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HNF-SD-WM-TI-707, Rev. 5

# Exposure Scenarios and Unit Factors for the Hanford Tank Waste Performance Assessment

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Richland, WA 99352
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Abstract: Unit factors have been prepared for the postulated intrusion scenarios as well as the various scenarios utilizing well water or water taken from the Columbia River. A total of 100 radionulcides and 177 chemicals are evaluated. The unit factors relate a unit concentration in the water to the various toxicity indicators (radiological dose, lifetime cancer risk, and hazard index).

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The present revision adds 4 radionuclides and 16 chemicals. Toxicity parameters for all chemicals were updated using the most recent information. The reference for the radioactive decay data was changed from ENDF/VI-B to the NuDat listing available from the USDOE National Nuclear Data Center.

Two of the mathematical models were revised to use more current methods. The model describing the fraction of waterborne radioactive contamination that adheres to plant foliage due to overhead irrigation was revised from the simple factor of 25% to a fraction that depends on crop yield. The irrigation interception fraction for chemicals (25%) remains the same in this version. The other model change is to use the newer dermal absorption model from EPA. For many chemicals the dermal absorption dose increases.

18. **Justification of the Change** (Use ECN Continuation pages as needed)

Revision 5 is needed to use current data and model parameters.

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Note: All revisions shall have the approvals of the affected organizations as identified in block 11 "Approval Designator," on page 1 of this ECN.

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| Operations Procedure | None | | |
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|---|---|---|
| ☐ Yes ☐ No<br>If Yes, Record Information on the ECN-2 Form, attach form(s), include a description of the interim resolution on ECN Page 1, block 17, and identify permanent changes. | NOTE: ECNs are required to record and approve all FCNs issued. If the FCNs have not changed the original design media then they are just incorporated into the design media via an ECN. If the FCN did change the original design media then the ECN will include the necessary engineering changes to the original design media. | ☐ Yes ☐ No<br>If Yes, as a minimum attach the one page checklist from TFC-ENG-DESIGN-P-17. |

**27. Approvals**

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|---|---|---|---|---|
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| Resp. Manager | RJ Puigh Roy J Puigh | 11-1-07 | Professional Engineer | |
| Quality Assurance | | | Project Engineer | |
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| NS&L Engineer | | | Safety | |
| Environ. Engineer | | | Designer | |
| Engineering Checker | RM Marusich RM Marusich | 11/1/07 | Environ. Engineer | |
| Other | JG Field JG Field | 11/8/07 | Other | |
| Other | | | Other | |
| Other | | | DEPARTMENT OF ENERGY / OFFICE OF RIVER PROTECTION | |
| Other | | | Signature or a Control Number that tracks the Approval Signature | |
| Other | | | | |
| Other | | | ADDITIONAL SIGNATURES | |
| Other | | | | |
| Other | | | | |

# PROCESS HAZARDS ANALYSIS APPLICABILITY SCREENING



**Title:** Exposure scenarios and Unit Factors for the Hanford Tank Waste Performance Assessment

**Change Description:** Change to HNF document. Adds 4 radionuclides and 16 chemicals to the analysis and updates information and modeling methods

**Document Type(s) and Identification Number(s):** ECN-725192 R. 0, HNF-SD-WM-TI-707

**Project Identification No.:** NA

**Area:** ☐ East ☐ West

**Facility:** ☐ SST ☐ DST ☐ 242-A Evaporator ☐ ATS/222-S Lab ☒ Other (specify): Vadose Zone

**Based on this evaluation, the change:**

○ Is a Current Activity requiring a PrHA with full HAZOP.

○ Is a New Activity and requires a PrHA with full HAZOP.

○ Is a Major Change and requires a PrHA with

○ full HAZOP ○ delta HAZOP ○ Other Technique (see page 4)

PrHA Team Lead Initials _____.

Process Analysis Director Initials _____
(Required if Other Technique Used)

⊙ Is a Minor Change and does not require a PrHA.

Justification: Document revision does not affect any operations and meets criteria in TFC-MD-054, Rev. A. Information for RCRA Facility Investigation Report and Performance Assessments

○ Is a change that is included in the scope of a previously conducted PrHA and does not require re-evaluation

Reference:

**SIGNATURES**

| | | |
|---|---|---|
| **Responsible Engineer**<br>Print Name: J. G. Field<br>Sign: J G Field 11-9-07 | Org./MSIN: 7H000<br>Phone: 376-3753 | Date: 11-9-07 |
| **Responsible Engineering Director**<br>Print Name: M. A. Knight<br>Sign: M A Knight 11/12/07 | Org./MSIN: 7G400<br>Phone: 373-1199 | Date: 11-9-07 |

# PROCESS HAZARDS ANALYSIS APPLICABILITY SCREENING



**PrHA Screening Criteria (see TFC-ENG-STD-28 for details):**

**1. Is the change a specified Current Activity?**

a. Is the activity a current SST Retrieval Project? ○ Yes ⊙ No

b. Is the activity an in-process SST or DST ventilation installation or start-up? ○ Yes ⊙ No

c. Is the activity an in-process DST Transfer pump installation or start-up? ○ Yes ⊙ No

d. Is the activity the first DST to DST transfer after implementation of TFC-MD-054? ○ Yes ⊙ No

e. Has TFC management determined that a PrHA of this activity or change be conducted? ○ Yes ⊙ No

**2. Is the change a New Activity?**

a. Does this change add a new process, new equipment, a new project, or a new activity that involves the storage, handling, or processing of radioactive and other hazardous materials including the transfer or physical/chemical manipulation of tank farm waste? ○ Yes ⊙ No

Justification for question answered "No": revised calcs for performance assessment

b. Does this change add a new process, new equipment, or activity whose failure could prevent the safe operation of existing systems, structures, or components used in the storage, handling, or processing of radioactive and other hazardous materials? ○ Yes ⊙ No

Justification for question answered "No": revised calcs for performance assessments

c. Is the change a new SST or DST retrieval project? ○ Yes ⊙ No

Justification for question answered "No": revised calcs for performance assessments for VZP

**3. Is the change a Major Change?**

a. Is this a change in a TFC facility or operation that alters the originally planned process, equipment, equipment size/capacity, piping, process configuration, sequence of operations, duration, facility or equipment layout, or location, involving the storage, handling, or processing of radioactive or other hazardous materials? ○ Yes ⊙ No

Justification for question answered "No": not a change in TFC facility or operation

b. Is this a change in a TFC facility or operation that adds or modifies equipment such that failure of the added/changed item could prevent the safe operation of existing systems, structures, or components used in the storage, handling, or processing of radioactive and other hazardous materials? ○ Yes ⊙ No

Justification for question answered "No": not a change in TFC facility or operation

c. Is this a change in a TFC facility or operation that results in different or increased quantities of radioactive and other hazardous materials in the process/operation such as changes in tank waste or process chemicals? ○ Yes ⊙ No

Justification for question answered "No": not a change in TFC facility or operation

d. Is this a change in a TFC facility or operation involving the storage, handling, or processing of radioactive or other hazardous materials that results in different operating parameters, including volume, flow rate, pressure, temperature, ventilation, rheological properties, chemical properties, etc. that are outside the minimum and maximum ranges previously evaluated by a PrHA? ○ Yes ⊙ No

