11	5.78E-09	2.19E-10	6.64E-07
Aug-50	2.12E-07	2.64E-10	1.17E-10	2.23E-08	2.83E-08	4.54E-08	1.41E-08	2.61E-11	1.90E-09	2.63E-10	1.35E-06
Sep-50	3.69E-07	1.50E-10	6.66E-11	1.21E-08	1.18E-08	7.77E-08	2.31E-08	7.78E-11	6.48E-09	1.52E-10	2.53E-06
Oct-50	4.82E-07	3.02E-10	1.34E-10	2.34E-08	2.03E-08	1.11E-07	2.75E-08	3.64E-10	1.19E-08	3.00E-10	3.75E-06

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Nov-50	4.53E-07	2.56E-10	1.14E-10	2.01E-08	1.83E-08	1.12E-07	3.27E-08	6.75E-10	1.46E-08	2.55E-10	3.72E-06
Dec-50	3.81E-07	2.08E-10	9.26E-11	1.64E-08	1.48E-08	1.20E-07	3.60E-08	6.58E-10	1.88E-08	2.08E-10	3.36E-06
Jan-51	2.27E-07	5.66E-10	2.52E-10	4.46E-08	4.08E-08	6.99E-08	2.25E-08	1.22E-09	2.64E-08	5.61E-10	2.38E-06
Feb-51	2.28E-07	6.56E-10	2.92E-10	5.30E-08	5.43E-08	6.01E-08	1.66E-08	4.97E-10	2.04E-08	6.52E-10	2.28E-06
Mar-51	3.18E-07	9.07E-10	4.03E-10	7.19E-08	6.82E-08	8.75E-08	2.51E-08	1.08E-09	2.40E-08	9.02E-10	2.82E-06
Apr-51	1.82E-07	5.37E-10	2.38E-10	4.44E-08	5.09E-08	5.16E-08	1.20E-08	2.37E-09	3.05E-08	5.34E-10	1.88E-06
May-51	4.98E-08	3.73E-10	1.65E-10	3.30E-08	5.26E-08	2.18E-08	2.99E-09	9.37E-10	1.74E-08	3.69E-10	8.22E-07
Jun-51	7.26E-08	2.50E-10	1.11E-10	2.22E-08	3.61E-08	1.99E-08	4.98E-09	9.07E-10	1.58E-08	2.48E-10	8.33E-07
Jul-51	7.24E-08	2.35E-10	1.04E-10	2.07E-08	3.19E-08	2.73E-08	5.51E-09	1.49E-09	2.06E-08	2.33E-10	1.02E-06
Aug-51	1.05E-07	4.55E-10	2.02E-10	3.82E-08	4.66E-08	5.15E-08	1.42E-08	2.93E-09	3.47E-08	4.52E-10	1.87E-06
Sep-51	2.56E-07	8.24E-10	3.67E-10	6.45E-08	5.72E-08	9.84E-08	2.61E-08	8.15E-09	7.64E-08	8.21E-10	3.11E-06
Oct-51	2.40E-07	1.12E-09	4.96E-10	8.77E-08	7.99E-08	8.93E-08	2.52E-08	9.26E-09	8.96E-08	1.11E-09	2.99E-06
Nov-51	1.66E-07	1.04E-09	4.64E-10	8.10E-08	6.91E-08	1.15E-07	2.61E-08	1.07E-08	1.16E-07	1.04E-09	3.40E-06
Dec-51	2.83E-07	1.46E-09	6.51E-10	1.12E-07	9.11E-08	1.04E-07	2.82E-08	1.40E-08	1.35E-07	1.45E-09	3.65E-06
Jan-52	3.32E-07	1.02E-09	4.53E-10	8.04E-08	7.33E-08	1.17E-07	2.78E-08	1.48E-08	1.27E-07	1.02E-09	3.07E-06
Feb-52	2.61E-07	1.62E-09	7.20E-10	1.25E-07	1.07E-07	8.90E-08	3.84E-08	1.48E-08	1.35E-07	1.61E-09	3.04E-06
Mar-52	3.32E-07	1.01E-09	4.51E-10	7.97E-08	7.12E-08	9.52E-08	2.61E-08	5.28E-09	7.80E-08	1.01E-09	2.96E-06
Apr-52	2.85E-07	1.44E-09	6.38E-10	1.14E-07	1.11E-07	7.59E-08	1.91E-08	9.41E-09	1.08E-07	1.43E-09	2.55E-06
May-52	9.11E-08	4.20E-10	1.86E-10	3.69E-08	5.68E-08	2.68E-08	6.62E-09	2.85E-09	3.68E-08	4.16E-10	9.21E-07
Jun-52	5.63E-08	4.77E-10	2.11E-10	4.18E-08	6.35E-08	2.12E-08	5.93E-09	2.47E-09	3.31E-08	4.73E-10	8.72E-07
Jul-52	8.60E-08	7.24E-10	3.21E-10	6.23E-08	8.60E-08	3.26E-08	1.03E-08	4.08E-09	5.13E-08	7.18E-10	1.12E-06
Aug-52	1.34E-07	1.25E-09	5.57E-10	1.02E-07	1.09E-07	5.01E-08	1.53E-08	6.85E-09	7.62E-08	1.25E-09	1.77E-06
Sep-52	2.10E-07	2.11E-09	9.38E-10	1.61E-07	1.30E-07	8.49E-08	3.60E-08	1.09E-08	1.17E-07	2.10E-09	3.10E-06
Oct-52	7.23E-07	2.38E-09	1.06E-09	1.79E-07	1.34E-07	1.25E-07	7.76E-08	1.15E-08	1.20E-07	2.38E-09	3.82E-06
Nov-52	7.50E-07	2.62E-09	1.17E-09	1.95E-07	1.37E-07	1.22E-07	6.79E-08	7.55E-09	8.57E-08	2.62E-09	4.47E-06
Dec-52	9.70E-07	2.78E-09	1.24E-09	2.00E-07	1.22E-07	1.66E-07	8.65E-08	5.37E-09	6.72E-08	2.77E-09	5.28E-06
Jan-53	1.22E-06	2.95E-09	1.31E-09	2.15E-07	1.40E-07	1.67E-07	1.25E-07	3.90E-09	4.98E-08	2.94E-09	4.96E-06
Feb-53	7.74E-07	2.16E-09	9.62E-10	1.67E-07	1.40E-07	1.21E-07	7.42E-08	5.55E-09	6.75E-08	2.16E-09	3.82E-06
Mar-53	8.58E-07	2.41E-09	1.07E-09	1.88E-07	1.69E-07	1.21E-07	7.87E-08	5.08E-09	7.19E-08	2.39E-09	3.22E-06
