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Ecological Dose Modeling of Aquatic and Riparian Receptors to Strontium-90 with an Emphasis on Radiosensitive Organs

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July 2011

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Summary

The 100-NR-2 site is the location of elevated releases of strontium-90 to the Columbia River via contaminated groundwater. The resulting dose to aquatic and riparian receptors was evaluated in 2005 (DOE 2009a) and compared to U.S. Department of Energy (DOE) dose guidance values. We have conducted additional dose assessments for a broader spectrum of aquatic and riparian organisms using RESRAD BIOTA and specific exposure scenarios. Because strontium-90 accumulates in bone, we have also modeled the dose to the anterior kidney, a blood-forming and immune system organ that lies close to the spinal column of fish. The resulting dose is primarily attributable to the yttrium-90 progeny of strontium-90 and very little of the dose is associated with the beta emission from strontium-90. All dose modeling results were calculated with an assumption of secular equilibrium between strontium-90 and yttrium-90.

Whole body mean dose rates to both aquatic and riparian receptors fall well below DOE guidance levels of 1.0 and 0.1 rad/d for aquatic and terrestrial receptors. The highest mean dose rates were observed in the raccoon and sculpin, 1.6E-05 and 5.8 E-06 rad/d, respectively.

Monte Carlo simulations of energy deposition in anterior kidney was used to estimate the dose rates to the anterior kidney of a model rainbow trout. The anterior kidney lies next to the spinal cord and because of the sensitivity of cell-mediated immune response and blood formation, it was selected as the target organ for modeling. Other organs, principally the gonads and gametogenesis, are also in close proximity to the spinal column and may be irradiated. Dose rates declined dramatically from 6.1 µrad/d per pCi/g strontium-90 at 0.1 mm from the spine to 2.1 µrad/d per pCi/g strontium-90 at 1.0 mm from the spine. At 1 cm from the spine, the dose rate was <0.0001 µrad/d per pCi/g strontium-90. Because the anterior kidney is slightly farther from the spinal column than the main body of the kidney, its dose rate is slightly less than the dose rate estimated for the posterior kidney. Based on a concentration of 1 pCi/g strontium-90 in secular equilibrium with yttrium-90, these dose rates are 0.6 and 1.1 µrad/d. Dose rates to other organ systems are lower due to greater distances to the spine.

The model dose rates for both whole organisms and anterior kidney are well below the DOE guidance levels (1.0 and 0.1 rad/d for aquatic and terrestrial organisms) and other predicted environmental dose rates. The proposed environmental dose rate benchmarks are predicted “no effect dose rates” that range between 0.005 and 0.024 rad/d. The cleanup goal for strontium-90 releases is 8 pCi/L. The modeled dose rate under continuous exposure is estimated to be 0.00004 rad/d. Consideration of these guidance values, predicted no effect dose rates, and the dose rate associated with the cleanup goal places the estimated dose rates in perspective for the low potential of strontium-90 releases to cause adverse effects in biota at the 100-NR-2 Area.

Acknowledgments

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Acronyms and Abbreviations

µCi	microcurie(s)
µrad	microrad(s)
ARAR	applicable or relevant appropriate requirement
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
Ci	curie(s)
cm	centimeter(s)
d	day(s)
DOE	U.S. Department of Energy
DWS	drinking water standard
EDE	effective dose equivalent
g	gram(s)
ICRP	International Commission on Radiological Protection
IAEA	International Atomic Energy Agency
L	liter(s)
MeV	megaelectron volt(s)
mGy	milligray(s)
mrad	millirad(s)
mrem	millirem(s)
NCRP	National Council on Radiation Protection and Measurements
pCi	picocurie(s)
PNNL	Pacific Northwest National Laboratory
rad	radiation absorbed dose
rem	roentgen equivalent man
^{90}Sr	strontium-90
WAC	Washington Administrative Code
y	year(s)
^{90}Y	yttrium-90
^{90}Zr	zirconium-90

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1.0 Introduction

This report expands on dose modeling efforts for aquatic and riparian receptors that may inhabit the 100-NR-2 shoreline area located on the Hanford Reach at the U.S. Department of Energy's (DOE's) Hanford Site. The 100-NR-2 area is an Operation Unit under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). The Pacific Northwest National Laboratory (PNNL) was engaged by the DOE and CH2M Hill Plateau Remediation Company to evaluate dose rates to these receptors and conducted specialized dose assessments on critical radiosensitive organ systems in fish.

Strontium-90 presents a noteworthy risk to biota because of the highly energetic beta decay associated with its yttrium-90 progeny and its well-understood propensity to accumulate in calcified tissue. To better understand the risk that this poses to animal life, the relationship between environmental concentrations of strontium-90, accumulation in biota, and the dose rates to the animals and particularly radiosensitive organs needs to be established. The long-standing paradigm that environmental standards that are protective of humans are also protective of aquatic life has recently been evaluated and a need to assess radiological impacts on the environment confirmed (ICRP 2008a). The study reported here complements prior evaluations of other species (DOE 2009a) and further evaluates strontium-90 dose rates to additional species of biota that are likely to inhabit the 100-NR-2 riparian and nearshore environment. One potential environmental threat to the Columbia River from the Hanford Site in southeastern Washington State is the potential discharge of strontium-90 into the river at the 100-NR-2 shoreline. In addition, the dose rates to particularly radiosensitive organs resulting from the accumulation of strontium-90 in bone in fish are evaluated. The information obtained from this assessment will help establish allowable levels of strontium-90 in groundwater discharge that are protective of endemic biota at the 100-NR-2 site.

There is currently an estimated inventory of 1300 Ci of strontium-90 in the vadose zone under the 1301 and 1325 trenches. These trenches received liquid waste from the 100-N reactor. This inventory is the source term for releases of strontium-90 that enter the Columbia River via groundwater migration at levels in excess of the remedial action goal of 8 pCi/L (DOE 2009b). Significant efforts have been made to reduce the release of strontium-90 into the Columbia River and mitigate the potential for exposure. The ecological effects of strontium-90 to aquatic organisms was reviewed in 2000 (Peterson and Poston 2000) and an impact assessment was performed in 2005 (DOE 2009a). The radiological dose for strontium-90 is dominated by the highly energetic beta emission of the yttrium-90 progeny. The primary yttrium-90 beta particle is emitted in a spectrum that has a maximum energy of 2.28 MeV and an average energy of 0.933 MeV (ICRP 107 [2008b]). In comparison, the maximum and average energy of the strontium-90 beta particle are 0.546 MeV and 0.20 MeV, respectively, and strontium-90 contributes little to the dose rate when compared to the yttrium-90 beta particle.

As the Hanford Site has proceeded towards cleanup under CERCLA, a number of engineered approaches to managing strontium-90 releases to the Columbia River have been evaluated. A physical barrier was attempted, but was unworkable. A pump-and-treat operation ran from 1997 to 2006 and removed a total of 1.83 Ci of strontium-90. Now, apatite injection is being implemented and a program evaluating phyto-remediaton as a method to control releases has been completed. The goal of these efforts is to reduce the release of strontium-90 to levels that pose acceptable risk to the environment.

1.1 Study Purpose and Scope

In support of cleanup at the 100-NR-2 Operable Unit, we have evaluated the potential for strontium-90 and its progeny (yttrium-90) to adversely affect biota that may inhabit the 100-NR-2 area. The study uses RESRAD-BIOTA in Tier 3 mode to evaluate whole body dose rates to selected biota that have the potential to be exposed along the Hanford shoreline. This essentially expands the assessment that was performed during the 2005 impact assessment to more species. The dose evaluation also assesses the potential for strontium-90 to accumulate in calcified tissue and irradiate critical radiosensitive organs in fish. The immune response has been shown to be one of the most radiosensitive systems in vertebrates (Hobbs and McClellan 1980). Immunocompetent cells are present in the anterior kidney of fish and the close proximity of this organ to the spinal column disposed the organ to exposure to beta radiation originating in the spinal column. Reproductive function and organ systems located in the body cavity may also be exposed.

There are two parts to the associated assessment. Part one is an assessment of whole body dose to fish and wildlife that may reside or occur at the 100-NR-2 shoreline. The selection of species is based on behavior and life histories that place them in close proximity to releases as they occur at the shoreline. The second part of the assessment evaluates the dose regime around the spinal column of a model fish and estimates the dose rates arising from strontium-90/yttrium-90 deposited in the bone. Of particular interest is exposure to the anterior kidney that lies close to the spinal column. Much of the cellular immune function in fish is provided by the anterior kidney. Bony fish also have a thymus and a spleen that contribute to immune function, but the majority of immunocompetent cells are found in the anterior kidney (Bowden et al. 2005; Rängel and Nilsson 1985). From a dose perspective, the thymus and spleen are more distant from the spinal column and would not receive the dose that the anterior kidney receives from radionuclides in the spinal column.

1.2 Report Contents and Organization

Section 2.0 of this report provides pertinent background information on dose assessment and standards. Section 3.0 describes the selection of biota for characterization of whole body dose at 100-NR-2 with RESRAD-BIOTA and the selection of key dose parameters for estimating dose to the organisms. Initial dose calculations are based on maximum observed concentrations at 100-NR-2 that are then adjusted to reflect more realistic exposure conditions based on spatial and temporal variables. Section 3.0 also describes the Monte Carlo methodology used to assess dose rates to the anterior kidney of fish and the tissue and organs surrounding the spinal cord. Section 4.0 presents the results of the dose assessments and the significance of these results is discussed in Section 5.0. Major conclusions are summarized in Section 6.0. Appendixes contain supplemental material: Appendix A describes the dose to fish kidney from strontium-90 and yttrium-90 in the spinal cord; Appendix B contains RESRAD-BIOTA dose profiles.

2.0 Background

The following sections provide information about radiological exposure in biota, current cleanup standards, and advances in biota dose assessment.

2.1 Background

A few fundamental concepts of radiological exposure in biota need to be understood to fully appreciate the value and limitations of biota dose assessment. This is meant to draw attention to the difficulties associated with dose estimation in wildlife where exposures vary with the animal's behavior and habitat.

1. Two attributes determine the severity of the exposure to radiation: the duration of exposure and the strength of the exposure. Where doses are constant, as in a controlled experiment, the exposure can be simply quantified as a rate (e.g., rad/d). When the duration of exposure is known and constant, the exposure can be expressed as total dose (expressed in total rad). If exposure is variable, some method is needed to accurately obtain total dose (e.g., dose rate averaging, integration and summation of variable dose rates).
2. Phylogenetically, the more highly developed organisms are more sensitive to radiological exposure than lower forms. Consequently, the most simplistic forms of life (bacteria, protozoans) are less susceptible to radiological exposure than mammals and birds (Figure 2.1). Intermediate forms of life (fish and invertebrates) fall in the middle. This observation is based on a collective assessment of numerous acute and chronic studies and it should be noted that with each major group of organisms there is a wide range of overlap in the dose rates used to construct the paradigm, but the general relationship is consistent and well documented (Sample and Irving 2011; DOE 2002; NCRP 1991; IAEA 1976).

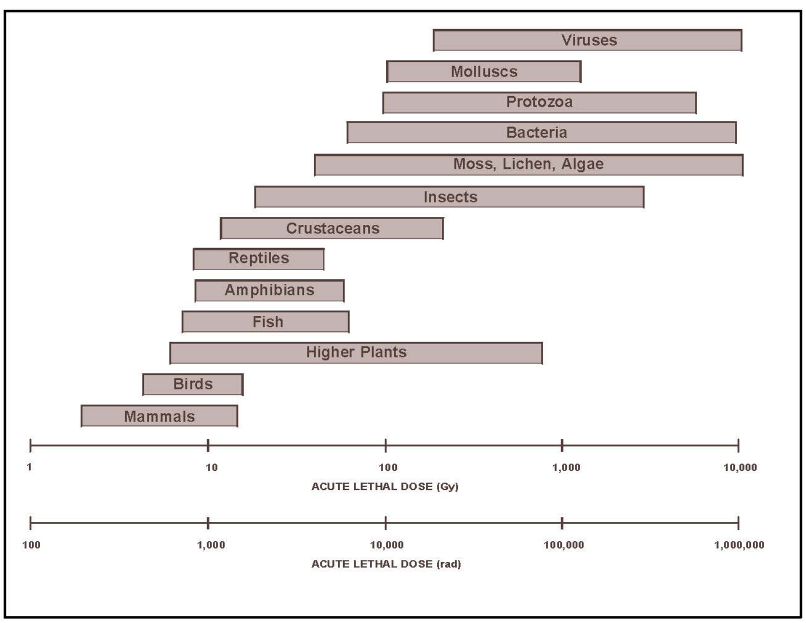


Figure 2.1. Phylogenetic Relationship of Major Classes of Biota and Acute Radiation Exposure (adopted from DOE 2002)

3. There is a great deal of variability both within phylogenetic groupings of life and between these groupings. When trying to establish lower limits of exposure and evaluating chronic effects, it not only is harder to detect effects, but the variability about those effects also increases.
4. Cytogenetic responses to low amounts of ionizing radiation can be seen at 0.01 to 0.05 rad/d. These responses may or may not have a longer impact on the well-being of the exposed organism. This is also the range of dose rates that are associated with hormesis or a stimulation of biological response that is commonly demonstrated in controlled exposure studies.
5. Rapidly dividing (reproducing) cells are more susceptible to radiation damage than slowly reproducing cells. Consequently, radiation therapy for cancer treatment results in nausea because the intestinal lining is constantly being replenished. Younger rapidly growing animals are more susceptible than adults that have finished growing, and warm-blooded vertebrates are slightly more susceptible than cold-blooded organisms. It is the sensitivity of rapidly dividing cells that predisposes the immune response, particularly the generation of blood cells, and gametogenesis to impacts from exposure to ionizing radiation and other toxic agents.