Justification for question answered "No": not a change in TFC facility or operation

e. In this a change in a TFC facility or operation that impact transfer pump type, pump performance, pump flow direction, pump location, pressure, temperature, chemistry of flush, dilution, mixing, agitation, purging, sparging, sluicing, water lancing, or

other waste impacting factors? ○ Yes ⊙ No

Justification for question answered "No": not a change in TFC facility or operation

f. Is this a change in a TFC facility or operation that adds or modifies energy source(s) that could inadvertently interact with the tank farm waste such as different or increased combustibles, flammables, compressed gases, steam sources, or reactive chemicals? ○ Yes ⊙ No

Justification for question answered "No": not a change in TFC facility or operation

g. Have multiple minor changes been made to this system such that the cumulative affect of the changes would constitute a major change? ○ Yes ⊙ No

Justification for question answered "No": not a system change

**4. Is the change a Minor Change?**

a. Is this a change that does not meet the criteria for a Current Activity, New Activity, or Major Change? ⊙ Yes ○ No

Justification for question answered "Yes": Not a change for an activity, performance assessment calculations

b. Is this activity a routine maintenance activity, including "replacement in kind" of components and equipment, which is not considered a "change" and is therefore exempt from the requirement to perform a process hazardous analysis? ○ Yes ⊙ No

Justification for question answered "Yes": not a maintenance activity

**5. Has the change been previously evaluated in a PrHA?**

a. Has the scope of this specific change been previously evaluated in a PrHA? ○ Yes ⊙ No

Justification for question answered "Yes": not needed; minor change

| PROCESS HAZARDS ANALYSIS APPLICABILITY SCREENING | Page 4 of 4 |
|---|---|

**Hazard Evaluation Technique Screening Criteria for Major Changes:**

1. **Full HAZOP** — ○ Yes ⊙ No

   The change affects multiple components/systems.

2. **Delta HAZOP (focused mainly on changes and Interfaces)** — ○ Yes ⊙ No

   The change affects a limited part of a system or process already evaluated by a full HAZOP.

   Discussion: change doesn't affect systems or processes

3. **Other Technique (Requires approval of Process Analysis Director)** — ○ Yes ⊙ No

   Technique:

   Discussion: Not a major change

| **Responsible PrHA Team Lead Reviewer** | | |
|---|---|---|
| Print Name: NA | Org./MSIN: NA | Date: NA |
| Sign: | Phone: NA | |

| **Process Analysis Director (if Other Technique is specified)** | | |
|---|---|---|
| Print Name: NA | Org./MSIN: NA | Date: NA |
| Sign: | Phone: NA | |

# EXPOSURE SCENARIOS AND UNIT FACTORS FOR HANFORD TANK WASTE PERFORMANCE ASSESSMENTS

Paul D. Rittmann PhD CHP

October 2007

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**Exposure Scenarios and Unit Factors for**
**Hanford Tank Waste Performance Assessments**
by Paul D. Rittmann PhD CHP

## 1.0 INTRODUCTION

Risk assessment calculations for tank waste involve models and parameters from many disciplines to predict the migration of hazardous materials (both radioactive and non-radioactive) from low-level waste disposal sites and the potential impacts this may have on members of the public some time after the disposal site is closed. The development of risk assessments for particular disposal options requires (1) knowledge of the waste inventory, (2) the waste characteristics that influence the release of waste from the disposal site into the air or vadose zone soil, (3) soil characteristics that influence the rate of travel away from the disposal site, and (4) potential pathways of exposure to the waste by persons living near the disposal site. The last item is the focus of this report.

This report describes exposure scenarios by which individuals living at or near the waste disposal site could accumulate a dose of the hazardous materials from the site. The word "dose" here refers to the amount of a radionuclide or hazardous chemical inhaled or ingested or absorbed through the skin. For each exposure scenario the various exposure pathways are examined to estimate what the dose of hazardous materials might be. The final step is to convert the dose to an established measure of risk to the health of the individuals. The objective is to provide scenario risk factors that relate a unit quantity in selected media (for example a groundwater concentration of 1 pCi/L) to the likely risk to an individual using that media according to the particular exposure scenario.

The unit factors are applied to the estimated contaminant concentrations in the media of concern (e.g., groundwater) to calculate the potential radiation dose, cancer induction risk, and hazard index to individuals or populations exposed to the hazardous materials as a result of various exposure scenarios. The unit factors are derived from standard formulas using data considered to be the most recent or most technically sound.

The unit factors in this document differ only slightly (in most cases) from those in Revision 4 of HNF-SD-WM-TI-707. The present revision adds 4 radionuclides and 16 chemicals that appeared in laboratory analyses of Hanford waste. Toxicity parameters for all chemicals were updated using the most recent information. The reference for the radioactive decay data was changed from ENDF/VI-B to the NuDat listing available from the USDOE National Nuclear Data Center. Two of the mathematical models were revised to use more current methods. The model describing the fraction of waterborne radioactive contamination that adheres to plant foliage due to overhead irrigation was revised from the simple factor of 25% to a fraction that depends on crop yield. The irrigation interception fraction for chemicals (25%) remains the same in this version. The other model change is to use the newer dermal absorption model from EPA. For many chemicals the dermal absorption dose increases.

Since many waste disposal site performance assessments have been prepared, both for the Hanford Site and other DOE-managed facilities, there is a body of knowledge associated with these assessments. Future PA documents must be consistent with previous PA documents to a considerable degree. However, there is always room for improvement. For example, there may be new exposure scenarios, or new exposure pathways within the old scenarios. Comparison with previous PA documents occurs frequently in this document.

In preparation for the detailed discussion of exposure scenarios in Section 2.0, it is useful to consider human health risk in a more general context. Later sections will apply this perspective to the particular exposure scenarios deemed appropriate for residual tank waste.

## 1.1 WHAT IS HUMAN HEALTH RISK?

The concept of risk has two elements: the likelihood of an undesirable event as well as the consequences of the undesirable event. Human health risk pertains to the likelihood that a given exposure or series of exposures may have damaged or will damage the health of individuals. Applied to tank remediation activities, human health risk assessment identifies significant sources of risk and is used to evaluate methods to reduce that risk.

Hazardous materials, whether radioactive or chemically toxic, generally act in two possible ways. Toxins that act in a carcinogenic manner increase the likelihood of inducing some form of cancer in the exposed individual. The greater the dose of the hazardous material a person receives, the greater the likelihood the person will develop some form of cancer. Carcinogens are generally of a stochastic nature in that exposure to a carcinogen increases the likelihood, but not the severity of the undesirable effect. It is assumed there is no threshold. Any amount of the carcinogen is effective in raising a person's likelihood of developing cancer. Hence, the exposure limits for carcinogens are based on an acceptable probability, such as 1 in a million. (For comparison, the lifetime doses people receive from naturally occurring radioactive materials lead to cancer induction probabilities of about 1 in 100.) It is recognized that certain groups within a population will show greater sensitivity to particular carcinogens. Thus safety factors are incorporated in the exposure limit.

Toxins may also act as stressors that impair the functioning of some part of the body. These toxins show a threshold below which no effect is seen. The body simply adapts to the stress and continues to function normally. Hence, the exposure limits for these toxins are based on keeping below the threshold. It is recognized that certain groups within a population will show greater sensitivity to the toxin. Thus safety factors are incorporated in the exposure limit.