Apr-53	4.79E-07	1.83E-09	8.16E-10	1.44E-07	1.27E-07	7.97E-08	5.80E-08	2.72E-09	4.63E-08	1.83E-09	3.02E-06
May-53	3.81E-07	1.12E-09	4.97E-10	9.30E-08	1.09E-07	6.44E-08	3.77E-08	2.66E-09	5.53E-08	1.11E-09	2.02E-06
Jun-53	1.44E-07	5.64E-10	2.50E-10	4.98E-08	7.79E-08	2.15E-08	1.19E-08	7.94E-10	2.03E-08	5.59E-10	8.52E-07
Jul-53	2.59E-07	8.80E-10	3.90E-10	7.64E-08	1.11E-07	3.23E-08	1.18E-08	1.20E-09	2.65E-08	8.72E-10	1.22E-06
Aug-53	7.35E-07	1.68E-09	7.44E-10	1.37E-07	1.50E-07	7.30E-08	2.91E-08	3.07E-09	5.20E-08	1.67E-09	2.53E-06
Sep-53	1.10E-06	1.58E-09	7.04E-10	1.25E-07	1.15E-07	1.05E-07	3.00E-08	1.19E-08	1.14E-07	1.58E-09	3.61E-06
Oct-53	1.35E-06	2.49E-09	1.11E-09	1.93E-07	1.66E-07	1.37E-07	4.40E-08	1.44E-08	1.50E-07	2.47E-09	4.38E-06
Nov-53	2.31E-06	2.26E-09	1.00E-09	1.73E-07	1.39E-07	1.49E-07	7.96E-08	2.30E-09	3.94E-08	2.25E-09	4.62E-06
Dec-53	2.02E-06	2.92E-09	1.30E-09	2.21E-07	1.69E-07	1.59E-07	1.04E-07	8.97E-09	9.46E-08	2.91E-09	5.19E-06
Jan-54	1.05E-06	1.50E-09	6.68E-10	1.15E-07	8.91E-08	1.65E-07	6.14E-08	6.59E-09	1.16E-07	1.51E-09	5.13E-06
Feb-54	9.81E-07	1.58E-09	7.05E-10	1.20E-07	9.06E-08	1.68E-07	5.46E-08	2.73E-08	2.30E-07	1.58E-09	5.46E-06
Mar-54	1.06E-06	1.76E-09	7.81E-10	1.35E-07	1.13E-07	1.71E-07	5.89E-08	2.23E-08	2.35E-07	1.75E-09	5.09E-06

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Apr-54	1.05E-06	1.85E-09	8.26E-10	1.42E-07	1.12E-07	1.67E-07	5.86E-08	3.24E-08	2.61E-07	1.85E-09	5.21E-06
May-54	3.20E-07	4.60E-10	2.04E-10	3.98E-08	5.68E-08	4.68E-08	1.49E-08	6.61E-09	7.29E-08	4.57E-10	1.84E-06
Jun-54	1.75E-07	2.69E-10	1.19E-10	2.40E-08	3.98E-08	3.33E-08	9.34E-09	7.63E-09	8.37E-08	2.66E-10	1.18E-06
Jul-54	2.08E-07	3.77E-10	1.67E-10	3.35E-08	5.47E-08	3.16E-08	1.11E-08	1.46E-09	2.70E-08	3.73E-10	1.13E-06
Aug-54	5.48E-07	6.81E-10	3.02E-10	5.77E-08	7.44E-08	5.54E-08	2.34E-08	1.32E-09	1.98E-08	6.76E-10	2.02E-06
Sep-54	7.74E-07	1.13E-09	5.03E-10	9.24E-08	9.92E-08	8.66E-08	3.67E-08	1.53E-09	3.31E-08	1.13E-09	3.11E-06
Oct-54	1.18E-06	2.14E-09	9.54E-10	1.66E-07	1.39E-07	1.49E-07	5.40E-08	1.40E-08	1.91E-07	2.13E-09	4.35E-06
Nov-54	9.83E-07	2.03E-09	9.02E-10	1.57E-07	1.32E-07	1.22E-07	5.32E-08	3.04E-09	4.52E-08	2.02E-09	3.92E-06
Dec-54	1.09E-06	2.76E-09	1.23E-09	2.12E-07	1.75E-07	1.37E-07	5.97E-08	3.54E-09	6.47E-08	2.75E-09	4.36E-06
Jan-55	1.09E-06	2.86E-09	1.27E-09	2.20E-07	1.78E-07	1.47E-07	5.57E-08	1.72E-08	1.59E-07	2.85E-09	4.15E-06
Feb-55	6.49E-07	1.25E-09	5.55E-10	9.68E-08	7.92E-08	9.47E-08	3.40E-08	9.42E-09	1.13E-07	1.26E-09	4.30E-06
Mar-55	1.36E-06	3.18E-09	1.41E-09	2.49E-07	2.27E-07	1.52E-07	5.64E-08	1.18E-08	1.45E-07	3.15E-09	4.83E-06
Apr-55	1.54E-06	2.19E-09	9.76E-10	1.71E-07	1.46E-07	1.38E-07	4.62E-08	2.39E-08	2.47E-07	2.20E-09	5.53E-06
May-55	1.83E-06	2.54E-09	1.13E-09	1.99E-07	1.77E-07	1.68E-07	4.63E-08	3.69E-08	3.35E-07	2.52E-09	5.94E-06
Jun-55	4.78E-07	5.35E-10	2.37E-10	4.70E-08	7.15E-08	4.17E-08	1.03E-08	8.96E-09	1.03E-07	5.31E-10	1.62E-06
Jul-55	4.03E-07	4.37E-10	1.93E-10	3.86E-08	6.08E-08	3.36E-08	9.11E-09	6.19E-09	8.81E-08	4.33E-10	1.34E-06
Aug-55	9.10E-07	1.65E-09	7.31E-10	1.36E-07	1.55E-07	7.07E-08	1.74E-08	1.60E-08	1.67E-07	1.63E-09	2.68E-06
Sep-55	1.08E-06	2.95E-09	1.31E-09	2.29E-07	1.93E-07	1.15E-07	3.08E-08	2.59E-08	2.37E-07	2.94E-09	4.66E-06
Oct-55	1.68E-06	3.03E-09	1.35E-09	2.29E-07	1.70E-07	1.72E-07	6.82E-08	3.13E-08	3.18E-07	3.03E-09	6.37E-06