Consideration of these basic factors has helped established dose-based benchmarks for assessing the potential impacts of exposure to ionizing radiation. The convention is to express these benchmarks as a dose rate (i.e., rad/d). For assessing the risk to 100-NR-2 receptors, we use a continuum using the DOE guidance levels and recommendations for predicted no-effect levels coming out of the international community (Sample and Irving 2011). The DOE benchmarks represent a dose rate that is protective of populations while acknowledging that some minor effects may affect individuals within a given population. These dose rates have been extensively reviewed and accepted by DOE. At the other end of the spectrum lie the predicted no observed effect levels. These are proposed benchmarks coming out of the international scientific community that have not been well vetted by the regulatory community in the United States. Their formulation is based on the same scientific literature used to develop the DOE guideline values and augmented by research from the European community and Chernobyl accident, which has significantly augmented the technical database for radiological effects in biota. Both of these benchmarks, while defining different endpoints, lie on a continuum of exposure. Between the dose rates established by DOE (2002) and the no observed effect dose rates lies a range of dose rates where sublethal effects may occur, but will not have an effect at the population level. These may be the lowest observed effect levels in a controlled study or other observations of effects that, when evaluated, will not seriously affect the well-being of the overall population of organisms. At dose rates above the DOE guideline values, the likelihood of adverse effects increases up to acute effects and mortality.

2.1.1 Dose Comparison: Standard Man and Biota

The drinking water standard is based on all radionuclides in the water source and the combined dose of those radionuclides such that the dose does not exceed 4 mrem/y to the standard man. The standard man consumes 2 L water/d, 365 d/y. To take this single pathway and apply it to biota residing in an aquatic or riparian environment requires multipathway models to estimate dose. A prior assessment for the exposure to developing salmon embryos at 17 pCi/L strontium-90 suggests that the dose to these eggs at 8 pCi/L (the remedial action goal) would be about 0.000004 rad/d (Peterson and Poston 2000). This estimated dose rate falls three orders of magnitude below the most conservative no-effect benchmark proposed by Andersson et al. (2008) of 0.005 rad/d. The dose rate is indistinguishable from natural background dose rates that may range from 0.0001 to 0.001 rad/d (Sazykina 2005).

2.1.2 Strontium-Calcium Relationship

The hazards associated with strontium-90 and its effect on fish and wildlife stem from its chemical similarity to calcium and its propensity to accumulate in calcified tissue such as bone, shell (egg or mollusk), and carapace. Consequently, biological effects associated with strontium-90 are those associated with the formation of these tissues and those in organs located in close proximity to them.

2.2 Current Cleanup Standards for Strontium-90

The drinking water standard (DWS) (40 CFR 141; WAC 173-201A) for strontium-90 of 8 pCi/L is the remedial action goal for cleanup at the Hanford Site and at 100-NR-2 (DOE 2009b). While the Atomic Energy Act of 1954 exempts state oversight of radiological releases, the state also recognizes the DWS of 8 pCi/L of strontium-90 as the ambient water quality standard for Washington State. The remedial action goal of 8 pCi/L is viewed as the target level for cleanup for the aquifer and groundwater discharged to the Columbia River.

While the cleanup standard targets exposure to humans, that route of exposure is drinking water and the focus of this report is ecological receptors. The 8-pCi/L DWS as promulgated is the level of strontium-90 that would result in an annual dose of 4 mrem effective dose equivalent (EDE) if consumed at a rate of 2 L/d for a year in the standard man (40 CFR 141). Exposure limits for ecological receptors are based on dose rate and have not been resolved for individual radionuclides.

2.3 Advances in Biota Dose Assessment

There has been a great deal of interest and research in assessing radiological dose to aquatic and terrestrial biota both in the United States and internationally. DOE put considerable effort spanning roughly a decade into the development of a biota assessment tool (DOE 2002). As a result of this activity, DOE has established dose limits for biota (DOE O 458.1). For aquatic organisms, the dose rate is 1.0 rad/d and for riparian animals, it is 0.1 rad/d (DOE 2002). These dose rates are based on reviews of research on radiation effects that have been summarized by the International Atomic Energy Agency (IAEA 1976) and National Council on Radiation Protection and Measurements (NCRP 1991). These dose rates are considered protective at the population level and assume that some minor level of radiotoxicological responses may occur in individual members of the population, but not at a level that would affect the well-being of individual members of the exposed population.

There have been additional opportunities to study elevated environmental radiation resulting from nuclear accidents (e.g., Chernobyl). Scientists have made significant scientific advancements in the assessment of dose to biota in the following two areas:

1. Dose response relationships have been refined as a result of the opportunity to study effects in biota at the site of nuclear accidents and in support of nuclear technology in foreign countries.
2. Advancements have been made in the methods and tools used to estimate dose to wild animals.

These advancements have recently been summarized by Sample and Irving (2011). Lower bench-marks defining no-effect concentrations and lowest observed effect have been proposed in Canada, Russia, and the European Union. These efforts have resulted in proposed "no-effect level" dose rates and "lowest observed effect level" dose rates that are lower than the DOE guideline values of 1.0 rad/d for populations of aquatic organisms and terrestrial plants and 0.1 rad/d for populations of terrestrial and riparian animals (Figure 2.2). The paradigm of considering dose rate benchmarks that are protective of populations is based on the fact that only a small segment of a population is exposed at the level of the standard and the majority of an exposed population is exposed at a level lower. Consequently, when the population-based standard is essentially set at a level where it is difficult to demonstrate a sublethal effect, the likelihood that the population will be adversely effected is very low and the benchmark is protective.

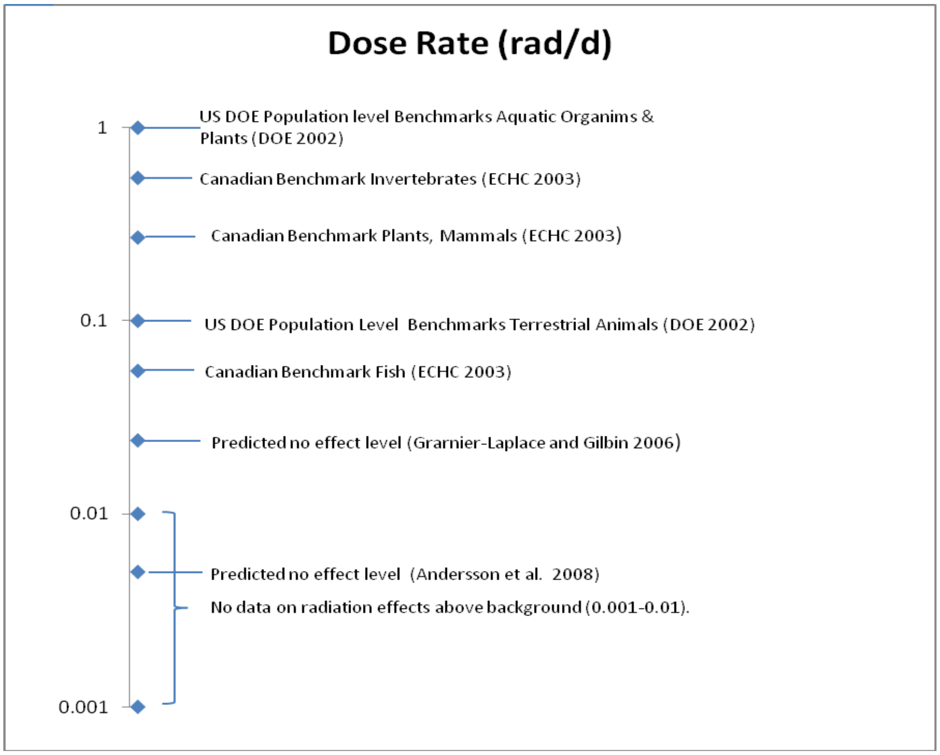


Figure 2.2. Relationship of DOE Biota Dose Benchmarks and Proposed Benchmarks Summarized by Sample and Irving (2011)

The proposed no-effect dose rate levels ranged from 0.005 rad/d (Andersson et al. 2008) to 0.024 rad/d (Garnier-Laplace et al. 2006). The relationship can be viewed as a continuum of dose effects ranging from minor physiological effects to individual members of a population for the guidance benchmarks and no-effect dose rates (Figure 2.2). Figure 2.2 is based on data reported by the IAEA (1976), NCRP (1991), and Sample and Irving (2011). Subsequent studies indicate reduced salmon egg survival at 0.1 to 0.5 rad/d chronic gamma exposure (Sazykina et al. 2003 cited by Sample and Irving 2011). These endpoints are compared with other examples of sublethal effects for fish to demonstrate the wide range of dose rates associated with sublethal effects (Table 2.1). The clarification for population-level effects is maintained in the standards. The proposed no-effect dose rate levels afford an opportunity to regulate at a level protective of individuals within a population, are based on a more comprehensive data base, and as such, have the utility of protecting regulated species and provided a means for assessing protectiveness.

Table 2.1. Comparison of Sublethal Effects Associated with Exposure to Ionizing Radiation (IAEA 1976; NCRP 1991; Sazykina et al. 2003)

Dose (rad)	Dose Rate (rad/d)	Effect
		1,000–10,000 Accumulated Dose
3970	8.5	Minimum dose at which oogenesis was suppressed, guppy
1776	>10	Severe reduction in spermatogonia, gamma ray exposure, medaka
1610	31.2	Testicular atrophy, mosquito fish
		100–<1,000 Accumulated Dose
850	9.5	Retarded gonadal development, Chinook salmon 89-day embryonic-larvae exposure
	4	Reduced brood size and increased sterility, guppy (lifelong exposure)
390	6.5	Increased sterility in male medaka (60-day exposure)
300	>10	Severe reduction in spermatogonia tritiated water exposure, medaka
		10–<100 Accumulated Dose
28	2.8	Temporary reduction in spermatogonia (10 days) gamma ray exposure, medaka
		1–<10 Accumulated Dose
5	1.0	Temporary reduction in spermatogonia tritiated water exposure, medaka
4	0.2	Suppressed humoral immune response (20-day embryological exposure)
		<1.0 rad Accumulated Dose
0.25	0.7	Immune system does not recover from initial effect (kidney dose from strontium-90), carp
0.005–0.02	0.1	Immune system affected, but recovers under continued exposure to strontium-90, carp
0.005	0.1	Lowest dose associated with some degree of immune dysfunction (kidney dose from strontium-90), carp

Several recent assessments conducted at 100-NR-2 have evaluated whole body radiological doses to ecological receptors. Poston et al. (2003) evaluated the dose rates to developing salmon embryos at 100-NR-2 and other reactor site areas along the Columbia River. Although salmon do not spawn near the 100-NR-2 shoreline, dose rates were estimated for a hypothetical situation to estimate dose rates for comparative purposes. The dose rate to salmon embryos in that exercise was based on exposure to strontium-90 and tritium and was 1.6E-03 mrad/d. The dose rates were based on Columbia River-specific bioaccumulation factors for soft tissue on a 1-cm sphere receptor (Baker and Soldat 1992).

Additional dose assessments were performed for riparian and nearshore receptors for the 2005 impact assessment (DOE 2009a). Dose rates were estimated using RESRAD-BIOTA and internal dose conversion factors for a number of receptors that were sampled. The modeled dose rates always exceed the dose rates based on internal tissue burdens. Dose rates were estimated for mice, sculpin, and clams and none exceeded the DOE guideline values of 0.1 rad/d for riparian animals or 1.0 rad/d for aquatic receptors (DOE 2009a).

The DOE guideline values apply to whole body dose rates. Recently, the IAEA established "reference animals for the assessment of dose to target radiosensitive organs and tissues." The immune system, digestive system, and reproductive systems are particularly radiosensitive because of the presence of rapidly reproducing cells. Evaluation of exposure and dose to radiosensitive systems provides a stronger assessment of potential impacts on aquatic biota.

3.0 Methods

This section describes the process for selecting biota for whole body dose assessment, the parameterization of the RESRAD-BIOTA code for conducting the whole body dose rates, and adjustments to the results to address conservatism in the process; temporal and spatial factors that affect dose were also assessed. Last, the methods for performing the Monte Carlo simulations of spinal column dosimetry are presented.

3.1 Selection of Species for RESRAD-BIOTA Assessment

Comprehensive species lists that have been developed for the Hanford Site served as a source for identifying potential receptors (DOE 2009a). Several key habitat characteristics must be met to result in maximum exposure for these species. The organisms must potentially reside in the riparian or nearshore environment of the 100-NR-2 site. This implies that the organism generally has a small home range or is relatively non-mobile in its ability to move. For example, a clam is not very mobile and would have a protracted length of exposure if it resided in the nearshore environment. Conversely, a river otter is a very mobile mammal that may cover a wide area in a single day and may be somewhat nomadic as it moves up and down the river. The initial selection of species was based on the broad knowledge of biota expected to occur along the Hanford Reach of the Columbia River in general and specifically at the 100-NR-2 shoreline. Because the primary route of exposure is ingestion, animals that feed on organisms residing in the riparian or nearshore environment are also preferred.