## 1.2 HOW IS HUMAN HEALTH RISK CALCULATED?

The risk to human health is quantified using toxicity factors as well as exposure or dose estimates. The toxicity factors relate the dose from a given toxin to the likelihood of an undesirable consequence, or nearness to a health impairing threshold. They are expressed in terms of a risk per unit intake via inhalation or ingestion, with special cases for absorption through the skin or external exposure from ionizing radiation. Toxicity factors are derived by

qualified professions, and do include safety factors to account for sensitive subgroups within a population. Toxicity factors are developed using human exposure data where possible, and also animal studies. In a few cases the toxicity factors are based only on the chemical similarity with a substance for which there is reliable toxicity data.

The exposures used to calculate risk are limited to the specific routes of intake that the toxicity factors apply to. In other words, the focus of the exposure estimates is on how much of a contaminant the individual inhales or ingests, as well as how much can be absorbed through the skin, and how much direct exposure there is to ionizing radiation. The exposures are developed using typical human activities in a given context, such as an occupational setting, or a residential setting. Thus land use is an important consideration in human health risk assessment. The human activities are known as exposure scenarios and are further discussed in the next section.

The risk of developing cancer from exposure to some toxin in the environment is calculated using the equations below. The first equation is for radionuclides, the second is for chemicals. (ILCR = incremental lifetime cancer risk, see Appendix D for definitions)

ILCR Rad = Lifetime Exposure * Rad Slope Factor
ILCR Chem = (Lifetime Average Daily Dose) * Chem Slope Factor

The radiological risk has always been associated with a total exposure. The radiological slope factors are developed for unit amounts of radioactivity in the context of a lifetime exposure. Chemical exposures have always been associated with routine intakes rather than totals over a lifetime. Hence, the slope factors for chemicals are developed in the context of daily doses rather than lifetime totals.

The need to limit non-carcinogenic effects from chemicals lead to the development of maximum daily doses that would pose no harm to even sensitive groups in a population. These maximum doses are known as reference doses. The quantitative assessment of risk from these chemicals is simply how close the average daily dose is to the reference dose. The formula below shows the method used. The quantity of interest is called the hazard quotient (HQ).

HQ = (Lifetime Average Daily Dose) / Reference Dose

The traditional method for limiting exposure to radioactive materials is to limit the total dose a person receives over the course of one year. This dose could be received in one day, or could be spread out in small amounts through the year. Total dose is called effective dose equivalent (EDE). It is the product of the annual exposure and a dose factor for that radionuclide.

EDE = Annual Exposure * Dose Factor

The magnitude of the exposure depends on the details of the exposure scenario in which someone comes in contact with the contaminants. Exposure scenarios are selected to represent a limited range of human activities. A range is needed because people have different preferences on how they will do things. For example, residential gardens do not have a standard set of

vegetables. Each person grows what they like to eat, given that they have a garden. Scenario parameters, such as food consumption and tilling depth, are selected to represent typical cases rather than extreme situations.

## 2.0 EXPOSURE SCENARIOS OVERVIEW

The many possible exposure scenarios fall into two broad categories based on the location of the individual relative to the waste. Individuals located directly over the waste site are said to be onsite. Individuals located no closer than the facility fence line are said to be offsite. Onsite and offsite exposure scenarios are contrasted in Table 1.

Onsite exposures are the result of human activity directly over the buried waste, for example, a residence. Since current regulations would prohibit such activities, the onsite exposure scenarios are assumed to be delayed for at least 100 years following site closure. (Note that records of land ownership in European countries have survived wars and other social upheavals. Thus, it is reasonable to delay any onsite scenarios at least 500 years.) Eventually all knowledge of the disposal site location is lost, and individuals may unknowingly trespass.

**Table 1. General Features of Performance Assessment Exposure Scenarios**

| Feature | Onsite Receptor | Offsite Receptor |
|---|---|---|
| Time delay following site closure | no less than 100 years | any time after site closure |
| Receptor location | directly over the waste disposal site | no closer than 100 meters from the edge of the buried waste, or the fenceline of the facility |
| Sources of exposure | (1) gases & vapors that migrate upward from the waste<br>(2) direct radiation exposure<br>(3) well water<br>(4) exhumed waste | (1) gases & vapors carried by the wind to the offsite location<br>(2) well water |
| Exposure scenarios | (1) well driller - person actually drilling through the waste<br>(2) residential - person living near the well<br>(3) basement excavation - person lives in a dwelling with a foundation directly over the waste | (1) industrial - people working at some commercial enterprise<br>(2) recreational - people who spend time near the site doing typical recreational activities<br>(3) residential - person living near the well<br>(4) farmer - subsistence farming operation that provides a portion of the individual diet<br>(5) native American Indian |

Offsite exposures are the result of airborne emissions from the site or migration into groundwater. Any delay in the exposure depends on contaminant migration rates through soil, either upward toward the air, or downward toward the groundwater.

Both onsite and offsite individuals are exposed to any gases or vapors that may diffuse through the soil cover. The difference lies in the intensity of the experience. Onsite individuals may find the gaseous toxins entering their residence or workplace by diffusion through the floor. Offsite individuals are only exposed after the gases have been transported by wind to their location.

Both onsite and offsite individuals may be exposed to any contaminants that may be transported through the vadose zone into the groundwater. The exposure to contaminated groundwater occurs through the use of well water for drinking and other household needs. Note that the onsite individual must first construct a borehole through the waste to reach groundwater. This construction brings some of the waste to the surface, which leads to a variety of possible exposure scenarios depending on what the individual does with the borehole cuttings.

In DOE performance assessments, it is necessary to examine the groundwater contamination separate from waste intrusion. The effect the waste site has on groundwater determines the need for water infiltration barriers or waste retrieval and relocation. The effect the waste site has on potential intruders determines the need for intrusion barriers or changes to the thickness or depth of the waste to reduce the amount exhumed. Because these are separate engineering problems, they require separate risk analyses. The onsite receptor may exhume a portion of the waste as a result of a borehole to groundwater, but the effect of any contamination in the groundwater is not modeled. The borehole cuttings may be spread in a garden, a cow pasture, or contribute to workplace/residential exposures at a commercial farm. All of these are current land uses in the vicinity of the Hanford Site.

The offsite receptor will use the groundwater for drinking water. In addition, he may irrigate the garden and cow pasture of a subsistence farm. The term "subsistence farm" means the individual is providing most of their dietary intakes from their garden or family cow. A number of intermediate scenarios are possible, as listed in Table 1. The Native American scenario examines the impacts to individuals with unique diet and customs. The offsite exposure scenarios cover the full range of likely groundwater usage scenarios.

The utility of the various exposure scenarios listed in Table 1 is that they can be used to generate scenario risk factors based on unit amounts in the environment. For example, the irrigation scenario with a subsistence farm will have scenario risk factors in terms of EDE/ILCR/HQ per unit concentration in groundwater. Using scenario risk factors, the modeling of contaminant release and transport through the vadose can be carried out independently of the health risk modeling. The fate and transport model applies the scenario risk factor to convert groundwater concentration (for example) into an appropriate risk metric (HQ, EDE, or ILCR) for the defined exposure scenarios.