Nov-55	1.45E-06	2.32E-09	1.03E-09	1.79E-07	1.46E-07	1.61E-07	6.46E-08	3.53E-08	3.40E-07	2.32E-09	6.53E-06
Dec-55	1.88E-06	3.14E-09	1.40E-09	2.37E-07	1.78E-07	2.23E-07	9.36E-08	7.88E-08	5.46E-07	3.13E-09	7.77E-06
Jan-56	1.06E-06	2.17E-09	9.66E-10	1.65E-07	1.27E-07	1.91E-07	4.71E-08	5.63E-08	4.57E-07	2.17E-09	6.89E-06
Feb-56	1.19E-06	3.07E-09	1.37E-09	2.33E-07	1.80E-07	1.80E-07	5.20E-08	5.49E-08	4.26E-07	3.05E-09	6.85E-06
Mar-56	1.38E-06	3.36E-09	1.50E-09	2.56E-07	1.99E-07	1.91E-07	1.10E-07	3.89E-08	3.08E-07	3.35E-09	6.63E-06
Apr-56	5.64E-07	1.21E-09	5.35E-10	1.02E-07	1.27E-07	6.59E-08	2.91E-08	8.86E-09	9.95E-08	1.20E-09	2.73E-06
May-56	3.09E-07	3.62E-10	1.60E-10	3.18E-08	4.81E-08	3.96E-08	1.43E-08	5.43E-09	6.44E-08	3.60E-10	1.69E-06
Jun-56	1.94E-07	5.62E-10	2.49E-10	5.02E-08	8.33E-08	2.79E-08	8.97E-09	3.30E-09	4.91E-08	5.56E-10	1.25E-06
Jul-56	4.71E-07	1.06E-09	4.68E-10	9.10E-08	1.26E-07	5.07E-08	1.14E-08	6.63E-09	7.30E-08	1.05E-09	2.16E-06
Aug-56	1.01E-06	1.66E-09	7.38E-10	1.35E-07	1.40E-07	1.03E-07	2.09E-08	1.05E-08	1.24E-07	1.65E-09	4.06E-06
Sep-56	1.44E-06	3.08E-09	1.37E-09	2.37E-07	1.97E-07	1.54E-07	3.77E-08	2.45E-08	2.02E-07	3.06E-09	5.20E-06
Oct-56	1.48E-06	3.24E-09	1.44E-09	2.46E-07	1.90E-07	1.34E-07	4.15E-08	1.15E-08	1.02E-07	3.23E-09	5.17E-06
Nov-56	1.92E-06	2.21E-09	9.85E-10	1.68E-07	1.28E-07	1.57E-07	6.96E-08	2.76E-08	2.08E-07	2.22E-09	7.20E-06
Dec-56	2.99E-06	5.12E-09	2.28E-09	3.82E-07	2.74E-07	2.54E-07	8.92E-08	3.96E-08	2.94E-07	5.07E-09	9.15E-06
Jan-57	3.76E-06	5.86E-09	2.61E-09	4.50E-07	3.67E-07	2.03E-07	1.01E-07	1.87E-08	1.43E-07	5.82E-09	7.86E-06
Feb-57	2.84E-06	4.13E-09	1.84E-09	3.16E-07	2.47E-07	2.56E-07	1.01E-07	3.77E-08	2.63E-07	4.14E-09	9.35E-06
Mar-57	2.09E-06	4.86E-09	2.17E-09	3.56E-07	2.32E-07	3.43E-07	1.21E-07	7.92E-08	5.51E-07	4.86E-09	1.15E-05
Apr-57	1.99E-06	3.78E-09	1.68E-09	2.88E-07	2.21E-07	2.14E-07	8.90E-08	3.33E-08	2.78E-07	3.77E-09	8.24E-06
May-57	5.98E-07	7.15E-10	3.16E-10	6.23E-08	9.16E-08	5.31E-08	2.15E-08	1.04E-08	9.95E-08	7.09E-10	2.02E-06
Jun-57	3.71E-07	7.67E-10	3.40E-10	6.72E-08	1.01E-07	3.48E-08	1.43E-08	5.24E-09	5.76E-08	7.60E-10	1.55E-06
Jul-57	7.28E-07	1.66E-09	7.36E-10	1.38E-07	1.63E-07	7.38E-08	2.51E-08	1.21E-08	1.50E-07	1.65E-09	3.34E-06
Aug-57	1.17E-06	3.83E-09	1.70E-09	3.03E-07	2.84E-07	1.51E-07	6.92E-08	4.65E-08	4.16E-07	3.80E-09	5.61E-06
Sep-57	1.88E-06	5.84E-09	2.60E-09	4.39E-07	3.21E-07	2.12E-07	8.45E-08	5.18E-08	4.23E-07	5.82E-09	6.61E-06

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Oct-57	2.39E-06	6.17E-09	2.75E-09	4.60E-07	3.24E-07	1.55E-07	9.69E-08	5.07E-08	4.13E-07	6.16E-09	5.56E-06
Nov-57	3.02E-06	5.55E-09	2.48E-09	4.14E-07	2.88E-07	1.64E-07	9.87E-08	4.23E-08	3.59E-07	5.56E-09	6.92E-06
Dec-57	5.01E-06	6.54E-09	2.92E-09	4.80E-07	3.18E-07	2.52E-07	2.12E-07	7.12E-08	5.49E-07	6.52E-09	8.88E-06
Jan-58	5.03E-06	6.55E-09	2.92E-09	4.84E-07	3.31E-07	2.41E-07	1.80E-07	6.35E-08	5.22E-07	6.53E-09	7.83E-06
Feb-58	4.25E-06	5.44E-09	2.42E-09	4.11E-07	3.10E-07	1.84E-07	1.36E-07	5.01E-08	4.48E-07	5.43E-09	6.81E-06
Mar-58	3.03E-06	4.72E-09	2.10E-09	3.70E-07	3.26E-07	1.63E-07	9.76E-08	4.82E-08	4.56E-07	4.70E-09	5.66E-06
Apr-58	2.34E-06	4.40E-09	1.96E-09	3.47E-07	3.18E-07	1.28E-07	1.75E-07	6.35E-08	5.57E-07	4.38E-09	4.59E-06
May-58	1.24E-06	1.70E-09	7.54E-10	1.46E-07	1.99E-07	5.10E-08	5.22E-08	1.88E-08	2.00E-07	1.69E-09	1.84E-06
Jun-58	5.26E-07	7.95E-10	3.52E-10	6.99E-08	1.07E-07	2.65E-08	3.13E-08	1.29E-08	1.76E-07	7.89E-10	1.20E-06