In addition, because radiosensitivity varies by phylogeny and vertebrate animals are more radiosensitive than invertebrates, representative mammals, birds, and fish were selected along with the crayfish as a representative aquatic invertebrate.

Mammal. The raccoon was selected as the 100-NR-2 mammal because it has a smaller home range and is less nomadic that other mammals; it feeds on amphibians, clams, and crayfish, as well as other plants and animals. While raccoons are found on the Hanford Site, there is no documented record of them occurring at 100-NR-2; hence they are a hypothetical receptor. Consideration was given to muskrat, beaver, and river otter. The muskrat and beaver were eliminated because their foodstuffs are plants, which are not abundant at the 100-NR-2 shoreline. The otter was eliminated because it is not likely to stay near the 100-NR-2 shoreline for any given length of time due to its nomadic tendencies. There are also no documented observations of muskrat, beaver, or river otter at 100-NR-2.

Bird. A number of aquatic birds were considered, but the great blue heron was selected. It feeds on fish, crayfish, and amphibians that are hunted in shallows or on land. Great blue herons develop habitual patterns of feeding; hence, they could frequent an area like 100-NR-2. Other birds that were considered include mergansers, Canada geese, egrets, pelicans, and ospreys.

Fish. Two species of fish were evaluated, sculpin and Chinook salmon (early life stage exposure). Sculpin were selected because they are believed to be territorial (particularly during breeding season), are known to inhabit the nearshore environment, and have been sampled in the past. As a benthic dwelling species, they are prone to more elevated exposures than species that are more free swimming in the water column. Whole body dose rates and dose rate to sculpin eggs were estimated.

The early life stage dose assessment for Chinook salmon was performed because of the economic, cultural, and recreational value of salmon. The aquatic habitat around 100-NR-2 does not support salmonid spawning, and exposure of salmonids includes seaward migrating juvenile salmon, adults migrating to spawning grounds upstream, and fall Chinook salmon that hold near the 100-NR-2 area. These behavior patterns of the juvenile and adult salmon greatly reduce the potential for exposure to strontium-90 in the nearshore environment. The assessment is more or less a screening assessment that follows an earlier assessment (Poston et al. 2003).

Invertebrate. Crayfish were also evaluated with RESRAD-BIOTA. The species found in the Columbia River is not prone to burrowing in mud; however, it is prone to hiding under rocks and the riprap barrier along the 100-NR-2 shoreline could provide habitat supporting this behavior. Dose rates to clams from strontium-90 deposits in shell tissue were extensively evaluated in the 2005 impact assessment (DOE 2009a). That analysis focused on the dose to the mantel lining the shell and did not assess the dose contribution to that tissue from the other shell of the clam.

3.2 RESRAD-BIOTA Dose Modeling

RESRAD-BIOTA, Version 1.5, was used to estimate the dose rates to the selected group of receptors. Maximum screening calculations were performed for aquatic and riparian organisms based on the highest observed concentrations of strontium-90 in Columbia River water, river sediment, and riparian soil at 100-NR-2 (Table 3.1). Estimated doses include the contribution from the beta decay progeny of yttrium-90. Subsequent adjustments were made by multiplying the maximum dose rates by the ratio of average media concentration for 100-NR-2 to the maximum value.

Table 3.1. Maximum and Mean Strontium-90 Concentrations Used for RESRAD-BIOTA Calculations

Category	Water	Sediment	Soil
Maximum	65 pCi/L	31.4 pCi/g	5.7 pCi/g
Mean	0.196	0.031	0.08

While these receptors have the greatest potential for exposure, they are not commonly observed in the 100-NR-2 area. Specific adjustments for each receptor were implemented in the RESRAD-BIOTA analysis as described in the following sections.

3.2.1 Aquatic Receptors

Calculations were made by adjusting the bioaccumulation factors (referred to as the "lumped parameter" in RESRAD-BIOTA; i.e., B_{iv} value, see Appendix B). The B_{iv} was based on the calcium concentration of river water (17 mg/L) using the equations developed by Vanderploeg et al. (1975). For those calculations, the B_{iv} for water to soft tissue was 5.7 and water to bone was 560. For the worst-case and mean exposure scenarios, a B_{iv} of 560 was used because bone was a critical receptor for strontium-90 for sculpin. It was also used for crayfish because the composition of the carapace of crayfish contains as much as 25% calcium wet weight (Zheng et al. 2010; Hunter et al. 1976). Concentrations of calcium in crayfish carapaces on a dry weight basis range from 66% to 67% (Welinder 1974). Accumulation from sediment was nulled. Other key variables for the RESRAD-BIOTA Tier 3 modeling effort were species-specific allometric variables (Appendix B).

3.2.2 Riparian Receptors

Dose rates to riparian receptors (great blue heron and raccoon) were calculated using species-specific allometric parameters (summarized in Appendix B). This approach does not use bioaccumulation factors (B_{iv}) from water or sediment and dose rates are driven by ingestion parameters and the body dimensions of the receptors. These parameters are also summarized in Appendix B.

3.2.3 Special Cases

Dose rates to clams (Corbicula) were estimated and reported for the 100-NR-2 impact assessment (DOE 2009a). The VARSKIN model estimates dose rates from slab geometries and was used to estimate dose rates and maximum dose rates were based on the maximum observed concentration of strontium-90 in clamshells (383 pCi/g). For this scenario, the receptor tissue was the mantle that lines the inner surface of the valve. As calculated, the dose rate did not account for irradiation from the opposite valve. The Monte Carlo simulations for fish spine define this relationship and the estimated dose rates reported by DOE (2009a) for clams would increase by factors of almost two where the shells come together to approximately 1.1 at the greatest distance between the two valves.

3.3 Monte Carlo Modeling of Dose to the Anterior Kidney in Fish

Dose rates to the anterior kidney of fish were conducted using MCNP5, Version 1.51[1] (X-5 Monte Carlo Team 2008a, 2008b, 2008c). MCNP5 is a Monte Carlo radiation transport code that can estimate dose rates to tissues in a mixed electron-photon mode [mode p e].[2] Additional detail is provided in Appendix A. Two methods were used. The first method, used mainly for complete organs, directly calculates the energy deposition, in MeV, in the target organ. The energy deposition in the target organ divided by the mass of the target organ yields dose to the target organ. It does not allow for the calculation of dose distribution within the organ. Dose distributions within organs were calculated by tabulating the estimated emission track length and electron flux (Schaart et al. 2002). The two methods were compared and their results were found to agree to within 0.5%.

The fish spine and kidney models were based on juvenile trout anatomy. The spine was a cylinder 4.2 cm long and 0.3 cm in diameter. It consisted of bone with a density of 1.04 g/cm^3. Conformations of fish kidney are variable and for this exercise, the anterior kidney was modeled as a slab measuring 0.21 cm deep and 1.41 cm wide running the length of the spine. The density of the tissue was 1.05 g/cm^3. The kidney model was partitioned into a 1.2-cm anterior and 3.0-cm posterior kidney to simulate the configuration of the trout kidney (Figure 3.1). The modeled anterior kidney deflects downwards away from the spinal cord at an angle of 10 degrees and the distance between the leading edge of the kidney and the spine is 0.25 cm (Figure 3.2).

[1] MCNP5 is available from the Radiation Shielding Information Computing Center (RSICC) at www.rsicc-ornl.gov.
[2] At several places in this report, the alphanumerical values of some MCNP5 commands are provided within square brackets and some items specific to the code are discussed. Comprehensive explanations of MCNP5 commands and computational methods are available in the MCNP5 user manual (X-5 Monte Carlo Team 2008b), to which the reader is referred.

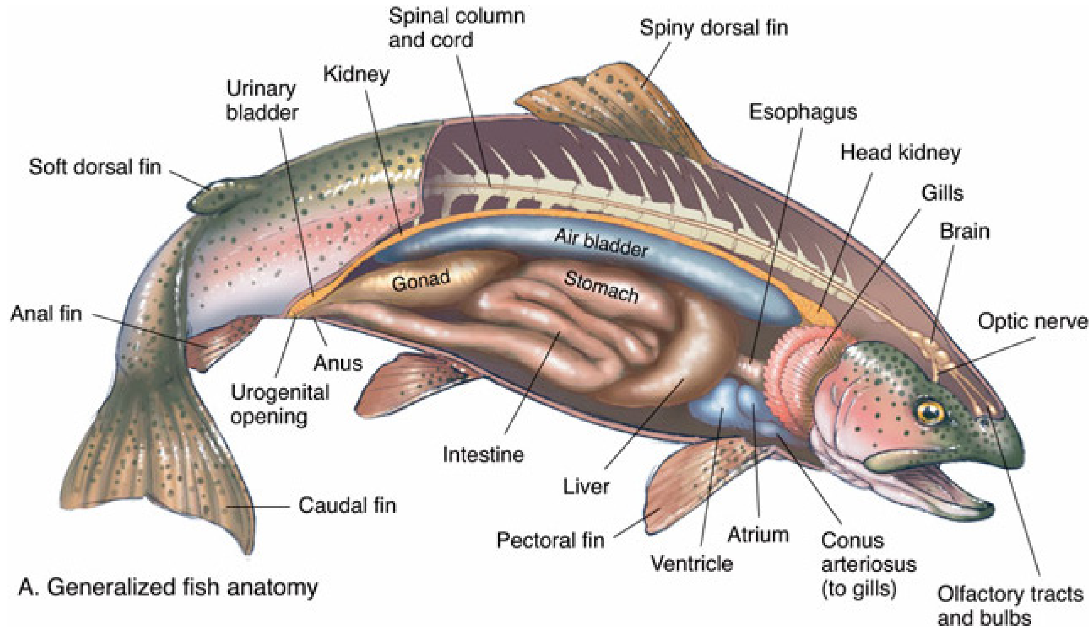
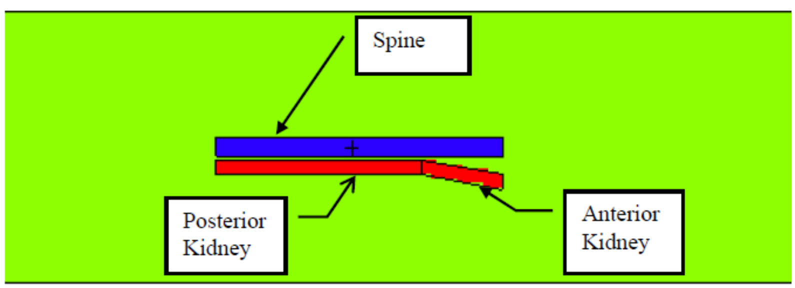


Figure 3.1. Generalized Trout Anatomy Showing Orientation of Kidney and Spine and Schematic of Model Used to Estimate Dose Rate to Anterior Kidney



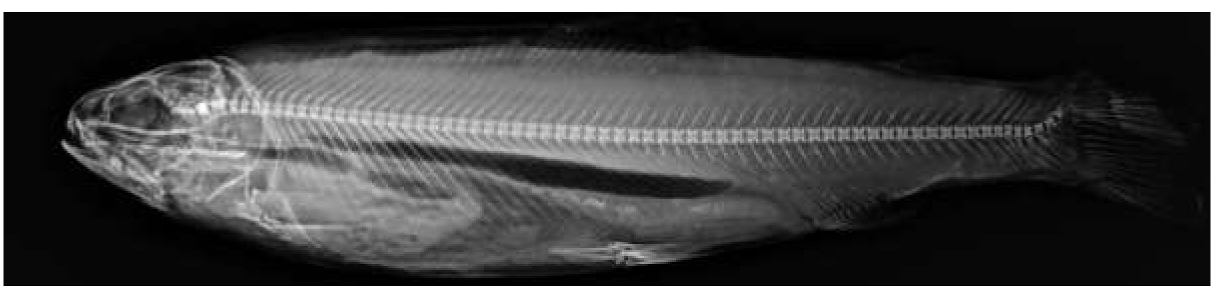


Figure 3.2. Normal Spinal Column of a Rainbow Trout Showing the Air Bladder (long dark body in upper visceral portion of the fish), Spinal Column, and Ribs. The kidney tissue is located between the air bladder and the spinal column (©Norfima AS).

For all dose calculations, strontium-90 and yttrium-90 are considered to be equally distributed throughout the spinal column at a concentration of 1.0 pCi/g and in secular equilibrium (i.e., for each decay of strontium-90, there is a corresponding decay of yttrium-90). Within the geometric bounds of this model, dose rates (rad/d) will vary in direct proportion to increases and decreases in the concentration of strontium-90 relative to 1.0 pCi/g.

4.0 Results

The results of RESRAD-BIOTA dose rate modeling, dose modeling to the anterior kidney, and the re-evaluation of dose rates to clams (from clamshell) and fish embryos are described in this section.

4.1 RESRAD-BIOTA Dose Modeling

The animals selected for this modeling exercise represent species that because of their natural history would have a propensity for exposure to strontium-90 at 100-NR-2. The initial dose calculations were based on maximum observed concentrations of strontium-90 at 100-NR-2 from the impact assessment (DOE 2009a) or surveillance data collected in recent years. Consequently, the predicted dose rates represent a maximum hypothetical exposure scenario. Once these initial calculations have been performed, dose rates for other scenarios can be easily calculated because the dose rates are linearly proportional to the ratio of strontium-90 concentrations in the different exposure media.