The unit factors developed in this report will be used in the evaluation of long-term performance of the residual waste remaining after closure of the 200 Area underground storage

tanks. For the tank waste risk assessment the exposure scenarios are constructed from the land use scenarios (HNF-EP-0828, Rev. 2), of which there are three general categories.

(1) The water infiltration rate at the disposal site is extremely low beneath a barrier constructed over the waste. Therefore, migration of near-surface contaminants to groundwater is negligible until the barrier degrades. The only contaminants leaving the waste site are gases and vapors, which diffuse upward through the soil to the ground surface. Potential exposure scenarios involve individuals living a short distance downwind from the waste, or directly above the waste, where the contaminant emission rate is greatest. These are the "air pathway" scenarios. In addition, the onsite individual may exhume a portion of the waste. These are the "intruder" scenarios.

(2) The water infiltration rate at the disposal site remains similar to the present natural infiltration rate. This may be the case after the infiltration barrier has degraded. Large-scale irrigation for commercial farming is excluded, but even with natural infiltration groundwater contamination eventually occurs. Potential exposure scenarios involve people living near the waste disposal facility and using the groundwater. These are the "groundwater" scenarios.

(3) The water infiltration rate at the disposal site is much larger than the present natural infiltration rate due to widespread irrigation of the central plateau of the Hanford Site. This changes the rate of migration of contaminants into the unconfined aquifer beneath the disposal site. Groundwater scenarios are used here also.

An additional constraint is the need to use representative, or typical situations in each part of the exposure scenario. If bounding, or worst-case situations are assumed, then the overall likelihood of that scenario becomes remote.

## 2.1 NO WATER INFILTRATION EXPOSURE SCENARIOS

For this land use category, the water infiltration rate is assumed to be extremely low due to the construction of a water infiltration barrier over the entire waste site. Thus, none of the waste materials in the disposal facility reach the groundwater. Any gases and vapors released from the waste will diffuse from the waste through the soil. These gaseous contaminants enter the air above the disposal site and may be carried by the wind to receptors located near the site. In addition, there may be inadvertent intrusion into the disposal site.

Table 2 summarizes the various exposure scenarios analyzed for the no water infiltration case. Note that dermal absorption refers to materials on the skin being absorbed into the body by passage through the skin. Note also that the first scenario (Offsite Farmer) applies any time after site closure, while the remaining scenarios in Table 2 require a minimum of 100 years delay (for loss of access control) before they can occur. The presence of passive barriers to intrusion, such as durable markers or thick asphalt over the waste should increase the time delay before intrusion.

The first exposure scenario requires modeling the average dilution and dispersion of gases released from the surface as they travel downwind to someone living nearby. An illustration of a simple diffusion calculation is given in Appendix E. Since the airborne emission from the disposal site is in the form of gases and vapors, there will be no appreciable deposition on the ground surface. However, plants and animals do absorb gases like water vapor and carbon dioxide directly from the air, leading to an ingestion dose to individuals consuming such produce. The emission rate from the ground surface may vary with time as the waste ages and radioactivity decays. The bounding doses for this scenario are achieved shortly after site closure. The offsite exposure scenario used for gaseous emissions is a farmer located nearby. The farmer is represented using the models contained in CAP88-PC for airborne emissions to maximize doses and show compliance with 10 CFR 61 regulations.

**Table 2. Exposure Scenarios for the No Water Infiltration Case**

| |
|---|
| Offsite Farmer -- gas/vapor emanations from the disposal site are carried downwind to a subsistence farm. Exposure pathways include:<br>• inhalation of plume,<br>• ingestion (plants & animals),<br>• external radiation exposure from plume,<br>• dermal absorption from air. |
| Onsite Resident -- gas/vapor emanations into the basement of a residence located over the disposal site. Exposure pathways include:<br>• inhalation (higher concentrations in a dwelling),<br>• external radiation exposure (from buried waste and air),<br>• dermal absorption (from air). |
| Intruder -- individual present while a borehole is being drilled through the waste disposal site. Exposure pathways include:<br>• inhalation (resuspended dust & gaseous emissions),<br>• ingestion (trace amounts of soil),<br>• external radiation exposure,<br>• dermal absorption (contact with soil). |
| Post-intrusion Resident -- spreads the exhumed waste into an area that is subsequently used in some manner. Exposure pathways include:<br>• inhalation (resuspended dust & gaseous emissions),<br>• ingestion (trace amounts of soil & garden produce or cow's milk),<br>• external radiation exposure (working in garden),<br>• dermal absorption (contact with soil). |
| Notes:<br>• "Dermal absorption" refers to materials on the skin being absorbed into the body by passage through the skin.<br>• The first scenario applies any time after site closure, while the other three require a delay of at least 100 years before they can occur. |

A second exposure scenario involves a residence located above the disposal site with a somewhat porous basement floor. Gas concentrations in the dwelling would depend on the emission rate from the soil and the assumed ventilation rate in the dwelling. For an individual to be living above the disposal site, all knowledge of the site must have been lost. The dose

calculation cannot begin until 100 years have elapsed from site closure. The waste will be covered with at least 15 ft of soil. Including the coarser components (rocks) ensures that wind erosion will not lessen this thickness during the first 1000 years. The assumed depth of excavation is less than 10 ft. Thus, at least 5 ft of soil still separates the waste and the dwelling. The potential exposures to the basement dweller are very small compared to the other exposure scenarios.

The third and fourth exposure scenarios listed on Table 2 assume the waste is unintentionally disturbed by human activity such as drilling a borehole through it to obtain groundwater. It is assumed that such intrusion is prevented for the first 100 years following site closure. After this period, it is assumed that knowledge of the disposal site becomes unavailable or is ignored. In addition, any markers or warnings are ignored. Compliance with performance objectives for the intruder is evaluated using typical present-day exposure scenarios during and after the inadvertent intrusion.

To bring some of the buried waste to the surface, the onsite individual carries out some type of excavation. Two common excavations are foundations for buildings and boreholes to groundwater. The typical building foundation penetrates less than 10 feet, so no waste is encountered. However, a water well could penetrate the waste. The exhumed waste materials are not recognized as hazardous because it is assumed that the appearance of the exhumed waste differs little from the native soil. Eventually the borehole cuttings become part of a garden or are spread in a cow pasture.

The drilling of water wells is a fairly common occurrence. However, the likelihood of a driller actually encountering the buried waste is low, since there are many places to drill, but few are over the buried waste. In addition, the presence of a thick soil barrier over the waste raises the surface, making the higher elevation less attractive as a site for a well.

After the drillers leave, the exhumed material is assumed to be spread around to level the area. The contaminated area is then included in a garden, or in a pasture for grazing milk cows, or in a field for production of hay for the cows or some commercial agricultural product. It will be assumed that the exhumed waste appears no different than soil. A number of parameters affect the eventual dose received by the individual who lives and works in the contaminated area. These include the borehole diameter, the depth of contamination in the soil, the area over which the contamination is spread, the portion of the person's diet that may be contaminated, and the amounts of soil inhaled and ingested.

Exposure scenario development begins with listing various ways the intruder can be exposed to the exhumed waste. These include inhalation of resuspended dust & gaseous emissions, ingestion of trace amounts of soil in the course of other activities, ingestion of garden produce, external radiation exposure, and absorption of contaminants that come in contact with skin.