Jul-58	1.20E-06	2.08E-09	9.24E-10	1.74E-07	2.08E-07	6.03E-08	9.15E-08	4.72E-08	5.71E-07	2.07E-09	2.66E-06
Aug-58	2.02E-06	7.33E-09	3.26E-09	5.77E-07	5.29E-07	1.29E-07	8.18E-08	4.22E-08	3.46E-07	7.27E-09	4.41E-06
Sep-58	2.71E-06	4.92E-09	2.19E-09	3.74E-07	2.76E-07	1.42E-07	8.85E-08	3.05E-08	2.65E-07	4.97E-09	5.89E-06
Oct-58	3.40E-06	6.06E-09	2.70E-09	4.58E-07	3.46E-07	1.92E-07	1.25E-07	5.41E-08	4.05E-07	6.03E-09	6.64E-06
Nov-58	3.97E-06	5.72E-09	2.55E-09	4.28E-07	3.06E-07	2.02E-07	1.30E-07	4.03E-08	3.04E-07	5.72E-09	7.39E-06
Dec-58	4.77E-06	1.27E-08	5.64E-09	9.56E-07	7.31E-07	2.22E-07	1.71E-07	4.67E-08	3.43E-07	1.25E-08	6.25E-06
Jan-59	3.25E-06	5.28E-09	2.35E-09	4.10E-07	3.35E-07	1.08E-07	1.53E-07	2.44E-08	2.21E-07	5.32E-09	4.41E-06
Feb-59	3.48E-06	4.97E-09	2.21E-09	3.87E-07	3.34E-07	1.28E-07	1.40E-07	2.25E-08	1.74E-07	4.95E-09	4.64E-06
Mar-59	2.90E-06	5.77E-09	2.57E-09	4.58E-07	4.33E-07	1.03E-07	1.42E-07	2.12E-08	1.75E-07	5.73E-09	3.51E-06
Apr-59	1.74E-06	4.33E-09	1.92E-09	3.53E-07	3.76E-07	6.73E-08	8.59E-08	1.12E-08	1.19E-07	4.31E-09	2.51E-06
May-59	8.60E-07	1.76E-09	7.81E-10	1.52E-07	2.10E-07	3.28E-08	3.68E-08	6.97E-09	7.69E-08	1.75E-09	1.23E-06
Jun-59	3.85E-07	6.34E-10	2.80E-10	5.62E-08	8.99E-08	1.64E-08	1.89E-08	4.41E-09	5.41E-08	6.29E-10	6.97E-07
Jul-59	4.54E-07	8.40E-10	3.72E-10	7.36E-08	1.11E-07	2.10E-08	2.55E-08	5.09E-09	6.92E-08	8.33E-10	8.25E-07
Aug-59	9.32E-07	2.90E-09	1.29E-09	2.38E-07	2.62E-07	4.04E-08	4.88E-08	5.84E-09	6.85E-08	2.88E-09	1.69E-06
Sep-59	1.08E-06	2.18E-09	9.67E-10	1.77E-07	1.81E-07	5.11E-08	5.47E-08	8.75E-09	8.78E-08	2.17E-09	2.24E-06
Oct-59	1.72E-06	2.28E-09	1.01E-09	1.85E-07	1.91E-07	6.42E-08	1.01E-07	1.26E-08	1.25E-07	2.27E-09	2.53E-06
Nov-59	1.42E-06	4.42E-09	1.96E-09	3.54E-07	3.49E-07	7.08E-08	1.35E-07	7.78E-09	8.17E-08	4.39E-09	3.07E-06
Dec-59	1.67E-06	8.26E-09	3.67E-09	6.51E-07	5.94E-07	1.06E-07	1.13E-07	3.71E-08	2.79E-07	8.20E-09	4.41E-06
Jan-60	3.60E-06	1.56E-08	6.94E-09	1.20E-06	9.79E-07	1.54E-07	1.82E-07	9.52E-08	7.89E-07	1.55E-08	5.56E-06
Feb-60	1.96E-06	1.07E-08	4.74E-09	8.20E-07	6.53E-07	1.50E-07	1.27E-07	6.15E-08	5.32E-07	1.07E-08	5.91E-06
Mar-60	2.82E-06	1.31E-08	5.82E-09	9.89E-07	7.47E-07	1.89E-07	1.92E-07	6.95E-08	5.31E-07	1.30E-08	6.29E-06
Apr-60	1.50E-06	3.62E-09	1.61E-09	3.04E-07	3.64E-07	6.52E-08	7.59E-08	1.68E-08	1.80E-07	3.61E-09	2.28E-06
May-60	1.15E-06	4.01E-09	1.78E-09	3.40E-07	4.36E-07	4.00E-08	6.08E-08	2.29E-08	2.04E-07	3.97E-09	1.67E-06
Jun-60	6.12E-07	1.79E-09	7.93E-10	1.56E-07	2.27E-07	2.94E-08	3.38E-08	9.16E-09	9.28E-08	1.78E-09	1.32E-06
Jul-60	5.64E-07	2.00E-09	8.86E-10	1.73E-07	2.44E-07	3.65E-08	3.75E-08	9.85E-09	1.06E-07	1.98E-09	1.45E-06
Aug-60	1.80E-06	4.29E-09	1.90E-09	3.49E-07	3.68E-07	6.64E-08	6.38E-08	3.78E-08	3.66E-07	4.26E-09	2.61E-06
Sep-60	1.82E-06	1.09E-08	4.83E-09	8.30E-07	6.63E-07	1.13E-07	8.68E-08	3.18E-08	2.76E-07	1.08E-08	4.07E-06
Oct-60	2.74E-06	9.15E-09	4.08E-09	6.89E-07	5.02E-07	1.21E-07	1.09E-07	5.38E-08	4.29E-07	9.16E-09	5.29E-06
Nov-60	3.18E-06	5.97E-09	2.66E-09	4.51E-07	3.31E-07	1.77E-07	1.80E-07	5.96E-08	5.20E-07	5.99E-09	6.56E-06
Dec-60	3.74E-06	1.62E-08	7.23E-09	1.19E-06	8.14E-07	2.14E-07	2.67E-07	1.13E-07	8.28E-07	1.61E-08	8.67E-06
Jan-61	4.83E-06	1.71E-08	7.64E-09	1.28E-06	9.06E-07	2.61E-07	2.95E-07	9.76E-08	7.08E-07	1.71E-08	8.35E-06
Feb-61	1.81E-06	1.14E-08	5.05E-09	8.89E-07	7.80E-07	1.35E-07	2.25E-07	4.39E-08	3.81E-07	1.13E-08	4.58E-06