4.1.1 Aquatic Receptors

The hypothetical maximum dose rates for the two aquatic species modeled with RESRAD-BIOTA ranged from 1E-03 to 7E-03 rad/d (Table 4.1). The dose rates can be adjusted to average conditions by calculating the ratios of the source terms for mean concentrations and maximum concentrations. Environmental monitoring data were used to determine mean water concentrations at Priest Rapids Dam (upstream location) and from four transect samples at the 100-NR-2 shoreline area. The selection of sediment values was more complicated. Sediment samples collected during the impact assessment were collected from crevasses in the basalt riprap that was emplaced along the 100-NR-2 shoreline in the 1980s. This material consisted of fines and had a consistency similar to mud. The normal substrate at 100-NR-2 consists of cobble and fines deposited in the voids between the cobble. Because of the current, this material is of a larger particle size and is essentially a sandy grit material. This material is the most representative of what aquatic receptors would be exposed to along the shoreline. However, because of the much lower surface area to mass ratio for the affected grains, the concentrations of strontium-90 in this material is greatly reduced and the material (along with the sediment in the riprap) has not been extensively sampled. The gritty material was not sampled during the 2005 impact assessment sampling (DOE 2009a), but it was sampled in 1997 at two locations, one upstream of the riprap and the other downstream of the riprap (Van Verst et al. 1998). The average of these two values was used to adjust the ratio for sediment.

Dose rates were significantly reduced by as much as three orders of magnitude when using the mean media concentrations (Table 4.1). Both the maximum dose rates and mean dose rates fell below the DOE guideline values of 1.0 rad/d for the protection of populations and the more conservative ecological no-effect levels of 0.005 and 0.024 rad/d proposed by Andersson et al. (2008) and Garnier-Laplace et al. (2006) and recently summarized by Sample and Irving (2011).

Table 4.1. Worst-Case and Mean Dose Rate Modeling (rad/d) with RESRAD-BIOTA for Aquatic Receptors

Species	Source		Total
	Water	Sediment	
Worst Case			
Crawfish	6.25E-04	9.44E-05	7.24E-04
Sculpin	1.88E-03	9.44E-05	1.98E-03
Mean			
Crawfish	1.88E-06	9.32E-08	1.98E-06
Sculpin	5.67E-06	9.32E-08	5.76E-06

4.1.2 Riparian Receptors

The soil concentrations of strontium-90 were based on the soil sampling conducted at 100-NR-2 during the 2005 impact assessment (DOE 2009a). These were rooting zone soils and many of the reported values were below detection. The rooting zone samples collected at Vernita during the impact assessment in 2005 had negative values and cannot be used. In place of those, a background strontium-90 concentration of 0.08 pCi/g that was derived for the Hanford Site was used.

For the riparian receptors, the same media values for water and sediment were used along with soil. Because the dose calculations for the riparian receptors were based on allometric parameters, B_{iv}s for water and sediment were not used to determine tissue burdens in the receptor, but were used to calculate the concentration of the food ingested by the receptor. In addition, soil was not used as a source of exposure for the great blue heron because its feeding behavior along the shoreline was considered to be 100% aquatic. These food sources were based on default parameters for riparian organisms. The estimated dose rates for both the raccoon and the great blue heron were similar for both the maximum exposures and the mean exposure scenarios (Table 4.2). The maximum dose rates were on the order of 1.4E-3 for the raccoon.

Table 4.2. Worst-Case and Mean Dose Rate Modeling (rad/d) with RESRAD-BIOTA for Riparian Receptors

Species	Water	Sediment	Soil	Total
Worst Case				
Great blue heron	4.02E-05	1.09E-03	NC	1.13E-03
Raccoon	5.02E-05	1.14E-03	1.93E-04	1.38E-03
Mean				
Great blue heron	1.21E-07	1.08E-06	NC	1.20E-06
Raccoon	1.21E-07	1.91E-07	1.60E-05	1.63E-05

4.1.3 Special Cases

As a result of the Monte Carlo simulations, the dose rates to clams (from clamshell) and fish embryos from prior studies were re-evaluated.

4.1.3.1 Clamshell Dose

Clamshell dose rates were also estimated using VARSKIN software in the 2005 impact assessment (DOE 2009a). The maximum observed shell dose rate was 0.022 rad/d based on the 383-pCi/g clamshell sample from 2002. As calculated, this represents the dose rate where the mantel lies up against the shell, but does not account for irradiation from the opposite shell. Soft tissue located where the two shells meet along the outer edge of each shell receives twice the dose rate than that originally reported for the single shell. Dose rates to the clam's soft tissue would be less than this value based on the thickness of the tissue and the amount of attenuation of beta energy. Under these circumstances, the dose rates could not exceed twice the clamshell surface dose rate (0.044 rad/d), but would exceed the single shell surface dose rate. These dose rates do not exceed the DOE guideline of 1.0 rad/d for population level effects, but do exceed the more conservative no-effect level ecological dose rate of 0.025 rad/d. This essentially places the dose rate at a level less than twice the no-effect level. From a phylogenetic perspective, the most sensitive aquatic organisms used to derive the DOE guideline value of 1.0 rad per day were fish. Fish are more radiosensitive than mollusks (DOE 2002; IAEA 1976; NCRP 1990).

4.1.3.2 Fish Embryos

Embryonic exposure of developing salmon eggs is another potential exposure route for groundwater discharges of strontium-90. Fall Chinook salmon spawning has been monitored in the Hanford Reach since 1948 and fall Chinook salmon do not spawn along the 100-NR-2 shoreline. Exposures at the 100-NR-2 shoreline were evaluated in 2003 as part of a Hanford Reach-wide assessment of hypothetical exposure of developing salmon embryos to groundwater discharge at the Hanford Site (Poston et al. 2003). The hypothetical exposure for 100-NR-2 was based on 22% dilution of seep water concentrations and a bioaccumulation factor of 5.7 for a 1-cm salmon egg. The egg life stage dose rate at the 100-N Area was 1.6E-06 rad/d.

Exposure data from the 2005 impact assessment (DOE 2009a) was used to reassess the potential exposure to fish eggs with RESRAD-BIOTA. The 2005 assessment included maximum concentrations observed at 100-NR-2 from 1990 to 2004 for eight radionuclides, but the dose rates were driven by strontium-90. The strontium-90 concentrations used were the maximum values adopted for this report (Table 4.1). In this exercise, the size of the egg was reduced to 0.2 × 0.2 × 0.2 cm, which is considerably smaller than a Chinook salmon egg and is probably closer in size to a sculpin egg. A bioaccumulation factor of 5.7 was used to estimate the accumulation of strontium-90 by the egg from water. The resulting dose rate was dominated by the dose from sediment (Table 4.3); however, the estimated dose rate of 8.25E-04 rad/d was well below the ecological benchmark of 0.025 rad/d.

Table 4.3. Dose Rate to a 0.2-cm Fish Egg

	Media		Dose Rate		
	Water (pCi/L)	Sediment (pCi/g)	Water (rad/d)	Sediment (rad/d)	Total Dose (rad/d)
^{90}Sr	65	38.5	7.02E-06	8.18E-04	8.25E-04

4.2 Monte Carlo Dose Modeling to the Anterior Kidney in Fish

Based on a reference concentration of 1 pCi/g of strontium-90 in the spine, the dose rate to the anterior kidney was 6.14 µrad/d. Dose rates to the anterior kidney were lower than dose rates to the posterior kidney because the distance between the anterior kidney and spinal cord is greater than the distance between the posterior kidney and spinal cord (Table 4.4). Over 99% of the dose rate in both the anterior and posterior kidney is attributable to yttrium-90 decay. For comparison, the dose rate to the spine is approximately 40 times greater than the dose rate to the anterior kidney and approximately 20 times greater than the dose rate to the posterior kidney. Dose rates as a function of distance from the spine decline dramatically in a very short distance (Figure 4.1). The dose rate to the middle and posterior sections of the kidney are greater than the dose rate to the anterior kidney because these sections of the kidney sit closer to the spine (Figure 4.2).

Table 4.4. Dose Rate to the Kidney and Spine from Strontium-90 and Yttrium-90 Evenly Distributed Through the Spinal Cord

Tissue	Average Dose Rate to the Tissue (µrad/d to tissue per pCi/g of ^{90}Sr or ^{90}Y in the spine)		
	^{90}Sr	^{90}Y	Total
Anterior kidney	4.24E-04	6.13E-01	6.14E-01
Posterior kidney	3.28E-03	1.13	1.14
Spine	8.75	1.77E-01	2.65E-01

To estimate the actual dose that may be attributable to the anterior kidney in fish at 100-NR-2, we can look at estimated concentrations of strontium-90 in fish bone and estimate the strontium-90 in fish bone based on bioaccumulation factors taken from the literature. Fish have been monitored along the 100-NR-2 shoreline for many years and sculpin were sampled as part of the 2005 impact assessment (DOE 2009a). The concentrations of strontium-90 in sculpin were below detection (0.05 pCi/g of whole body weight). Surveillance sampling over the past 30 years was summarized by DOE (2009a) and the maximum carcass sample concentration was observed in a carp carcass sample collected in 2004. This concentration was 1.14 pCi/g. We assumed that the geometrical configuration for the anterior kidney to the spine is the same as that for the model based on trout and that this concentration is at equilibrium in the fish. The resulting dose rate to the anterior kidney is 0.9 µrad/d.

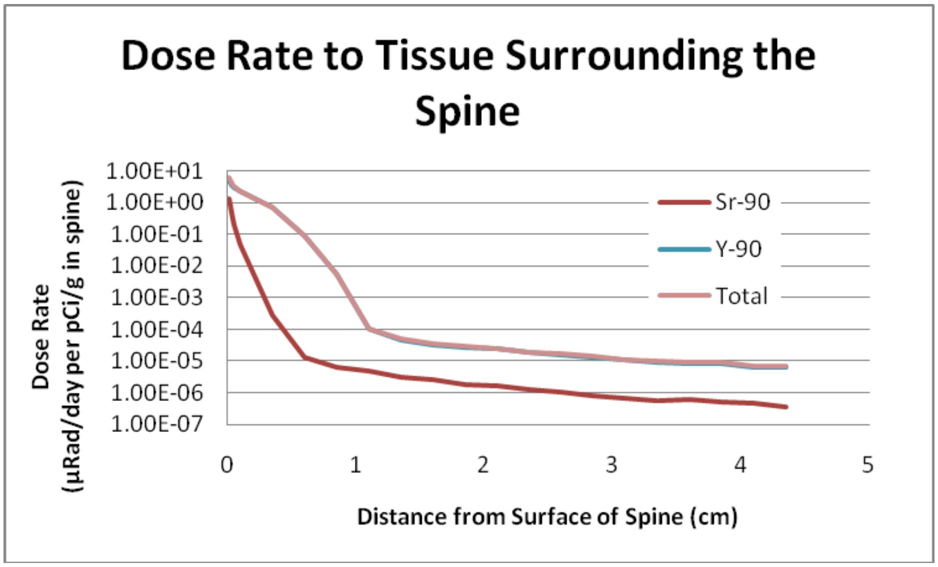


Figure 4.1. Dose Rate to Fish Tissue Surrounding the Spine When the Spine Contains 1 pCi of Strontium-90 and Yttrium-90 per Gram of Spinal Bone

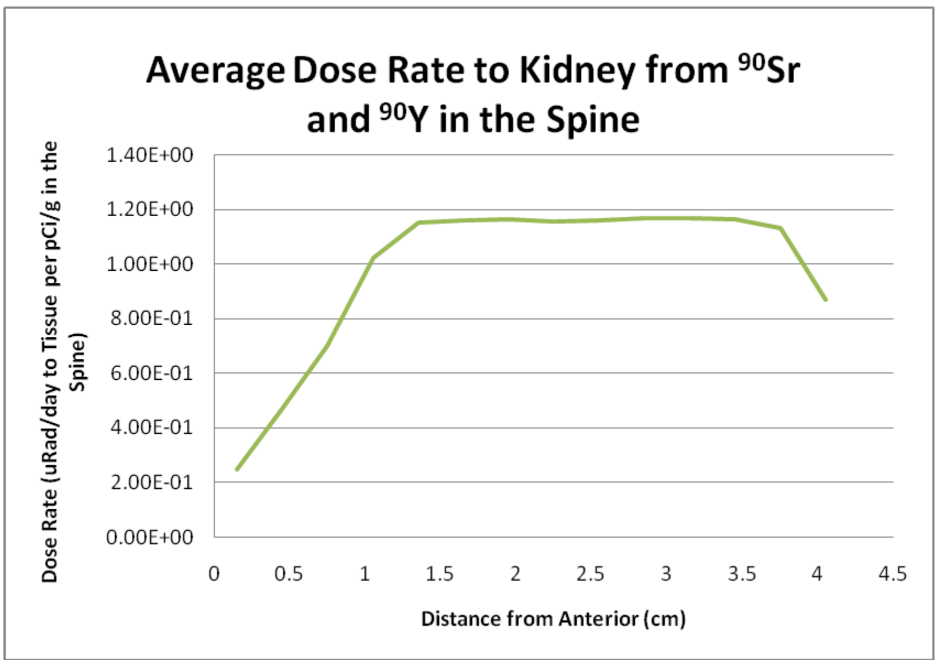


Figure 4.2. Average Dose Rate to the Kidney from Strontium-90 (^{90}Sr) and Yttrium-90 (^{90}Y) in the Spine. The concentration of ^{90}Sr and ^{90}Y in the spinal cord is 1 pCi/g. The relatively low dose rate in the anterior portion of the curve is due to the curvature of the anterior of the kidney. The apparent decrease in dose rate in the posterior portion of the curve is an artifact of the model in that the modeled spine does not extend beyond the end of the kidney.