### 2.1.1 Borehole Characteristics

In this scenario, one or more individuals are exposed to the waste because the waste site has been returned to the public and no restrictions on land use prevent such an event. The drilling of water wells is a fairly common occurrence. However, the likelihood of a driller actually encountering the buried waste is low, since there are many places to drill, but few are over the buried waste. In addition, the presence of a thick soil barrier over the waste raises the surface, making the higher elevation less attractive as a site for a well.

The well extends from the ground surface to the unconfined aquifer. Based on well log data from the State of Washington from 1960 to 2003, the diameter of the borehole could range from 1 inch up to 30 inches, as described in Appendix A, Section A7.0. The larger the diameter, the more waste will be brought to the surface at the time the borehole is constructed. The basis for this diameter is the December 2003 database of water well logs for the counties near Hanford. About 70% of the water wells driven to depths between 200 feet and 400 feet deep have a 6-inch diameter.

The actual diameter of the borehole is slightly larger than 6 inches due to the typical technique used to drill the well. The well is drilled with a bit that is slightly less than 6 inches. It is lowered down a steel casing with an inside diameter of 6 inches. The casing's lower edge is made of hardened steel so the casing can be driven from above to follow the bit. The actual borehole is about 6.5 inches in diameter. If the casing cannot be driven any deeper then the well may be drilled further without casing. To calculate the volume of soil removed from the borehole, it is assumed to have a diameter of 6.5 inches over its entire length.

Prior Hanford performance assessments assumed that the borehole diameter is 12 inches (30 cm). A borehole diameter of 6.5 inches (16.51 cm) is more typical of domestic wells drilled near the Hanford Site, and will be assumed in this report when example calculations are presented.

The irrigation of the rural pasture is a small-scale operation, but requires a larger pump than normal domestic service. Hence, an increased well diameter of 10 inches (10.5 inch borehole diameter) was selected for the rural pasture scenario.

A commercial irrigator typically uses a larger diameter well to extract water at a higher flow rate. Wells drilled for irrigation have diameters that range from 6 to 30 inches. A 16-inch diameter well (16.5-inch borehole diameter) is used as a representative diameter in this setting. It is the most likely large diameter well for irrigation purposes, as shown in Appendix A.

The total volume of borehole cuttings produced by the well drilling is the product of the borehole cross sectional area and the thickness of soil between the unconfined aquifer and the ground surface. In the 200 East Area, for example, this thickness is about 100 meters. Thus, the total volume of borehole cuttings excavated by drilling the 6.5-inch diameter borehole is 2.14 $m^3$. In addition, this volume must be adjusted for the decrease in density. Using an initial density (undisturbed) of 1.7 kg/L and a final density on the surface of 1.5 kg/L, the volume of borehole cuttings on the surface is 2.43 $m^3$, as shown below.

$$\text{Soil Volume} = (3.14159)(0.08255\ \text{m})^2(100\ \text{m})\left(\frac{1.7\ \text{kg/L}}{1.5\ \text{kg/L}}\right) = 2.43\ \text{m}^3$$

The volume of waste exhumed is the product of the borehole cross sectional area and the waste thickness at the location of the well. The disposal facility design will determine the waste thickness. By way of example, if the waste were 8 meters thick, then the total volume of waste excavated by the drilling operation would be 0.17 $m^3$. For comparison, the Grouted Waste PA (WHC-SD-WM-EE-004) used a waste volume of 0.64 $m^3$.

### 2.1.2. Spreading Area for the Borehole Cuttings

The dose rate the worker is exposed to depends on the soil concentration and the worker's proximity. Thus the dose rate varies from hour to hour according to the depth of the borehole and how the borehole cuttings are scattered. To represent this exposure to the well driller, an average concentration is used for the full exposure period of 40 hours. In the present document, the average is calculated using the volume of the borehole cuttings. The average soil concentration for the well driller is the total activity exhumed divided by the total volume of borehole cuttings at the surface.

In previous performance assessments (PA) the average soil concentration was calculated assuming the contaminated soil was spread over an area and mixed to a depth of 15 cm. In the Grouted Waste PA (WHC-SD-WM-EE-004) and the 2001 ILAW PA (DOE/ORP-2000-24) the area used was 100 $m^2$. Thus the exhumed waste was diluted to a total volume of (100 $m^2$)(0.15 m)=15 $m^3$. Because the volume of cuttings used in the present work is typically an order of magnitude smaller than 15 $m^3$, the unit dose factors in the present work are an order of magnitude greater than in older performance assessments.

The 200 West Area Burial Ground PA (WHC-EP-0645, Rev. 0) did not consider doses to the driller in detail, because the dose to the driller is less than the dose to the post-drilling resident for all nuclides.

After the drillers leave, the exhumed material is spread around to level the area. The contaminated area is then included in a garden, or in a pasture for grazing milk cows, or in a field for production of hay for the cows or some commercial agricultural product. It is assumed that the exhumed waste appears no different than soil. A number of parameters affect the eventual dose received by the individual who works in the contaminated area. These include the area considered to be contaminated, the depth of contamination in the soil, the annual intakes or exposure time. Each of these is discussed below.

The borehole cuttings are spread over an area that depends on how level the individual wants to make the landscape. In general this will not exceed 100 $m^2$ due to the limited volume of the cuttings. However, the spreading area is not relevant for developing unit dose factors. What does matter is the area of the garden or cow pasture, assuming all the cuttings are present in either the garden or the pasture. Garden produce is harvested from all parts of the garden. Some

vegetables will be more contaminated than others, depending on where in the garden they grew. By eating from all parts of the garden, the exposed individual effectively averages the soil concentration over the entire garden area. Similarly, the cow grazes from all parts of the pasture. Hence, the cow effectively averages the soil concentration over the entire pasture area.

The customary tilling to prepare the surface soil for planting is assumed to affect only the top 15 cm (6 inches) of soil. This 15 cm tilling depth has been used in prior Hanford Site performance assessments. The greatest tilling depth likely to be encountered is about 60 cm, while the shallowest depth would be no tilling at all. The deeper the soil is tilled, the more dilute the waste becomes in the surface layer. This leads to lessened doses (from all pathways) to persons using the contaminated area.

The 15 cm depth is typical for root systems of garden vegetables. Hence, the tilling depth is chosen to match the root system depth both for reasons of economy (why till to a greater depth than the plants need?) and to bound the potential doses from garden vegetables. If the tilling depth were greater than the root depth, the soil concentration is reduced unnecessarily. If the tilling depth were less than the root depth, then the plant concentrations are reduced by the fraction of roots in the contaminated layer, offsetting the effect of the increased soil concentration. The 15 cm tilling depth will be assumed in this report. Some garden plants have root systems that penetrate deeper than 15 cm. However, it will be assumed that most of the nutrients taken from the soil will come from the top 15 cm, so that corrections for root depth are not necessary.