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Mar-61	2.74E-06	8.63E-09	3.84E-09	6.81E-07	6.17E-07	1.03E-07	2.38E-07	4.34E-08	3.51E-07	8.62E-09	3.21E-06
Apr-61	1.94E-06	7.77E-09	3.45E-09	6.21E-07	6.01E-07	6.04E-08	1.89E-07	3.45E-08	3.14E-07	7.73E-09	2.10E-06
May-61	9.71E-07	4.74E-09	2.10E-09	4.06E-07	5.48E-07	2.31E-08	7.96E-08	1.03E-08	9.94E-08	4.69E-09	9.74E-07
Jun-61	2.12E-07	8.71E-10	3.85E-10	7.82E-08	1.32E-07	1.17E-08	2.77E-08	8.07E-09	8.42E-08	8.65E-10	3.95E-07
Jul-61	4.37E-07	1.85E-09	8.20E-10	1.57E-07	2.00E-07	1.43E-08	3.40E-08	6.33E-09	8.22E-08	1.84E-09	7.09E-07
Aug-61	7.72E-07	3.10E-09	1.38E-09	2.47E-07	2.34E-07	4.11E-08	3.49E-08	3.51E-08	3.05E-07	3.09E-09	1.83E-06
Sep-61	9.30E-07	1.26E-08	5.60E-09	9.35E-07	6.69E-07	8.31E-08	7.65E-08	6.96E-08	4.85E-07	1.24E-08	3.32E-06
Oct-61	1.17E-06	1.12E-08	4.97E-09	8.31E-07	5.78E-07	1.06E-07	9.74E-08	1.30E-07	9.75E-07	1.12E-08	3.25E-06
Nov-61	1.23E-06	6.22E-09	2.77E-09	4.62E-07	3.11E-07	7.44E-08	1.08E-07	1.26E-07	8.79E-07	6.28E-09	2.85E-06
Dec-61	1.26E-06	5.46E-09	2.43E-09	3.97E-07	2.49E-07	9.83E-08	1.03E-07	4.45E-08	3.99E-07	5.47E-09	3.89E-06
Jan-62	8.75E-07	3.42E-09	1.52E-09	2.57E-07	1.88E-07	1.03E-07	1.05E-07	9.26E-08	6.65E-07	3.42E-09	3.60E-06
Feb-62	9.57E-07	2.54E-09	1.13E-09	1.93E-07	1.47E-07	8.03E-08	9.66E-08	5.12E-08	4.04E-07	2.54E-09	3.87E-06
Mar-62	2.13E-06	1.04E-08	4.63E-09	7.60E-07	5.07E-07	1.65E-07	1.79E-07	9.64E-08	7.23E-07	1.03E-08	5.82E-06
Apr-62	1.18E-06	7.29E-09	3.24E-09	5.84E-07	5.77E-07	8.57E-08	9.59E-08	1.59E-08	1.53E-07	7.24E-09	3.82E-06
May-62	5.59E-07	4.84E-09	2.15E-09	4.07E-07	5.00E-07	6.55E-08	6.41E-08	4.78E-08	4.25E-07	4.81E-09	2.20E-06
Jun-62	2.94E-07	1.29E-09	5.72E-10	1.12E-07	1.61E-07	2.42E-08	3.04E-08	1.92E-08	1.97E-07	1.29E-09	9.08E-07
Jul-62	3.14E-07	2.54E-09	1.13E-09	2.15E-07	2.78E-07	2.70E-08	3.17E-08	7.85E-09	9.05E-08	2.52E-09	1.32E-06
Aug-62	5.23E-07	4.19E-09	1.86E-09	3.40E-07	3.56E-07	5.92E-08	6.38E-08	1.06E-08	1.11E-07	4.16E-09	2.44E-06
Sep-62	7.40E-07	9.67E-09	4.31E-09	7.26E-07	5.34E-07	1.17E-07	1.09E-07	1.79E-08	1.91E-07	9.63E-09	4.08E-06
Oct-62	7.00E-07	8.17E-09	3.64E-09	6.14E-07	4.44E-07	1.12E-07	8.47E-08	8.54E-08	6.38E-07	8.17E-09	3.49E-06
Nov-62	5.49E-07	5.93E-09	2.64E-09	4.51E-07	3.47E-07	7.48E-08	7.33E-08	3.14E-08	2.91E-07	5.93E-09	2.79E-06
Dec-62	6.76E-07	6.15E-09	2.74E-09	4.76E-07	4.00E-07	6.96E-08	7.31E-08	2.64E-08	2.54E-07	6.12E-09	2.29E-06
Jan-63	4.12E-07	3.12E-09	1.39E-09	2.42E-07	1.97E-07	4.69E-08	6.55E-08	5.67E-08	5.25E-07	3.13E-09	2.12E-06
Feb-63	4.72E-07	4.45E-09	1.98E-09	3.48E-07	3.08E-07	6.90E-08	5.50E-08	3.92E-08	3.29E-07	4.42E-09	2.92E-06
Mar-63	1.91E-06	7.75E-09	3.45E-09	5.94E-07	4.81E-07	1.05E-07	1.19E-07	9.27E-08	7.41E-07	7.69E-09	3.59E-06
Apr-63	1.07E-06	5.83E-09	2.59E-09	4.63E-07	4.35E-07	7.07E-08	9.85E-08	7.79E-09	9.20E-08	5.80E-09	2.36E-06
May-63	6.65E-07	3.10E-09	1.37E-09	2.56E-07	2.90E-07	3.90E-08	5.02E-08	7.29E-09	7.38E-08	3.08E-09	1.53E-06
Jun-63	3.77E-07	1.39E-09	6.17E-10	1.21E-07	1.75E-07	2.12E-08	2.71E-08	5.72E-09	7.68E-08	1.38E-09	8.71E-07
Jul-63	4.78E-07	2.48E-09	1.10E-09	2.11E-07	2.76E-07	2.77E-08	3.32E-08	4.92E-09	6.47E-08	2.46E-09	1.10E-06
Aug-63	8.35E-07	3.45E-09	1.53E-09	2.77E-07	2.73E-07	5.23E-08	4.59E-08	1.54E-08	1.50E-07	3.44E-09	2.02E-06
Sep-63	1.03E-06	3.94E-09	1.75E-09	2.98E-07	2.24E-07	8.11E-08	6.58E-08	2.62E-08	2.39E-07	3.94E-09	3.52E-06
Oct-63	1.26E-06	5.93E-09	2.64E-09	4.42E-07	3.16E-07	1.31E-07	9.22E-08	3.24E-08	3.43E-07	5.90E-09	3.84E-06