An alternative method for estimating dose rates to the anterior kidney is to estimate the concentration in bone based on the concentration of strontium-90 and calcium in river water (Vanderploeg et al. 1975). Nearshore river water transect samples have been collected at four locations along the 100-NR-2 shoreline since 1999. Samples are taken along the shoreline at mid depth in the shallows, which best represents surface water concentrations at the 100-NR-2 shoreline. The strontium-90 data from 1999 through 2009 were characterized and the maximum and mean values were used to characterize water level concentrations to estimate strontium-90 concentrations in bone. A concentration factor for fish bone of 560 was calculated based on an equation developed by Vanderploeg et al. (1975) and Peterson and Poston (2001).

At 100-NR-2, the maximum expected concentration of strontium-90 in bone was 750 pCi/g of bone and the mean predicted bone concentration was 110 pCi/L. For comparison, strontium-90 bone concentrations were estimated from upstream river water sampling at Priest Rapids Dam (Table 4.5). The estimated bone concentrations were 17 and 2.6 pCi/g for maximum and minimum concentrations, respectively. The resulting dose to the anterior kidney for the estimated mean bone concentration at the Priest Rapids location was 1.6 µrad/d. The dose rate to the anterior kidney based on the average strontium-90 in 100-NR-2 nearshore Columbia River water was 68 µrad/d based on an estimated mean strontium-90 concentration of 110 pCi/g of bone. The calculations based on the maximum observed strontium-90 concentrations are provided for a worst-case perspective because most fish will most realistically experience exposure conditions reflected by the mean strontium-90 water concentration.

Table 4.5. Estimated Dose Rates to Anterior Kidney of a Hypothetical Fish Residing at 100-NR-2 and Priest Rapids Dam

	Nearshore Surface Water ^{90}Sr Concentration (pCi/L)	Estimated ^{90}Sr Concentration in Bone (pCi/g)	Anterior Kidney Dose Rate (µrad/d)
100-NR-2 Nearshore			
Maximum concentration	1.34	750	460
Mean concentration	0.196	110	67.5
Priest Rapids Dam, 2004–2008			
Maximum concentration	0.031	17.36	10.7
Mean concentration	0.0047	2.63	1.62

5.0 Discussion

Both the worst-case and average dose rate estimated by RESRAD-BIOTA for the four primary aquatic and riparian receptors fell below the no-effect dose rates predicted by Andersson et al. (2008) and Granier-Laplace et al. (2006). As calculated, the worst-case scenario is a hypothetical exposure scenario that is basically unrealistic. Spatially, the area of the 100-NR-2 shoreline and nearshore areas that have these elevated concentrations is very small. Temporally, the amount of time a mobile receptor would spend at these locations is also small. The dose rates associated with the average concentrations of strontium-90 at 100-NR-2 are more representative of what would be expected as a realistic exposure scenario.

Estimated dose rates based on average strontium-90 concentrations approach 1.0E-5 rad/d and are well below the background dose rates based on naturally occurring radionuclides in the Hanford Reach. External radiation levels measured upstream of the reactor areas average about 0.1 mR/d. While there are no hard estimates of the internal dose rates to fish from natural radioactivity, they would likely be similar to values established for humans. The internal dose rate for humans is 134 mrem/y, or 3.7E-04 rem/d. The estimated dose rates are attributed to the uranium and thorium decay chains, rubidium-87, and potassium-40 (Eisenbud 1987). Hence the estimated combined dose rate (external and internal) is 4.7E-04 rad/d and falls within the range of background dose rates reported by Sazyikina (2005) of 0.0001 to 0.001 rad/d.

Under the assumption that 1 rad = 1 rem, these background dose rates are very useful for putting the estimated dose rates for biotic receptors at 100-NR-2 in perspective. The worst-case dose rates essentially exceed the combined internal and external background dose rate (4.7E-04 rad/d) by an order of magnitude, but still fall below the more conservative ecological dose rate benchmark of 0.005 rad/d (Andersson et al. 2008) (Figure 5.1). The estimated dose rates based on average exposure concentrations of strontium-90 fall one order of magnitude below the estimated average background dose rate for riparian receptors and two orders of magnitude for aquatic receptors. Consequently, the dose rates represented by "average exposure conditions," are lower than background dose rates and may in fact be indistinguishable from background dose rates because they fall within 10% of the value.

5.1 Anterior Kidney Dose Rates in Fish

The Monte Carlo simulations for anterior kidney are applicable to any organ system that lies within the effective path of the modeled beta radiations. Radiological damage to the immune system has been inconsistently observed at dose rates as low as 0.02 rad/d (0.2 mGy/d; Real et al. 2004 as cited by Sample and Irving 2011). The ovaries and testes of fish are also located in the upper body cavity, but beneath the kidney; consequently, dose rates in these reproductive organs would be lower than the modeled dose rates in the kidney. The lower end of reproductive effects was reported by Sample and Irving (2011) to occur at 0.055 rad/d (5.5 mGy/d). These endpoints are the more sensitive endpoints that form the technical basis of the no-effect ecological benchmarks for radiological exposure.

To achieve a dose rate of 0.02 rad/d in the anterior kidney of the modeled fish, the concentration of strontium-90 would have to reach 32,400 pCi/g in the spinal column. Based on the maximum observed water concentrations of 65 pCi/L (Table 3.1) and a B_{iv} of 560, the maximum predicted concentration of strontium-90 in fish bone is 36 pCi/g. Over the past 28 years, the maximum observed concentration in fish carcass (consisting primarily of bone) was 1.14 pCi/g in a carp carcass sample collected in 2002. This value is an order of magnitude greater than the value predicted in bone based on an average water concentration of 0.196 pCi/L of strontium-90.

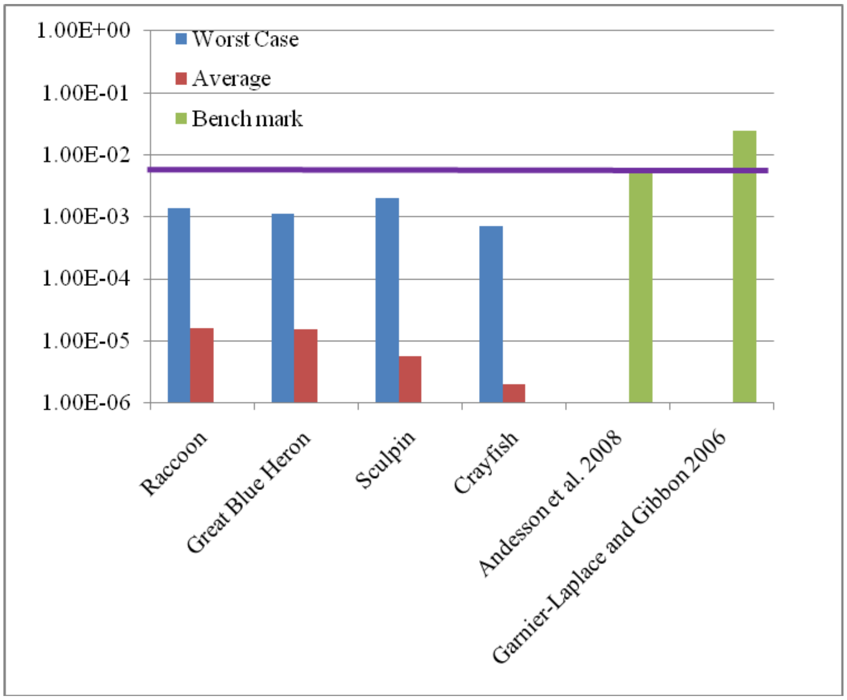


Figure 5.1. Comparison of Dose Rates from Worst-Case and Mean Exposure Scenarios Using RESRAD-BIOTA for 100-NR-2 Receptors Compared to Predicted No-Effect Dose Benchmarks

5.2 Dose Rates to Raccoon (Mammal Bone)

Mammal bone is more dense than fish bone, in part because it must support the animal's body whereas much of the support for a fish is augmented by the water column. Strontium-90 accumulates in bone tissue. Blood-forming stem cells develop in the bone marrow of mammals where they are susceptible to radiation exposure from strontium-90. However, while some leucocytes associated with immune function originate in the bone marrow, the spleen and the thymus are the major organs that support immune function in mammals. Cell-mediated immune response is as much if not more at risk in mammals as it is in fish due to the deposition of strontium-90 in bone. Strontium-90 deposited in trabecular bone will directly irradiate stem cells that give rise to immunocompetent white blood cells and red blood cells that develop in the bone. Estimated whole body dose rates for raccoons due to exposure to strontium-90 exceed the dose rates estimated for sculpin based on average exposure conditions (Table 5.1). In this context, the raccoon may be considered the critical receptor at 100-NR-2. The primary source of this exposure in the RESRAD-BIOTA calculations was inadvertent ingestion of sediment.

Table 5.1. Summary of RESRAD-BIOTA Dose Rate Estimates

Receptor	Dose Rate (rad/d) Worst Case	Dose Rate (rad/d) Average
Raccoon	1.38E-03	1.63E-05
Great blue heron	1.13E-03	1.54E-05
Sculpin	1.98E-03	5.76E-06
Crayfish	7.24E-04	1.98E-06

The impact of strontium-90 on the riparian receptors was not addressed as it was for fish modeling of strontium-90 in the spine. Some insight can be gained by evaluating other studies with mammals. Reproductive studies were performed with miniature swine that were fed chronic doses of strontium-90 over three generations (Clarke et al. 1970). The swine were fed food such that they received from 1 to 625 µCi/d of strontium-90 over three generations (11 years). There was no effect on litter size, percentage of stillborn births, or birth weight over the three generations. The 625-µCi/d dose treatment resulted in a reduced weaning weight in the offspring that was attributed to reduced levels of milk in the F_1 generations dams. Swine fed 3100 µCi/d did not survive the initial exposure period for gestation of the F_1 generation. In these studies, over 99% of the ingested strontium-90 was deposited in the skeleton. Studies with miniature swine have used a dose conversion factor for strontium-90 in bone of 50 µrad/d per pCi/g of bone (Clarke et al. 1970) that is almost twice the value developed for fish (mean value of 26.5 µrad/d) used for the fish spine. The estimated dose rate to bone in these swine ranged from 64,000 µrad/d to 40 rad/d for the 625-µCi/d exposure treatment (Table 5.2).

Table 5.2. Summary of Multi-Generation Swine Study (modified from Clarke et al. 1970)

Feed Level (µCi/d)	^{90}Sr in Bone[(a)] (µCi/g) F_0 Dams	^{90}Sr in Bone[(a)] (µCi/g) F_1 and F_2 Adults	Dose Rate (rad/d) F_0 Dams	Dose Rate (rad/d) F_1 and F_2 Generations In Utero[(b)]	Dose Rate (rad/d) F_1 and F_2 Generations Adults
1	0.0032	0.0016	0.64	0.004	0.072
5	0.016	0.018	0.32	0.02	0.36
25	0.08	0.09	1.6	0.1	1.8
125[(c)]	0.4	0.53	8	0.5	11
625[(c)]	2		40	2.5	NS[(d)]
3100	NR[(e)]	NR	NR	NR	NR

(a) Value converted from ash weight based on 40% mean ash.
(b) Determined during second half of gestation.
(c) Bone tumors developed in some swine.
(d) None of the second generation survived to adulthood.
(e) Not reported; exposed F_0 dams died before littering.

To compare the swine study to the modeled results for the raccoon, you have to compare the ingestion rates of strontium-90 under the mean exposure scenario and the expected dose rates to bone. These exposure levels exceed expected exposure levels from raccoons feeding and drinking at 100-NR-2 by several orders of magnitude. Under the worst-case exposure, the estimated daily ingestion of strontium-90 is 1.1 nCi/d, essentially three orders of magnitude lower than the lowest exposure level in the swine study of 1 μCi/d. The mean exposure scenario would result in the daily ingestion of 1.3 pCi/d of strontium-90, a full six orders of magnitude lower that the lowest treatment level of 1 μCi/d in the swine study and seven orders of magnitude lower than the highest no observed effect dose of 25 μCi/d.

From a dose perspective, we can conservatively assume that the dose to the raccoon is entirely dose to bone. The mean scenario dose rate from the RESRAD-BIOTA analysis was 16.3 µrad/d. The dose rate to bone in the dam in the swine study at the highest treatment level where there was no birth effect observed in either the F_1 or F_2 generations was 11 rad/d (Clarke et al. 1970). During the swine study, researchers placed thermoluminescent dosimeters in the developing fetuses (55 to 110 days of development) and did not measure any apparent dose from the strontium-90/yttrium-90 deposited in the maternal skeleton.

While no reproductive effects were noted in the lower exposures, there were numerous and significant radiation effects. None of the second-generation swine exposed to 626 μCi/d survived. Blood disorders were observed in F_0, F_1, and F_2 dams at rates in clear excess of the control treatment. At the time the report was published, there had been observations of bone cancer in the two treatment levels of 125 and 625 μCi/d.

The point to be made here is that even under "worst-case" scenarios that are highly unrealistic and the more realistic mean exposure scenarios for the raccoon, the potential at 100-NR-2 to have an exposure to strontium-90 that results in a measureable adverse affect is very remote and that under current exposure conditions, actual dose rates are likely to fall within the range of background dose rates.