Having chosen a tilling depth, the dose received by the exposed individual is proportional to the product of the soil concentration and the quantity of soil that is ingested, inhaled, absorbed through the skin, or incorporated into any food items. In addition, there is the external radiation dose from simply being in the contaminated area. These are summarized as the internal (inside the body) and external (outside the body) dose contributions. The proportionality with soil concentration assumes the contaminants are present in trace amounts which neither affect the physical characteristics of the soil (e.g., resuspension into the air) or biological uptake in plants. The waste in the contaminated area looks and acts like normal soil. This relationship is summarized in the equation below.

$$\text{Resident's Dose} \sim (\text{Soil Conc})(\text{Intake or Exposure Time})$$

The soil concentration is inversely proportional to the averaging area. Thus, smaller gardens or pastures have higher soil concentrations. However, the intake/exposure time is directly proportional to the averaging area. Thus, smaller gardens require less time in the garden and produce less food. The smaller exposure times mean smaller inhalation and ingestion intakes, less external exposure, and less contact with skin. Smaller pastures mean higher concentrations in the fodder, but a full diet requires the cow be given uncontaminated food grown elsewhere. In effect, changes to the averaging area result in little change in the dose. It is only necessary to find a realistic combination of averaging area and intake/exposure times. Thus, a broad range of cases has been adequately represented.

The garden size needed to supply a person's entire annual vegetable, fruit, and grain intake was estimated using two approaches. The first is commercial food production in Washington State (WA Department of Agriculture 1994). Using the statewide food production per acre figures, the estimated garden area can be computed. The computed total garden area (233 $m^2$) is mostly for production of grains (138 $m^2$).

The second approach to estimating garden size uses garden production estimates published by the Washington State University (WSU) Cooperative Extension (1980). The document provides estimates of pounds of produce per 10-foot row in a garden. In addition, it gives recommended row spacing. The spacing was treated as the row width to compute production per unit area. The WSU production estimates are higher than the commercial production averages hence the needed garden area is smaller (207 $m^2$). Again, the grains occupy most of this area (140 $m^2$).

From these references it will be assumed that an efficiently planned and maintained garden of 100 $m^2$ can supply most of one average person's vegetable needs, excluding grains. This is a typical residential garden containing various vegetables and some fruit, but no grains. The quantity of food obtained from the garden by one person is proportional to the area of the garden up to a maximum of 100 $m^2$. Beyond 100 $m^2$ there is more food than the individual is likely to eat. With more than one person in the household, the needed garden area increases proportionately. However, as discussed in Appendix A, Section A3.1.1, people with gardens typically obtain about 25% of their vegetable diet from the garden (EPA/600/P-95/002Fa, *Exposure Factors Handbook*). Thus, a family of four would likely have a garden no larger than 100 $m^2$.

The chosen garden area of 100 $m^2$ differs considerably from prior Hanford performance assessments (e.g. WHC-SD-WM-EE-004 and WHC-EP-0645), which have used a garden area of 2,500 $m^2$. The more realistic area of 100 $m^2$ leads to average soil concentrations that are about 25 times greater for the same volume of waste exhumed. One justification for the larger area assumption used in prior performance assessments is that the waste has not yet decomposed into fine particles suitable for uptake into plants or suspension in air. In the present approach a reasonable garden size will be used and the portion of the exhumed waste that is unavailable to give internal dose, i.e., the chunky fraction, will be estimated from waste characteristics.

The chosen garden area is consistent with recent performance assessments at other DOE sites. The Class L-II disposal facility at the Oak Ridge Reservation has an intruder garden area of 200 $m^2$ (ORNL-TM/13401). This garden area was judged adequate "to provide half the entire yearly intake of vegetables" (page G-50). A performance assessment for the Nevada Test Site (SAND2001-2977) uses an intruder garden area of 70 $m^2$ based on food consumption.

Historically, the 200 Area plateau has never been the site of a permanent community. People choose instead to settle near the Columbia River. Areas like the 200 Area plateau become commercial farms in which some agricultural product is raised for sale. With the rural setting in mind, two additional post-intrusion scenarios were developed, the rural pasture and commercial farm.

One alternate use for the borehole cuttings that would generate some contaminated food items is to spread them into a cow pasture. In this scenario the land surface area needed to grow food for the cow must be estimated. Based on reports found through internet searches using phrases such as "animal unit month" and "pasture size" for semi-arid locations, the area needed for the cow is estimated in Section A4.1 to be 5,000 $m^2$. About half this area is used for grazing during the irrigation season. The other half is used to raise hay and grain for the non-irrigation season. There is considerable variety in the size and species of cows that may be found in this pasture. The cow typically tramples 40% of the standing biomass, making it unavailable. In addition, the cow eats only half of the remaining biomass. The cow must graze in different parts of the pasture to allow time for the grass to grow back. The pasture/field areas were derived from the milk cow parameters presented in Table A35 to ensure overall consistency with the representative cow assumed in this report. Note that the pasture area is much larger than the spreading area for the borehole cuttings. Thus, the averaging is not based on physical mixing of the contamination into the pasture, but rather on the grazing habits of the cow.

The most likely alternate use for the borehole cuttings is based on historical land use in areas surrounding the Hanford Site, namely, a commercial farm. The borehole cuttings are assumed to be present in a field producing some crop for the market. The field area is assumed to be a typical land unit, 160 acres (647,500 $m^2$). The exposed individual spends time in various parts of the field, so his average dose is based on the average concentration in the field. The individual consumes none of the crop produced in this manner.

In summary, the no infiltration exposure scenarios assume that people live directly over the waste sites and that specific types of waste intrusion occur. Given that the unlikely event of people living directly over the waste has occurred, the dose consequences are calculated for typical land uses and typical scenario parameters, such as borehole diameter, garden area, individual intakes and exposure times. The unlikely portion of the scenario is the chances of a borehole actually penetrating a waste site. A small fraction of the available land surface lies above the buried waste. An additional concern is that the borehole cuttings are broken rocks and sand. These materials are more likely to be placed on a driveway than a garden or pasture. The combination of typical parameters with unlikely situations gives assurance that the exposure scenarios provide reasonable bounds on the potential impacts to exposed individuals.

## 2.2 LOW WATER INFILTRATION EXPOSURE SCENARIOS

In this land use category, the natural water infiltration causes contaminants in the disposal site to migrate into the groundwater. This also would be the situation after a water infiltration barrier placed over the waste disposal site begins to degrade, allowing natural precipitation to migrate through the waste. Two general categories for the exposure scenarios are human intrusion by well-drilling through the waste and groundwater use following well-drilling down gradient from the waste.

The intrusion scenarios discussed in the preceding section can be used here with the same results. However, chemicals with greater mobility in the soil will begin to reach the groundwater and thus can contribute dose to the intruder. Chemicals with low mobility may never reach the groundwater during the period of interest.

The offsite scenarios establish compliance with performance objectives at the point of highest projected dose or concentration beyond a buffer zone surrounding the disposal site (RPP-14283). Exposure scenario development begins with listing various ways the well water could be used and selecting those activities that could lead to significant radiation exposure. Table 3 lists potential dose contributors. Some of the listed pathways turn out to be insignificant. The irrigation activities by assumption are not located directly over the disposal site. Thus, water infiltration at the disposal site continues at the natural rate. Also note that dermal absorption refers to materials on the skin being absorbed into the body by passage through the skin.