Nov-63	1.21E-06	5.14E-09	2.29E-09	3.79E-07	2.50E-07	9.65E-08	9.75E-08	4.23E-08	3.49E-07	5.15E-09	3.55E-06
Dec-63	1.48E-06	7.30E-09	3.25E-09	5.39E-07	3.68E-07	1.09E-07	1.26E-07	3.25E-08	2.96E-07	7.26E-09	4.18E-06
Jan-64	1.57E-06	5.01E-09	2.23E-09	3.65E-07	2.25E-07	1.28E-07	1.28E-07	4.45E-08	3.53E-07	5.04E-09	4.44E-06
Feb-64	1.17E-06	3.65E-09	1.63E-09	2.80E-07	2.25E-07	9.31E-08	9.89E-08	1.36E-08	1.49E-07	3.64E-09	3.52E-06
Mar-64	1.56E-06	4.71E-09	2.10E-09	3.50E-07	2.44E-07	1.27E-07	1.66E-07	3.75E-08	3.01E-07	4.70E-09	4.99E-06
Apr-64	1.31E-06	5.28E-09	2.35E-09	3.93E-07	2.74E-07	1.49E-07	1.23E-07	7.78E-08	5.87E-07	5.26E-09	6.05E-06
May-64	8.31E-07	1.93E-09	8.55E-10	1.62E-07	1.95E-07	7.34E-08	6.44E-08	1.91E-08	2.12E-07	1.92E-09	2.40E-06
Jun-64	3.53E-07	9.53E-10	4.21E-10	8.46E-08	1.37E-07	1.89E-08	1.91E-08	9.12E-10	2.91E-08	9.44E-10	6.81E-07
Jul-64	3.60E-07	1.25E-09	5.53E-10	1.09E-07	1.63E-07	1.68E-08	1.68E-08	2.65E-09	4.80E-08	1.24E-09	7.03E-07
Aug-64	5.53E-07	2.89E-09	1.29E-09	2.37E-07	2.59E-07	3.75E-08	2.70E-08	6.48E-09	1.02E-07	2.88E-09	1.50E-06

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Sep-64	1.13E-06	3.39E-09	1.51E-09	2.61E-07	2.07E-07	6.81E-08	6.30E-08	2.05E-08	2.08E-07	3.40E-09	2.55E-06
Oct-64	9.87E-07	1.78E-09	7.90E-10	1.40E-07	1.26E-07	6.35E-08	4.88E-08	2.64E-08	2.97E-07	1.78E-09	2.55E-06
Nov-64	1.23E-06	6.85E-09	3.05E-09	5.19E-07	4.02E-07	9.64E-08	9.22E-08	2.81E-08	3.16E-07	6.78E-09	3.42E-06
Dec-64	1.29E-06	7.42E-09	3.30E-09	5.62E-07	4.28E-07	9.17E-08	9.75E-08	2.67E-08	3.02E-07	7.40E-09	3.46E-06
Jan-65	7.00E-07	3.92E-09	1.74E-09	3.05E-07	2.56E-07	9.77E-08	1.07E-07	3.31E-08	3.36E-07	3.93E-09	2.96E-06
Feb-65	4.84E-07	2.29E-09	1.02E-09	1.83E-07	1.73E-07	5.47E-08	6.44E-08	1.77E-08	1.95E-07	2.28E-09	2.11E-06
Mar-65	1.00E-06	5.08E-09	2.26E-09	3.99E-07	3.62E-07	6.76E-08	1.18E-07	9.94E-09	2.02E-07	5.03E-09	2.34E-06
Apr-65	9.66E-07	3.50E-09	1.56E-09	2.83E-07	2.88E-07	4.92E-08	9.83E-08	8.03E-09	1.23E-07	3.49E-09	1.95E-06
May-65	6.78E-07	1.22E-09	5.39E-10	1.05E-07	1.43E-07	2.63E-08	4.18E-08	6.04E-09	8.84E-08	1.21E-09	9.56E-07
Jun-65	3.61E-07	1.01E-09	4.49E-10	8.88E-08	1.33E-07	1.40E-08	1.93E-08	1.94E-09	3.71E-08	1.01E-09	5.96E-07
Jul-65	4.30E-07	1.21E-09	5.34E-10	1.02E-07	1.31E-07	1.81E-08	1.78E-08	4.14E-09	7.86E-08	1.20E-09	7.91E-07
Aug-65	8.43E-07	2.13E-09	9.47E-10	1.72E-07	1.72E-07	2.83E-08	3.21E-08	5.75E-09	8.17E-08	2.12E-09	1.24E-06
Sep-65	1.18E-06	3.63E-09	1.61E-09	2.75E-07	2.04E-07	4.78E-08	5.75E-08	1.22E-08	1.40E-07	3.61E-09	2.11E-06
Oct-65	2.52E-06	3.77E-09	1.68E-09	2.78E-07	1.80E-07	6.56E-08	9.83E-08	1.83E-08	1.91E-07	3.77E-09	2.58E-06
Nov-65	1.65E-06	3.10E-09	1.38E-09	2.31E-07	1.59E-07	5.84E-08	7.43E-08	2.23E-08	2.25E-07	3.10E-09	2.18E-06
Dec-65	1.52E-06	2.71E-09	1.21E-09	2.04E-07	1.47E-07	4.79E-08	7.85E-08	1.31E-08	1.69E-07	2.71E-09	1.71E-06
Jan-66	9.31E-07	2.72E-09	1.21E-09	2.02E-07	1.35E-07	3.91E-08	7.70E-08	5.83E-09	9.70E-08	2.72E-09	1.45E-06
Feb-66	8.14E-07	1.73E-09	7.72E-10	1.32E-07	1.00E-07	2.88E-08	4.67E-08	5.31E-09	8.61E-08	1.73E-09	1.34E-06
Mar-66	1.33E-06	2.66E-09	1.18E-09	2.01E-07	1.48E-07	3.89E-08	8.87E-08	2.34E-09	7.67E-08	2.64E-09	1.56E-06
Apr-66	9.31E-07	2.31E-09	1.03E-09	1.74E-07	1.26E-07	3.83E-08	6.42E-08	4.87E-09	4.87E-08	2.31E-09	1.77E-06
May-66	4.80E-07	1.14E-09	5.07E-10	9.54E-08	1.12E-07	2.15E-08	2.95E-08	4.82E-09	5.44E-08	1.13E-09	7.19E-07
Jun-66	3.04E-07	4.39E-10	1.94E-10	3.79E-08	5.26E-08	6.60E-09	1.48E-08	1.68E-09	1.95E-08	4.36E-10	1.91E-07