5.3 Great Blue Heron

Dose rates to the great blue heron were similar to those estimated for the raccoon. Blood cells develop in the Bursa of Fabricius, an organ located in the posterior of the body cavity. As a soft tissue organ, the risk for blood disorders is lower than expected for mammals where blood cells develop in the bone marrow. Otherwise, the dose rates and potential for adverse effects are likely similar, with the main difference being that strontium-90 can accumulate in eggshells; as the embryo develops it may be exposed to beta radiation when its body is close to the eggshell during development and uptake due to the translocation of calcium from the eggshell into the bloodstream of the developing embryo.

5.4 Sculpin

The sculpin was selected as the most likely vertebrate aquatic receptor and was the focus of this study. Pacific salmon, however, have been the focus of earlier studies and are a more economically, politically, and culturally sensitive species and a main concern to Native American stakeholders and the public. Fall Chinook salmon and steelhead do not spawn in or even near the 100-N shoreline area (Dauble and Watson 1997). Adults that return to the Hanford Reach each fall may hold in deeper waters off of the 100-NR-2 shoreline, but have not been observed along the shallow shoreline waters. Passage of out-migrant salmonids at 100-NR-2 and potential exposure to strontium-90 releases was evaluated by Poston (2010) and found to be inconsequential because of the brief amount of time the migrating fish would actually spend close to the shoreline where they would be exposed. Fall Chinook salmon that spawn in the Hanford Reach migrate to the Columbia River during the spring freshet within 30 to 60 days of hatching. The increased flow rate and discharge volume effectively reduce exposure of these juvenile fall Chinook and the propensity of extended exposure to strontium-90 releases at the 100-NR-2 shoreline is very small. Upriver Columbia River spring Chinook salmon and upriver steelhead are regulated threatened and endangered species. After spawning and hatching, the juvenile upriver salmonids remain in their natal streams for at least a year before migrating. As observed with the fall Chinook salmon, once they start their seaward migration, the amount of time they could likely spend along the 100-NR-2 shoreline is very short and would involve, if it occurs at all, short feeding forays along the shoreline. When migrating, these larger year-old fish keep to the main channel where the currents are greatest.

Embryonic exposure of developing salmon eggs is another potential exposure route for groundwater discharges of strontium-90 and it was evaluated in 2003 (Poston et al. 2003). Fall Chinook salmon spawning has been monitored in the Hanford Reach since 1948 and fall Chinook salmon do not spawn along the 100-NR-2 shoreline. From a physiological perspective, developing fish embryos do not form calcified bone tissue until after hatching (Figure 5.2). Their need for calcium is small and, consequently, the potential to accumulate strontium-90 is also reduced.

Figure 5.2. Calcification of the Skeleton of a Rainbow Trout, Day 0 (swim-up stage) to Day 87 Post Swim Up. Fish are stained with alcian blue for cartilage and alizarin red for calcified bone (Fontagné et al. 2009).

While salmon are not viable receptors at 100-NR-2, prickly sculpin do inhabit the nearshore area and it is possible that the riprap barrier installed at 100-NR-2 could harbor breeding sites. While there is little information about sculpin life history in the Hanford Reach, prickly sculpin have been studied in other areas on the Pacific Coast. Sampling at 100-NR-2 in 2005 yielded only juveniles along the 100-NR-2 shoreline. Older adults are prone to be found in deeper water (>7 m), which might explain why only small fish were collected (White and Harvey 1999). Males build and defend nests and may spawn with as many as 10 females. They pick areas with rocks and cobble and egg masses are deposed and stick to the rocks (McLarney 1968; Krejsa 1967). Spawning in British Columbia occurs from March through May (Krejsa 1967). Once the eggs hatch, the planktonic larvae are flushed downstream where they eventually settle into a demersal habitat. The same factors that minimize the accumulation of strontium-90 in salmon embryos also apply to sculpin eggs. The developing embryos most likely do not have calcified bones until after hatching and yolk sac adsorption. If eggs are deposited in the 100-NR-2 shoreline area, the larval fish would be transported downstream after hatching until they settled to the bottom in more quiet waters.

5.5 Crayfish

The RESRAD BIOTA dose estimates for crayfish were similar to those calculated for sculpin. On a phylogenetic scale, invertebrates are less radiosensitive than vertebrates and in particular, warm-blooded vertebrates (DOE 2002). The presence of calcium in the carapace of crayfish could give rise to higher concentrations of strontium-90 than would be expected in non-calcified hard tissue (e.g., keratin). Consequently, a B_{iv} for bone was used to estimate the dose to crayfish. Strontium-90 levels in the carapace would equilibrate with environmental levels at the time the carapace is formed. When the crayfish molt, the burden of strontium-90 is removed and the concentration in the replaced carapace would reflect the current expose levels of strontium-90. Hence, molting physiology would mitigate exposure to some degree in crayfish.

6.0 Conclusions

This assessment evaluated the exposure of nearshore riparian and aquatic receptors to strontium-90 at 100-NR-2 and resulting dose estimates. The dose assessment included emissions from strontium-90 and its progeny, yttrium-90. To assess the potential to affect ecological receptors, whole body dose rates were estimated from maximum worst-case exposures and mean exposures based on nearshore data collected as part of the 2005 impact assessment (DOE 2009a) and other readily available surveillance data. Because strontium-90 is a bone seeker, and the highly energetic beta emission associated with the yttrium-90 emission can penetrate several centimeters into soft tissue, the potential for exposure to immunocompetent tissue in fish was assessed by Monte Carlo modeling of dose rates around the spinal cord of a hypothetical fish. Fish gonadal tissue may also be subjected to irradiation from strontium-90 deposited in the spinal column of fish.

Maximum and mean estimated whole body dose rates to a sculpin and a crayfish fell below the most conservative ecological "predicted no-effect" levels proposed by international scientists. Under mean exposure concentrations, the estimated dose rates were less than 20 µrad/d for riparian receptors and less than 6 µrad/d for aquatic receptors. For both of the aquatic receptors, strontium-90 concentrations in water contributed the most to dose rates. The primary source for the raccoon was ingested sediment and soils.

The DOE guideline values of 1.0 and 0.1 rad/d for riparian and aquatic organisms are still valid in terms of protecting biota at the population level. The ecological "predicted no-effect level" benchmark shifts the focus from sublethal effects to a "no-effect level" benchmark.

The DOE guideline values (DOE 2002) and the predicted no-effect levels represent a continuum of on which to evaluate potential effects and risk. The lower predicted no-effect levels are at this point simply proposed values, but have undergone scientific review and acceptance internationally. They have not been reviewed or established as applicable or relevant appropriate requirements for CERCLA cleanup. The predicted no-effect level dose rates greatly exceed the modeled dose rates that would be expected at the remedial action goal of 8 pCi/L.

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Appendix A

Dose to a Fish Kidney from Strontium-90 and Yttrium-90 in the Spinal Cord

Appendix A

Dose to a Fish Kidney from Strontium-90 and Yttrium-90 in the Spinal Cord

By RJ Traub

Strontium is an element that emulates calcium in that it will tend to concentrate in the bones. The isotope of interest, strontium-90 (^{90}Sr), will undergo beta decay to yttrium-90 (^{90}Y), which is also radioactive and decays by emission of a beta particle to zirconium-90 (^{90}Zr), which is stable.

Beta particles are emitted from the nucleus with a spectrum of energies. Figure A.1a shows the beta spectrum for ^{90}Sr and Figure A.1b shows the beta spectrum of ^{90}Y. For ^{90}Sr, the maximum beta energy is 0.546 MeV and the mean energy is 0.198 MeV (ICRP 107 [2008]). For ^{90}Y, the maximum beta energy is 2.28 MeV and the mean energy is 0.933 MeV (ICRP 107 [2008]). In addition to the beta emissions, ^{90}Y emits X and γ photons and Auger and Internal conversion electrons (ICRP 107 [2008]). The photon and electron emissions were not included in the calculations to be described because they are either of very low intensity, energy, or both.

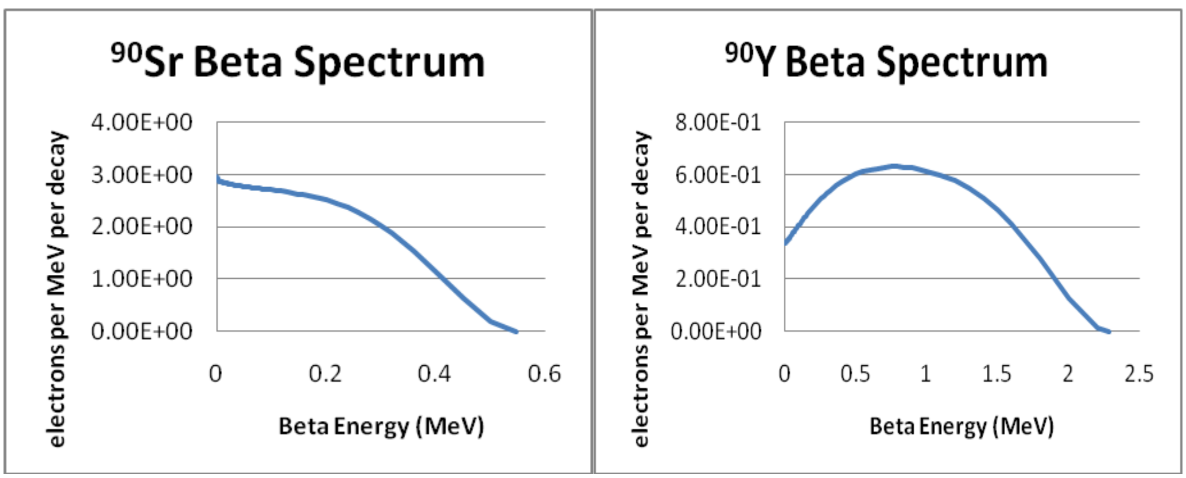

Figure A.1. Beta Spectra of ^{90}Sr and ^{90}Y

A.1 Materials and Methods

All calculations were performed with MCNP5, Version 1.51[1] (X-5 Monte Carlo Team 2008a, 2008b, 2008c). MCNP5 is a Monte Carlo radiation transport code that can be operated in a fully coupled electron-photon mode, which means that photon interactions can produce electrons that are transported by the code and electrons can produce photons that are also transported by the code. All calculations

[1] MCNP5 is available from the Radiation Shielding Information Computing Center (RSICC), www.rsicc-ornl.gov.

described in this report were performed in a mixed electron-photon mode [mode p e].[1] The Integrated Tiger Series ITS 3.0 electron energy indexing algorithm was used [dbcn 17j 1].

Dose to the organs and tissues was calculated using one of two methods. The first method, applied mainly for complete organs, used a type of tally known as the *f8 tally. This tally directly calculates the energy deposition, in MeV, in the target organ. The energy deposition in the target organ divided by the mass of the target organ yields dose to the target organ. A problem with the *f8 tally is that it is not possible to partition the target tissue to obtain a distribution of doses within the organ. Dose distributions within organs were calculated using an f4 tally, which is a track length estimator of electron flux that was modified by a dose response function that was based on the restricted mass electronic stopping power as described by Schaart et al. (2002). The two methods were compared and their results were found to agree to within 0.5%.

A.1.1 Fish Model

The fish spine, kidney, and surrounding tissue was modeled. The spine was implemented as a 4.2-cm long, 0.15-cm radius cylinder of sternum spongeosium at 1.041 g/cm^{-3}. The kidney was implemented as a 0.21-cm deep, 1.41-cm wide slab of kidney tissue at 1.05 g/cm^{-3}. The kidney extended the length of the spine but was partitioned into two regions. The 3-cm long posterior region was parallel to the spine, as shown in Figure A.2; a 0.05-cm gap separated the spinal cord from the kidney. The 1.2-cm long anterior region of the kidney diverged from the spine at an angle of 10 degrees as shown in Figure A.2; at the anterior most aspect of the kidney, the gap between the spine and the kidney was 0.25 cm. The spinal cord and kidney were immersed in a 2-cm radius cylinder of muscle. Figure A.3 shows a cross sectional view of the fish spine and posterior region of the kidney. The elemental compositions and densities of the materials were assumed to be the same as human tissue (ICRP 110 [2009]).

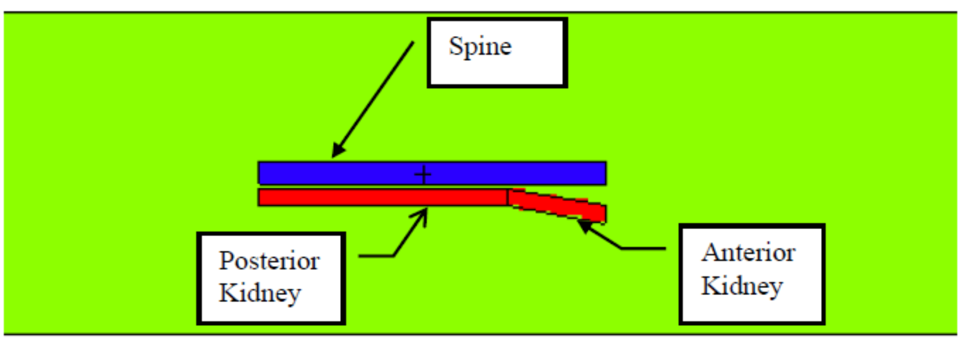

Figure A.2. A Sagittal Section of a Stylized Fish Showing the Spine that Contains ^{90}Sr and ^{90}Y (blue) and the Anterior and Posterior Regions of the Kidney

[1] At several places in this report, the alphanumerical values of some MCNP5 commands are provided in square brackets and some items specific to the code are discussed. Comprehensive explanations of MCNP5 commands and calculational methods are available in the MCNP5 user manual (X-5 Monte Carlo Team 2008b), to which the reader is referred.