**Table 3. Exposure Pathways for the Natural Water Infiltration Case**

| |
|---|
| (1) Drinking the water (also cooking with it) |
| • ingestion |
| (2) Showering, bathing, swimming and boating |
| • inhalation (sprays and vapors)<br>• ingestion (small amounts)<br>• external radiation exposure (from water & shoreline sediments)<br>• dermal absorption (contact with water and shoreline sediments) |
| (3) Irrigation (and working the soil) |
| • inhalation (sprays & resuspended dust)<br>• ingestion (produce & trace amounts of soil)<br>• external radiation exposure<br>• dermal absorption (contact with soil) |
| (4) Water used by animals |
| • ingestion (e.g., eggs, poultry, beef, milk, fish, deer, and waterfowl)<br>• external radiation exposure (proximity to domesticated animals) |
| (5) Irrigating livestock pastures |
| • inhalation (sprays & resuspended dust)<br>• ingestion (e.g., beef and milk)<br>• external radiation exposure (while in pasture) |
| (6) Sweat lodge/wet sauna |
| • inhalation (steam)<br>• dermal absorption (contact with steam)<br>• external radiation exposure (soil, walls, steam) |

The per capita water withdrawal rate from domestic wells mentioned on page 27 of Miller (1980) is 65 gallons per day, or 90,000 liters per year. This number covers the principal domestic uses, namely, washing and bathing, drinking and cooking for one person. For the

farming operation, the expected irrigation rate of 82.3 cm/year (32.4 inches/year) is applied over a minimum area of 2 hectare (5 acres), the total annual water need for the farmer is approximately $1.7 \times 10^7$ liters. This value was assumed in prior Hanford performance assessments. The ability of a well to supply water at this rate must be confirmed before dose calculations based on it are carried out.

As groundwater enters the Columbia River, it is diluted by the large flow of surface water. From 1989 to 1999 the average flow rate measured at Priest Rapids Dam is about 3,360 cubic meters per second (PNNL-6415). Hazardous materials in the groundwater would then be transported to various water intakes for use as irrigation and public drinking supplies. Due to the dilution that occurs when the groundwater enters the Columbia River, doses to an individual irrigating from the river are orders of magnitude smaller than doses to the same farmer irrigating from a well down gradient from the waste site. The addition of the fish pathway offsets this decrease somewhat. Finally, since a large number of people would be affected by contamination in the river, a total population dose will be estimated.

As in prior performance assessments (e.g., WHC-SD-WM-EE-004, WHC-EP-0645, and DOE/ORP-2000-24) a total population of 5 million people between the Hanford Site and the Pacific Ocean will be assumed to derive all of their drinking water from the Columbia River. The population estimate is a realistic upper bound and will be used in this report also.

Offsite exposure scenarios will use one or more of the pathways listed in Table 3. Some pathways may be ruled out by characteristics of the environmental setting. For example, irrigation of a garden from a well is reasonable, but irrigation of pastures may not be possible, depending on the bounding pumping rate from the well. Possible exposure scenarios have been selected to represent future uses of the land. They are listed in Table 4. The contaminated water source may be either a well or the Columbia River.

The exposure scenarios listed in Table 4 use the naming convention of DOE/RL-91-45, *Hanford Site Risk Assessment Methodology* (HSRAM), Revision 3. The customary disposal site performance assessment all-pathways scenarios are included as an alternate for the agricultural scenario. Differences in modeling assumptions are discussed in later sections.

One version of the Native American scenario was presented in the Columbia River Comprehensive Impact Assessment (CRCIA) (DOE/RL-96-16). This individual represents a bounding case whose intakes of contaminated foodstuffs and exposures to environmental contamination are maximized. Because the exposure parameters for this scenario have not been finalized, the Native American scenario will not be analyzed.

**Table 4. Exposure Scenarios for the Natural Water Infiltration Case**

| |
|---|
| Industrial Scenario - represents potential doses to workers in a commercial industrial setting. Exposure pathways include drinking water (1), showering (2), and contact with irrigated portions (3) of the property. |
| Recreational Scenario - represents potential doses to individuals visiting a recreation area. Exposure pathways include drinking water (1), showering and swimming (2), contact with irrigated portions and shoreline sediment (3), and game animals (4). |
| Residential Scenario - represents potential doses to individuals living in a community near the disposal site. Exposure pathways include drinking water (1), showering and swimming (2), irrigating a garden (3), and fishing (4). |
| Agricultural Scenario - represents potential doses to individuals who may take up residence on the Hanford Site to operate a subsistence farm. Exposure pathways include drinking water (1), showering and swimming (2), irrigating a garden (3), and fishing (4), and raising livestock (5). This scenario includes all of the pathways listed in Table 3 except the sauna. |
| Native American Scenario - represents bounding doses to special groups of individuals. Exposure pathways include hunting, fishing, gathering wild produce, and using a sweat lodge. All of the pathways listed in Table 3 can be used. |

## 2.3 HIGH WATER INFILTRATION EXPOSURE SCENARIOS

In this land use category, the water infiltration rate at the disposal site is much larger than the present natural infiltration rate due to irrigation of the land over the waste disposal site. The higher infiltration rate changes the rate at which hazardous materials are released from the disposal site in addition to the rate at which they travel through the vadose zone. The higher infiltration rate may change the aquifer flow causing increased dilution as the waste materials that enter the aquifer. Thus the resulting groundwater concentrations are generally higher than in the low infiltration case.

As with the low infiltration case, compliance with performance objectives is measured at the point of highest projected dose or concentration beyond a buffer zone surrounding the disposal site (RPP-14283). The offsite exposure scenarios discussed for the low water infiltration case also apply here. The only difference is the contaminant concentration in the groundwater pumped from the well. Since water concentrations determine the dose, it is essential to have a credible model for the release and transport of waste contaminants through the soil.

Intrusion is unlikely to occur at locations that are irrigated. Theoretically, a borehole could be driven through the waste to obtain water to irrigate nearby fields and pastures. Due to the depth of the water table and the proximity of surface water, it is likely that large scale irrigation water would be derived from surface water rather than a well. Remnants of irrigation trenches

are still present on the Hanford site from the days before the land was claimed by the Manhattan Project.

## 3.0 EXPOSURE SCENARIO DESCRIPTIONS

Table 5 summarizes the exposure pathways for the typical performance assessment scenarios. There are 9 scenarios presented in Table 5. The first four are the waste intruder cases, namely, the well driller and the post-intrusion residents. The next four are individuals exposed to a contaminated water source, either a water well or the Columbia River. The final scenario considers the collective effect on the population residing down river from Hanford.

The intruder scenarios are divided into two kinds. The first kind deals with the human exposures during the actual intrusion event and is represented in the Well Driller seenario. The second kind deals with how the exhumed contaminants may affect individuals living near the well in subsequent years. A variety of living situations are represented in the Suburban Garden, Rural Pasture, and Commercial Farm scenarios. These are referred to as the post-intrusion scenarios because they occur after the well is drilled.

For the Well Driller, the unit factors are calculated based on the average concentration of the contaminant in the borehole. The entire mass of material from the ground surface to the water table is used for the average. The exposure period is the period needed to drill the borehole, namely, 5 days. For the other post-intrusion cases, the unit factors are based on a unit quantity of activity removed from the borehole and spread on the ground in a garden, a cow pasture, or an agricultural field. Radiation doses are calculated during the first year after the well is drilled. Lifetime cancer risks and hazard quotients cannot be calculated for the Well Driller due to the short exposure period of an adult. The toxicity parameters require lifetime exposures or perhaps short-duration exposures of a population with all ages represented.