Jul-66	8.09E-08	2.83E-10	1.25E-10	2.41E-08	3.11E-08	1.84E-09	3.85E-09	4.09E-10	4.30E-09	2.82E-10	9.43E-08
Aug-66	1.18E-07	1.57E-09	6.98E-10	1.24E-07	1.14E-07	5.01E-09	5.80E-09	1.22E-09	1.11E-08	1.56E-09	5.65E-07
Sep-66	7.13E-07	4.65E-09	2.07E-09	3.48E-07	2.48E-07	3.37E-08	5.95E-08	1.27E-08	1.11E-07	4.61E-09	1.30E-06
Oct-66	8.73E-07	2.57E-09	1.15E-09	1.91E-07	1.25E-07	3.15E-08	5.58E-08	7.64E-09	7.12E-08	2.60E-09	1.20E-06
Nov-66	5.87E-07	1.87E-09	8.33E-10	1.38E-07	9.06E-08	2.85E-08	5.12E-08	6.55E-09	5.66E-08	1.87E-09	1.33E-06
Dec-66	7.65E-07	3.00E-09	1.34E-09	2.24E-07	1.60E-07	3.45E-08	5.63E-08	1.20E-08	1.01E-07	2.98E-09	1.40E-06
Jan-67	1.01E-06	2.43E-09	1.08E-09	1.84E-07	1.33E-07	3.30E-08	5.61E-08	7.54E-09	6.08E-08	2.43E-09	1.24E-06
Feb-67	6.15E-07	2.35E-09	1.04E-09	1.77E-07	1.29E-07	2.74E-08	5.92E-08	5.44E-09	3.88E-08	2.34E-09	1.36E-06
Mar-67	7.94E-07	3.01E-09	1.34E-09	2.32E-07	1.89E-07	3.48E-08	5.31E-08	1.17E-08	1.19E-07	2.99E-09	1.44E-06
Apr-67	1.17E-06	2.80E-09	1.24E-09	2.16E-07	1.76E-07	3.38E-08	8.25E-08	6.94E-09	4.85E-08	2.79E-09	1.55E-06
May-67	7.23E-07	2.00E-09	8.90E-10	1.63E-07	1.69E-07	2.77E-08	6.28E-08	6.89E-09	6.99E-08	1.99E-09	1.34E-06
Jun-67	3.18E-07	6.97E-10	3.08E-10	6.18E-08	9.93E-08	1.13E-08	1.79E-08	1.59E-09	1.53E-08	6.91E-10	4.82E-07
Jul-67	2.83E-07	1.09E-09	4.84E-10	9.44E-08	1.33E-07	1.36E-08	2.17E-08	4.66E-09	5.31E-08	1.08E-09	5.63E-07
Aug-67	6.25E-07	2.27E-09	1.01E-09	1.82E-07	1.79E-07	2.59E-08	4.84E-08	1.12E-08	8.92E-08	2.26E-09	1.22E-06
Sep-67	6.17E-07	3.32E-09	1.48E-09	2.53E-07	1.94E-07	4.94E-08	6.16E-08	4.00E-08	3.12E-07	3.31E-09	1.83E-06
Oct-67	9.93E-07	3.47E-09	1.55E-09	2.60E-07	1.83E-07	4.47E-08	6.70E-08	2.71E-08	2.16E-07	3.47E-09	1.68E-06
Nov-67	7.18E-07	2.43E-09	1.08E-09	1.84E-07	1.33E-07	3.90E-08	4.92E-08	1.39E-08	1.37E-07	2.43E-09	1.56E-06
Dec-67	9.21E-07	1.74E-09	7.76E-10	1.35E-07	1.09E-07	3.36E-08	5.18E-08	1.15E-08	1.02E-07	1.74E-09	1.31E-06
Jan-68	1.09E-06	1.77E-09	7.87E-10	1.34E-07	9.94E-08	3.51E-08	5.16E-08	1.09E-08	8.51E-08	1.76E-09	1.56E-06

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Feb-68	9.02E-07	2.63E-09	1.17E-09	1.97E-07	1.42E-07	4.58E-08	8.74E-08	1.75E-08	1.33E-07	2.61E-09	1.92E-06
Mar-68	9.89E-07	1.61E-09	7.14E-10	1.27E-07	1.16E-07	3.45E-08	6.70E-08	1.33E-08	1.08E-07	1.60E-09	1.33E-06
Apr-68	8.78E-07	1.40E-09	6.21E-10	1.10E-07	9.54E-08	3.07E-08	8.23E-08	1.39E-08	1.10E-07	1.39E-09	1.41E-06
May-68	4.10E-07	1.28E-09	5.67E-10	1.03E-07	1.02E-07	3.00E-08	6.61E-08	1.13E-08	1.10E-07	1.27E-09	1.07E-06
Jun-68	1.79E-07	4.53E-10	2.01E-10	3.91E-08	5.40E-08	9.42E-09	1.26E-08	1.84E-09	2.79E-08	4.50E-10	3.80E-07
Jul-68	2.04E-07	5.62E-10	2.49E-10	4.77E-08	6.16E-08	9.57E-09	1.23E-08	2.77E-09	3.02E-08	5.58E-10	4.97E-07
Aug-68	4.11E-07	1.29E-09	5.72E-10	1.02E-07	9.58E-08	2.58E-08	3.87E-08	6.59E-09	6.01E-08	1.28E-09	1.11E-06
Sep-68	3.91E-07	1.30E-09	5.79E-10	1.01E-07	8.36E-08	3.09E-08	4.26E-08	7.06E-09	6.37E-08	1.30E-09	1.34E-06
Oct-68	7.03E-07	1.72E-09	7.66E-10	1.30E-07	9.66E-08	3.88E-08	4.63E-08	2.76E-08	1.91E-07	1.71E-09	1.43E-06
Nov-68	5.95E-07	8.86E-10	3.94E-10	6.76E-08	5.04E-08	3.09E-08	3.78E-08	6.96E-09	4.84E-08	8.92E-10	1.32E-06
Dec-68	5.97E-07	1.20E-09	5.35E-10	9.30E-08	7.68E-08	2.95E-08	3.92E-08	7.96E-09	6.58E-08	1.19E-09	1.08E-06
Jan-69	4.26E-07	5.75E-10	2.56E-10	4.55E-08	4.06E-08	1.91E-08	3.18E-08	5.07E-09	5.13E-08	5.77E-10	8.02E-07
Feb-69	4.10E-07	1.33E-09	5.90E-10	1.06E-07	1.02E-07	1.67E-08	3.49E-08	3.50E-09	3.86E-08	1.31E-09	9.22E-07