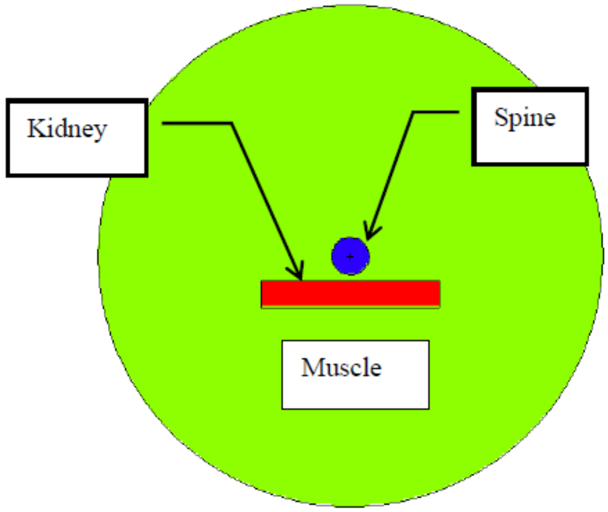

Figure A.3. Cross Section of a Stylized Fish Showing the Spine that Contains ^{90}Sr and ^{90}Y (blue) and the Anterior and Posterior Regions of the Kidney (red). The green area are the organs and muscle of the fish.

A.1.2 Radiation Emissions

Strontium-90 decays to ^{90}Y by the emission of a beta particle with a half-time of 28.79 years (ICRP 107 [2008]; Firestone et al. 1996). Figure A.1 shows the beta spectrum of ^{90}Sr and the average and maximum energies of the beta particle are listed in Table A.1. Yttrium-90 is also radioactive and decays to ^{90}Zr by the emission of a beta particle with a half-time of 64.10 h (ICRP 107 [2008]; Firestone et al. 1996). Figure A.1 shows the beta spectrum of ^{90}Y. The beta emission of ^{90}Y can take three pathways; the average and maximum energies of the predominant branch are shown in Table A.1. The other two beta branches occur with probabilities of 0.0115% and 1.4E-06% and are not listed in Table A.1. Consequent to the emission of the beta particle, ^{90}Y also emits characteristic x-rays, auger electrons, and internal conversion electrons (ICRP 107 [2008]; Firestone et al. 1996) but these radiations were neglected in the dose calculations because they have negligible energies and/or frequency of emission. The calculations accounted for the beta emission spectra of both radionuclides. The probability density functions of the beta spectra were obtained from ICRP Publication 107 (ICRP 107 [2008]).

Table A.1. Average and Maximum Energies of the Beta Particles Emitted by ^{90}Sr and ^{90}Y

Nuclide	E_{ave} (MeV)	E_{max} (MeV)
^{90}Sr	1.96E-01	0.546
^{90}Y	9.33E-01	2.28

A.2 Calculations

The dose rate calculations were normalized to an average of 1 pCi/g^{-1} of each radionuclide in the spinal cord of the reference fish. The dose rates are then reported in units of µrad/d^{-1} to the kidney.

All calculations described in this section are based on the assumption that the ^{90}Sr and ^{90}Y activity is evenly distributed through the entire spinal cord and that the ^{90}Sr and ^{90}Y are in secular equilibrium, that is, that the activity of ^{90}Sr and ^{90}Y are equal.

A.2.1 Attenuation of Beta Radiation by Tissue

The first set of calculations was intended to show how the dose rate to tissue would decrease as the distance from the spinal cord increased. For this calculation, the dose rate to annular regions of tissue surrounding the spinal cord was calculated for both radionuclides. The results of the calculations are listed in Table A.2 and are plotted in Figure A.4. In Figure A.4, the plot of the ^{90}Y data and the total data are superimposed and cannot be distinguished by visual inspection of the plot except at very small distances from the fish spine.

Table A.2. Dose Rate to Tissue that Surrounds the Spinal Cord that Contains ^{90}Sr and ^{90}Y Evenly Distributed Through the Spinal Cord

Distance from Surface of the Spine (cm)	Dose Rate to Tissue that Surrounds the Spinal Cord (µrad/d^{-1} to tissue per pCi/g^{-1} of ^{90}Sr or ^{90}Y in the spine)		
	^{90}Sr	^{90}Y	Total
0.01	1.37	4.74	6.11
0.02	8.10E-01	4.11	4.92
0.03	5.02E-01	3.63	4.14
0.04	3.15E-01	3.24	3.55
0.05	1.93E-01	2.93	3.12
0.1	4.85E-02	2.20	2.25
0.35	2.77E-04	6.97E-01	6.97E-01
0.6	1.30E-05	9.06E-02	9.06E-02
0.85	6.64E-06	5.22E-03	5.23E-03
1.1	4.71E-06	1.01E-04	1.06E-04
1.35	3.09E-06	4.51E-05	4.82E-05
1.6	2.51E-06	3.34E-05	3.59E-05
1.85	1.82E-06	2.71E-05	2.89E-05
2.1	1.67E-06	2.36E-05	2.53E-05
2.35	1.26E-06	1.82E-05	1.95E-05
2.6	1.09E-06	1.57E-05	1.68E-05
2.85	7.76E-07	1.34E-05	1.42E-05
3.1	6.85E-07	1.05E-05	1.12E-05
3.35	5.53E-07	9.39E-06	9.95E-06
3.6	6.26E-07	8.25E-06	8.88E-06
3.85	5.35E-07	8.24E-06	8.78E-06
4.1	4.49E-07	6.65E-06	7.10E-06
4.35	3.42E-07	6.34E-06	6.69E-06

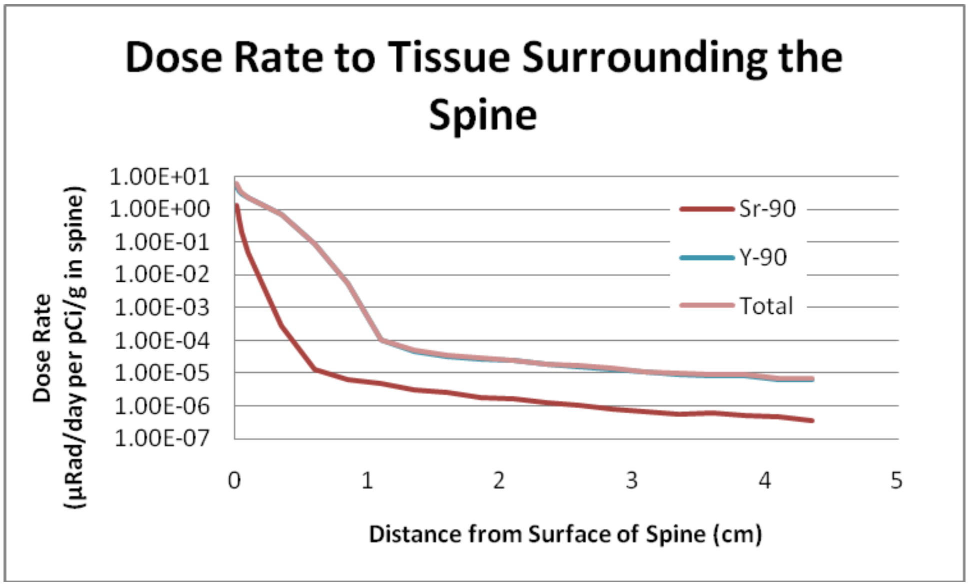

Figure A.4. Dose Rate to Fish Tissue Surrounding the Spine when the Spine Contains 1 pCi of ^{90}Sr and ^{90}Y per Gram of Spinal Cord

In Figure A.4, the dose rate curves appear to be bimodal; a rapid decrease in dose rate is followed by a fairly flat region. The nature of the flat region isn't clear because it extends beyond the continuous-slowing-down approximation range of the beta particles emitted by ^{90}Sr and ^{90}Y and may be an artifact of the algorithms used by the MCNP5 computer code. In any event, the dose rate in the flat region is very low compared to the dose rates at distances that separate the spinal cord from the kidney of the fish.

A.2.2 Dose Rate Along the Length of the Kidney

Referring to Figure A.2, the anterior and posterior regions of the kidney were partitioned into 0.3-cm-long segments and the dose rate to each segment was calculated. The results of the calculation are shown in Figure A.5 and are listed in Table A.3. As the dose region advances from the head (front) of the kidney to the tail, the dose rate increases because the distance separating the spine and kidney decreases. The dose rate levels off and remains constant until the tail end of the kidney where the dose rate decreases. The data indicate that the dose rate to the kidney remains fairly constant in the central region of the kidney where the distance separating the spine and kidney are also constant. The decrease in dose rate at the tail of the kidney is due to an "edge effect" because the ^{90}Sr and ^{90}Y activity do not extend beyond the end of the kidney and the kidney is irradiated by a smaller source than is the case in the center of the kidney where the kidney tissue is irradiated by ^{90}Sr and ^{90}Y that is both in front of and behind the irradiated region.

The average dose rates to anterior and posterior regions of the kidney were calculated using two MCNP5 tally types. The first method was to average the dose rates to the partitioned kidney using an [f4] fluence tally modified by a dose function (as described above). The second method was to use the MCNP5 [*f8] tally. The two tally types agreed and the results of the calculations are shown in Figure A.6 and listed in Table A.4. The data show that the average dose rate to the spine is 23 times greater than the average dose rate to the kidney. The data also show that the radiation dose to the kidney is almost entirely due to the ^{90}Y.

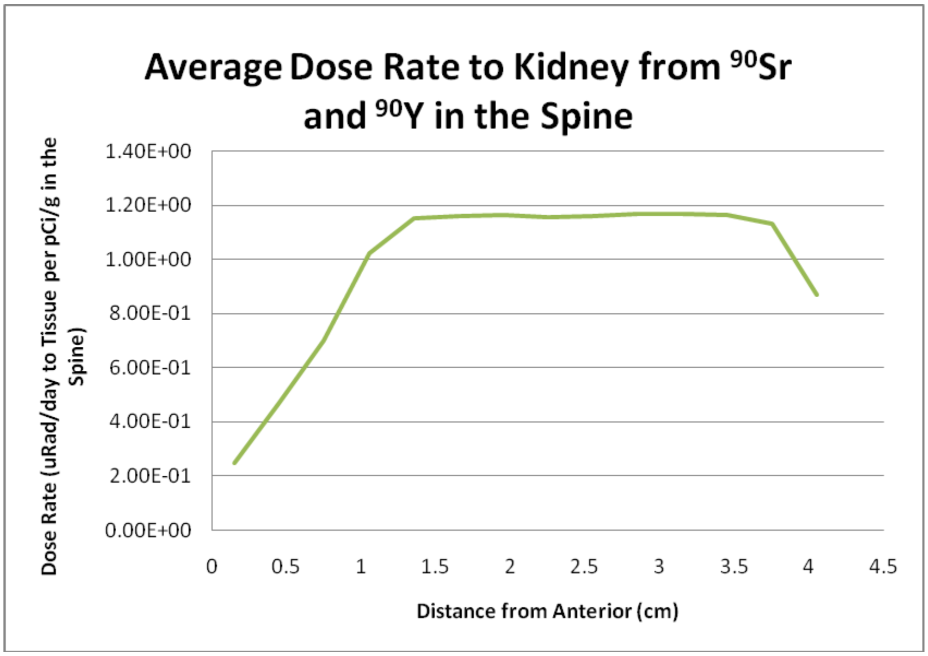

Figure A.5. Average Dose Rate to the Kidney from ^{90}Sr and ^{90}Y in the Spine. The concentration of ^{90}Sr and ^{90}Y in the spinal cord is 1 pCi/g. The relatively low dose rate in the anterior portion of the curve is due to the curvature of the anterior of the kidney. The relatively low dose rate in the posterior portion of the curve is because the spine does not extend beyond the kidney.