Mar-69	7.79E-07	9.14E-10	4.06E-10	7.24E-08	6.52E-08	3.07E-08	5.74E-08	6.34E-09	7.53E-08	9.15E-10	1.36E-06
Apr-69	4.90E-07	4.83E-10	2.14E-10	4.04E-08	4.80E-08	1.88E-08	3.02E-08	3.04E-09	3.24E-08	4.80E-10	6.86E-07
May-69	3.52E-07	3.95E-10	1.75E-10	3.37E-08	4.44E-08	8.59E-09	1.21E-08	9.88E-10	9.88E-09	3.92E-10	3.90E-07
Jun-69	2.80E-07	3.52E-10	1.56E-10	3.01E-08	3.96E-08	8.32E-09	1.14E-08	1.07E-09	1.19E-08	3.50E-10	3.41E-07
Jul-69	2.76E-07	2.88E-10	1.28E-10	2.42E-08	2.91E-08	7.51E-09	1.56E-08	1.90E-09	2.41E-08	2.87E-10	4.12E-07
Aug-69	4.00E-07	6.19E-10	2.75E-10	4.86E-08	4.29E-08	1.91E-08	3.34E-08	4.66E-09	6.15E-08	6.15E-10	6.94E-07
Sep-69	5.59E-07	6.66E-10	2.97E-10	5.05E-08	3.71E-08	1.58E-08	3.26E-08	2.13E-09	1.72E-08	6.66E-10	5.26E-07
Oct-69	5.07E-07	4.40E-10	1.96E-10	3.38E-08	2.62E-08	8.59E-09	2.93E-08	1.94E-09	1.41E-08	4.41E-10	3.45E-07
Nov-69	3.74E-07	4.40E-10	1.96E-10	3.40E-08	2.78E-08	6.99E-09	1.45E-08	1.57E-09	1.31E-08	4.38E-10	3.86E-07
Dec-69	4.57E-07	3.85E-10	1.71E-10	3.01E-08	2.59E-08	1.01E-08	1.55E-08	3.40E-09	2.60E-08	3.84E-10	6.67E-07
Jan-70	2.84E-07	2.81E-09	1.25E-09	2.16E-07	1.75E-07	2.33E-08	1.12E-08	2.66E-08	3.50E-07	2.78E-09	5.74E-07
Feb-70	1.36E-08	1.23E-10	5.50E-11	1.09E-08	7.15E-09	1.83E-09	6.64E-10	1.02E-09	1.23E-08	1.60E-10	9.61E-08
Mar-70	1.14E-08	3.15E-10	1.40E-10	2.42E-08	1.94E-08	4.47E-09	2.38E-09	4.82E-09	6.91E-08	3.11E-10	3.93E-07
Apr-70	1.52E-07	1.05E-09	4.66E-10	8.12E-08	6.83E-08	1.47E-08	1.07E-08	2.06E-08	2.52E-07	1.04E-09	5.58E-07
May-70	8.12E-08	7.75E-10	3.44E-10	6.28E-08	6.39E-08	8.71E-09	3.29E-09	1.13E-08	1.47E-07	7.71E-10	3.58E-07
Jun-70	3.93E-08	5.32E-10	2.36E-10	4.45E-08	5.31E-08	6.05E-09	1.26E-09	7.90E-09	1.10E-07	5.29E-10	2.61E-07
Jul-70	2.10E-07	8.13E-10	3.61E-10	6.55E-08	6.52E-08	8.82E-09	1.20E-08	4.62E-10	1.79E-08	8.08E-10	3.18E-07
Aug-70	1.56E-07	6.98E-10	3.10E-10	5.50E-08	4.87E-08	7.68E-09	1.03E-08	1.18E-10	8.53E-09	6.98E-10	3.79E-07
Sep-70	3.43E-07	1.57E-09	7.00E-10	1.18E-07	8.70E-08	1.52E-08	2.14E-08	4.48E-10	2.71E-08	1.56E-09	6.24E-07
Oct-70	3.53E-07	1.77E-09	7.86E-10	1.34E-07	9.87E-08	1.63E-08	1.95E-08	4.66E-10	2.72E-08	1.76E-09	6.10E-07
Nov-70	3.52E-07	1.53E-09	6.79E-10	1.15E-07	8.47E-08	1.47E-08	2.14E-08	2.93E-10	2.56E-08	1.52E-09	7.14E-07
Dec-70	3.16E-07	1.25E-09	5.58E-10	9.52E-08	7.14E-08	2.16E-08	2.42E-08	5.49E-10	2.12E-08	1.25E-09	7.64E-07
Jan-71	3.22E-07	1.33E-09	5.92E-10	9.95E-08	7.01E-08	1.79E-08	2.19E-08	2.80E-10	2.25E-08	1.33E-09	3.84E-07
Feb-71	7.47E-09	2.91E-11	1.30E-11	2.68E-09	2.02E-09	6.59E-10	5.05E-10	5.98E-12	5.07E-10	3.84E-11	5.19E-10
Mar-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Apr-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
May-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jun-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Jul-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F-10. Monthly-Average Aqueous-Phase Radionuclide Concentrations at Richland for ^{76}As, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{93}Y, ^{95}Zr, ^{122}Sb, ^{131}I, ^{133}I, ^{137}Cs, and ^{239}Np (Ci m^{-3})

Month-Year	^{76}As	^{89}Sr	^{90}Sr	^{90}Y	^{93}Y	^{95}Zr	^{122}Sb	^{131}I	^{133}I	^{137}Cs	^{239}Np
Aug-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sep-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Oct-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nov-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dec-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00