Table A.3. Dose Rate to the Kidney from ^{90}Sr and ^{90}Y Evenly Distributed Through the Spinal Cord

Distance from Anterior of Kidney (cm)	Average Dose Rate to the Kidney (µrad/d to tissue per pCi/g of ^{90}Sr or ^{90}Y in the spine)		
	^{90}Sr	^{90}Y	Total
0.15	2.03E-05	2.49E-01	2.49E-01
0.45	3.09E-05	4.70E-01	4.70E-01
0.75	7.41E-05	6.99E-01	7.00E-01
1.05	1.58E-03	1.02	1.02
1.35	3.29E-03	1.15	1.15
1.65	3.31E-03	1.16	1.16
1.95	3.14E-03	1.16	1.16
2.25	3.42E-03	1.15	1.16
2.55	3.39E-03	1.16	1.16
2.85	3.28E-03	1.17	1.17
3.15	3.22E-03	1.16	1.17
3.45	3.36E-03	1.16	1.16
3.75	3.23E-03	1.13	1.13
4.05	3.08E-03	8.66E-01	8.69E-01

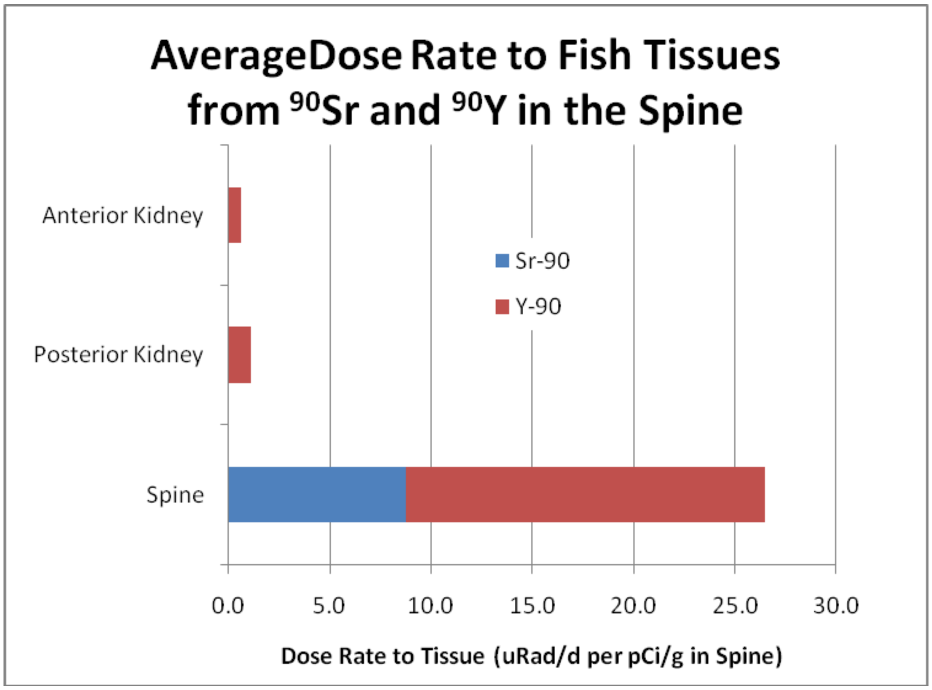

Figure A.6. The Average Dose Rate to the Anterior and Posterior Regions of the Kidney and the Spine from ^{90}Sr and ^{90}Y in the Spine at a Concentration of 1 pCi/g. The dose rate to kidney tissue is almost exclusively due to the ^{90}Y in the spine.

Table A.4. Dose Rate to the Kidney and Spine from ^{90}Sr and ^{90}Y Evenly Distributed Through the Spinal Bone

	Average Dose Rate to the Tissue (µrad/d to tissue per pCi/g of ^{90}Sr or ^{90}Y in the spine)		
Tissue	^{90}Sr	^{90}Y	Total
Anterior Kidney	4.24E-04	6.13E-01	6.14E-01
Posterior Kidney	3.28E-03	1.13	1.14
Spine	8.75	1.77E-01	2.65E-01

A.2.3 Dose Gradient Study

The steep decline in dose rate with distance from the spine, as seen in Figure A.4 and Figure A.5, implies that the dose rate to the kidney might not be uniform across the width of the kidney. Referring to Figure A.3, the rectangular cross section of the posterior kidney region was partitioned into 15 sub-regions, also called voxels; 5 regions from left to right (x-axis) and 3 regions from top to bottom (z-axis). Referring to Figure A.2, the posterior kidney was partitioned into three regions along the length of the region (y-axis). The dose rate to each of the 45-dose voxels was calculated and the results for the center y-axis region are listed in Table A.4. The table contains only three offset columns because the geometry of the fish kidney has bilateral symmetry around the origin. The data show that the maximally exposed voxel, found at the top and center region of the kidney, receives a dose rate about 32 times that of the minimally exposed voxel, which is the bottom-outermost voxel.

Comparing the data from Table A.4 to the data from Table A.5, it is seen that the dose rate to the maximally exposed posterior kidney voxel is about 3.9 times the dose rate averaged over the entire posterior kidney region. Also, the average dose rate to the posterior kidney region is 8.5 times greater than the dose rate to the minimally exposed voxel.

Table A.5. Dose Rate to Tissue that Surrounds the Spinal Cord that Contains ^{90}Sr and ^{90}Y Evenly Distributed Through the Spinal Cord (μrad/d to tissue per pCi/g of ^{90}Sr or ^{90}Y in the spine)

Vertical Offset of Voxel (cm)	Horizontal Offset Distance of Voxel		
	0.0 cm	0.282 cm	0.564 cm
	^{90}Sr		
-0.035	3.07E-03	2.87E-05	1.57E-06
-0.105	2.45E-05	3.58E-06	1.85E-06
-0.175	4.89E-06	3.07E-06	1.63E-06
	^{90}Y		
-0.035	2.78E-01	1.16E-01	1.71E-02
-0.105	1.61E-01	7.51E-02	1.27E-02
-0.175	9.55E-02	4.85E-02	8.49E-03
	Total		
-0.035	4.44	1.84	2.71E-01
-0.105	2.54	1.19	2.01E-01
-0.175	1.51	7.68E-01	1.34E-01

A.3 Conclusions

The dose rate to the kidney of a small fish from ^{90}Sr and ^{90}Y in the spinal cord of that same fish was calculated. The calculations indicate that the dose rate from ^{90}Y greatly exceeds the dose rate from ^{90}Sr because the beta particles emitted by ^{90}Y have, on average, more energy than those emitted by ^{90}Sr and are thus able to penetrate the tissue between the spine and the kidney and deposit some of their energy in the kidney.

A large gradient in dose rate occurs in the fish kidney. The gradient is seen in two different situations. In Figure A.3, it is seen that the dose rate in the kidney varies along the length of the kidney. This gradient is due to the divergence of the spine and the kidney that occurs as the dose region of interest approaches the head of the fish. In an actual fish, a similar divergence of the kidney and spine occurs at the tail end of the fish but this divergence was not modeled for these calculations. The calculations for this report indicate that the divergence effect will reduce the dose rate by a factor of about 4.7.

The second dose gradient occurs across the width of the kidney and shows that the maximal dose rate to the kidney can be 4.9 times the average dose rate to the kidney.

The dose gradient data point out that the spatial relationship of the spinal cord (as the source) and the kidney (as the target tissue) is very important for dose estimation. For the calculations described in this report, the ^{90}Y activity was assumed to be evenly distributed throughout the spine in similarity to ^{90}Sr. In humans, yttrium tends to be located on bone surfaces (ICRP 1980) rather than in the bone volume as was modeled for this report. At the same time, the ^{90}Y is formed in the volume of the bone consequent to the decay of ^{90}Sr and the ^{90}Y may not appreciably transition from the volume of the bone to the surface of the bone in the short time between its formation and subsequent decay.

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Appendix B

RESRAD-BIOTA Dose Profiles

Appendix B

RESRAD-BIOTA Dose Profiles

B.1 Source Term Concentrations

Maximum concentrations were used for the base case with the base case representing the highest documented "hypothetical" exposure concentrations (Table B.1).

Table B.1. Maximum Media Concentrations for Dose Modeling

Media	Strontium-90 Concentration	Source
Surface Water	65 pCi/L	DOE (2009)
Sediment	31.4 pCi/g	DOE (2009)
Riparian Soil	5.37 pCi/g	DOE (2009)

B.2 Aquatic Receptors

Aquatic animals were set as the crayfish and the sculpin. Juvenile sculpin are expected to inhabit the nearshore environment and larger more mature fish inhabit deeper water. Sculpin mass was set at 10 g. The crayfish had the same geometry as the sculpin, but its mass was set at 30 g as the length was set from the tip of the rostrum to the end of the tail and the carapace, claws, and other appendages add more weight. The difference in weight is the primary difference between modeled dose rates.

RESRAD-BIOTA parameters used in the worst-case calculations are summarized for crayfish and sculpin (Table B.2 and B.3, respectively).

Table B.2. RESRAD-BIOTA Modeling Parameters for Crayfish (Size Category 3)

Geometry/Parameter	Dimension/Value	Units	Comment
Geometry	10 × 2 × 2	cm	
Body Mass	0.03	kg	
B_{iv} (water)	560	pCi/g tissue per pCi/ml water	Used in calculations, also assumes ingestion of water
B_{iv} (sediment)	0	pCi/g tissue per pCi/g sediment	Not used, no sediment ingestion
Internal Dose Conversion Factor (DCF)	1.89E-02	(rad/y per pCi/g)	
External DCF	2.19E-03	(rad/y per pCi/g)	
External Exposure Geometry Factor	0.50	NA	Water
External Exposure Geometry Factor	0.50	NA	Sediment
Area Factor	1.00	NA (Fraction)	100 Utilization

Table B.3. RESRAD-BIOTA Modeling Parameters for Sculpin (Size Category 3)

Parameter	Dimension/Value	Units	Comment
Geometry	10 × 2 × 2	cm	
Body Mass	0.01	kg	
B_{iv} (water)	560	pCi/g tissue per pCi/ml water	Used in calculations, also assumes ingestion of water
B_{iv} (sediment)	0	pCi/g tissue per pCi/g sediment	Not used, no sediment ingestion
Internal Dose Conversion Factor (DCF)	1.89E-02	(rad/y per pCi/g)	
External DCF	2.19E-03	(rad/y per pCi/g)	
External Exposure Geometry Factor	0.50	NA	Water
External Exposure Geometry Factor	0.50	NA	Sediment
Area Factor	1.00	NA (fraction)	100 Utilization

B.3 Riparian Receptors

The riparian receptors were the great blue heron and the raccoon. There are three great blue heron rookeries on the Hanford Reach, but none are within 3 miles of the 100-NR-2 shoreline area. Great blue herons could feed in the nearshore environment of the 100-NR-2 shoreline, are common, and develop habitual patterns and preferred feeding areas and spots.

The raccoon was selected because of its propensity to feed in nearshore areas where clams (Corbicula) and crayfish are likely prey organisms.

RESRAD-BIOTA parameters used in the worst-case calculations are summarized for crayfish and sculpin (Table B.4 and B.5, respectively).

Table B.4. RESRAD-BIOTA Modeling Parameters for Great Blue Heron (Size Category 4, allometric)

Parameter/Equation	Dimension/Value	Units/Comment
Geometry	45 × 8.7 × 4.9	cm
Body mass	3	kg
DCF (internal)	2.08E-02	rad/y per pCi/g
DCF (external)	2.64E-04	rad/y per pCi/g
$T_{1/2}$ Biological	857.9	days
B_{iv} (water)	6.20E+03	Not used in allometric calculations
B_{iv} (sediment)	2.48	Not used in allometric calculations
Calculation of Biological Half-Life for Strontium-90, Model Parameters[(a)]		
f1	a	b
0.3	107	0.26

Table B.4. (contd)

Parameter/Equation	Dimension/Value	Units/Comment	
Radiological decay constant (L_rad (d-1))			6.53E-05
External exposure geometry factor	0.5	0.5	0
Ingestion >	X	X	--
Inhalation/ingestion correction factor (PT_IT)[b]	200		
Food intake (r = a/(dc) * 70 M)[b]	145	g/d	
M – Body mass, kg	3	User input	
a – Ratio of active to basal metabolic rate	2	Default	
c – Caloric value of food kcal/g	5	Default	
d – Fraction of energy ingested that is assimilated and oxidized	0.44	Default	
Mass loading factor	0.0001	Default	
b exponent in calc.	0.75	Default	
Sediment intake rate (sed = f * r)	14.5	g/d	f = 0.1
Water ingestion	0.266	L/d	
Inhalation (r)	1.11E-04	g/d	
Breathing (r b)	1.11	m^3/d	

(a) Where f1 is the fraction of Sr-90 transferred from the gut to the blood stream; a and b are used to estimate the biological half time in the body of a riparian animal.
(b) Factor used to account for relative contribution of similar amounts of soil by inhalation and ingestion pathways (Table 4.6, DOE 2002).

Table B.5. RESRAD-BIOTA Modeling Parameters for Raccoon (Size Category 5, allometric)

Parameter/Equation	Dimension/Value	Units/Comment	
Geometry	50 × 26 × 13	cm	
Body mass	8.8	kg	
DCF (internal)	2.08E-02	rad/y per pCi/g	
DCF (external)	2.64E-04	rad/y per pCi/g	
$T_{1/2}$ Biological	1135	days	
B_{iv} (water)	6.20E+03	Not used in allometric calculations	
B_{iv} (sediment)	2.48	Not used in allometric calculations	
Calculation of Biological Half-Life for Strontium-90, Model Parameters[a]			
f1	a	b	
0.3	107	0.26	
Radiological decay constant (L_rad (d-1))			6.53E-05
External exposure geometry factor	0.5	0.5	0
Ingestion >	X	X	X
Inhalation/ingestion correction factor (PT_IT)[b]	200		
Food intake (r = a/(dc) * 70 M)[b]	325	g/d	

Table B.5. (contd)

Parameter/Equation	Dimension/Value	Units/Comment	
M – Body mass, kg	8.8	User input	
a – Ratio of active to basal metabolic rate	2	Default	
c – Caloric value of food kcal/g	5	Default	
d – Fraction of energy ingested that is assimilated and oxidized	0.44	Default	
Mass loading factor	0.0001	Default	
b exponent in calc.	0.75	Default	
Sediment intake rate (sed = f * r)	32.5	g/d	f = 0.1
Water ingestion	0.701	L/d	
Inhalation r	2.51E-04	g/d	
Breathing (r b)	2.51	m^3/d	

(a) Where f1 is the fraction of Sr-90 transferred from the gut to the blood stream; a and b are used to estimate the biological half time in the body of a riparian animal.
(b) Factor used to account for relative contribution of similar amounts of soil by inhalation and ingestion pathways (Table 4.6, DOE 2002).

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