For the post-intrusion scenarios the cancer risks and hazard quotients from a lifetime exposure could be calculated for a child growing to maturity. These calculations were not carried out because the regulatory criteria for the post-intrusion scenarios are strictly the first year EDE.

In Table 5 the water pathways contribute nothing to the intruder scenario doses. This means the water obtained from the well is uncontaminated. In a real world intrusion scenario, this might not be the case. First of all, the intrusion could occur after mobile contaminants had reached the groundwater. This would lessen the amount of the mobile contaminants that are exhumed, but would add contaminated groundwater pathways. Second, the presence of a well would accelerate migration of contaminants to the groundwater. This follows from the water added to the surface and possible contaminant migration along the borehole. While contaminants would probably not be present the first year after drilling, they could show up in the groundwater in later years.

**Table 5. Exposure Pathway Summary for Standard Performance Assessment Scenarios**

| | | Standard Performance Assessment Exposure Scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Exposure Scenarios → | Waste Intruders (EDE only) | | | | All Pathways Farmer | | Native American | Columbia River Population |
| | Exposure Pathways | Driller | Suburban Garden | Rural Pasture | Commercial Farm | GW | River | | |
| Water | Ingestion | | | | | • | • | • | • |
| | Vapor Inhalation | | | | | • | • | • | • |
| | Shower, dermal | | | | | • | • | | • |
| | Swimming, dermal | | | | | | | • | • |
| | Sweat Lodge, inhalation | | | | | | | • | |
| Shore Sediment | Ingestion | | | | | | • | • | • |
| | Inhalation | | | | | | | | |
| | Dermal Contact | | | | | | • | • | • |
| | External Radiation Dose | | | | | | • | • | • |
| Soil | Ingestion | • | • | • | • | • | • | • | • |
| | Inhalation | • | • | • | • | • | • | • | • |
| | Dermal Contact | | | | | • | • | • | • |
| | External Radiation Dose | • | • | • | • | • | • | • | • |
| | Tritium Vapor Inhalation | | • | • | • | • | • | • | • |
| Food Chain | Garden Produce | | • | | | • | • | • | • |
| | Grains | | | | | | | | |
| | Beef & Milk | | | milk only | | • | • | • | • |
| | Poultry & Egg | | | | | • | • | • | • |
| | Fish | | | | | | • | • | • |
| | Wild Game | | | | | | | • | |

Notes:

- The exposure pathways for the Native American scenario are for information only. Doses and risks will not be calculated for this scenario.
- The annual effective dose equivalent (in mrem) is calculated for each exposure scenario, excluding Native American. The EDE is the only risk quantifier for the waste intruders. The other scenarios also have incremental cancer risk from a lifetime exposure for both radionuclides and chemicals, and hazard quotient for chemicals.

The intruder scenarios presented in this document follow the standard approach in DOE 435.1. The contaminants are assumed to be stationary. Groundwater contamination is assumed zero. This approach separates the impacts of intrusion and the impacts of contaminant migration into groundwater to facilitate the design of the disposal facility. If intruder doses exceed criteria, then the inventory must be limited or intrusion barriers added. If groundwater contamination exceeds criteria, then the inventory must be limited or the contaminant release and migration rates reduced.

The All Pathways Farmer exposure scenarios in Table 5 represent individuals who use contaminated water. The contaminated water may be obtained from either a well or the Columbia River. When the Columbia River is the source of contaminated water, the risk calculations include the fish pathway and exposure to shoreline sediments. Otherwise, the pathways used for the ground and surface water sources are identical. This situation occurs long in the future, when the hazardous materials have migrated into the groundwater and/or the Columbia River. The All Pathways Farmer is a representative average individual who grows much of his own food. His intakes of food and water, for example, are population averages. The risk from hazardous chemicals is included in these calculations. For the All Pathways Farmer, the averaging time is 30 years, based on population relocation frequencies.

The Native American represents a bounding individual, particularly with regard to fish consumption. The doses and risks for this individual will be excluded from this document due to uncertainty over the parameters to use to represent the various pathways.

The collective exposure to millions of individuals living near the Columbia River is evaluated in the Columbia River Population scenario. This situation occurs long in the future, when the hazardous materials have migrated with the groundwater to the Columbia River. There are no performance objectives for total population dose, but it is a general indicator of collective harm under the linear, no-threshold theory of health effects. In this theory, any amount of exposure to a hazardous material carries some detriment. Even small doses among large numbers of people can sum to a significant detriment.

Table 6 summarizes the exposure pathways for the HSRAM scenarios (DOE/RL-91-45 Rev. 3) used to assess human health risks associated with specific waste disposal options. The scenarios are consistent with early EPA guidance and the Tri-Party Agreement. Ongoing refinement of EPA risk assessment scenarios has made continued reliance on the HSRAM questionable. For the HSRAM scenarios, the annual radiation dose is not calculated. Only the lifetime average cancer risk and hazard quotient are of interest. The final two columns in Table 6 show the exposure pathways used for the State of Washington groundwater and surface water cleanup calculations (WAC 173-340 Part VII -- Cleanup Standards). Method B is a residential setting, while Method C uses an occupational setting.

The hazard quotient for chemicals and the incremental cancer risk for both chemicals and radionuclides are calculated for each scenario in Table 6, and all of the irrigation scenarios in Table 5. The lifetime radiation dose (in mrem) resulting from the first year of exposure is calculated for all of the scenarios shown in Table 5. In effect, the individual moves away after one year. Most of the dose is received during the year of exposure. For nuclides that are

retained in the body for many years (e.g., Sr-90 and Pu-239) a portion of the dose is received in following years. This is how radiation doses are calculated under the system of dose limitation developed by the International Commission on Radiological Protection (ICRP). The internal and external doses to various organs are represented as weighted sums of the organ doses known as an effective dose equivalent. Because the dose factors include external dose received during the year of exposure, it is also known as a total effective dose equivalent (TEDE). Additional information on radiation dose nomenclature is presented in Sections A3.5 and A3.6.

There is one difference between radiological and chemical exposure pathways that is not apparent from Tables 5 and 6. The radiological exposures do not include dermal pathways. This is discussed in greater length in Section A3.4. Radioactive materials generally are found as inorganic compounds which tend to have lower dermal absorption. It is argued in Section A3.4 that the dermal exposures are small compared to the ingestion dose and therefore can be neglected. The only exception in the list of radionuclides being analyzed is tritium, which is assumed to be in the form of tritiated water. Dermal absorption of tritiated water is included in all the inhalation calculations for tritium.

Each exposure scenario is presented in a subsection below. The scenario factors include removal mechanisms from the surface layer of soil, i.e., leaching, volatilization, and radioactive decay. The equations describing the calculations are unique to this report. Partly this was to ensure a consistent labeling of variables, and partly to conform to the layout of the calculations used in the spreadsheets.

To simplify the presentation, the treatment of radioactive decay chains is discussed in Appendix B. In most cases, the decay chains have no effect on the resulting unit factors. In keeping with the general strategy of simplifying formulas, the Greek prefixes that are part of the units for some parameters are not explicitly converted to other units in the formulas. Also, the time unit conversions are omitted. Note that more significant digits are presented than are reasonable. This is done to permit duplication of the numbers in this document. The final unit dose, risk, and hazard quotient factors are shown with three significant digits, which is also too many. The user of these unit factors should round their calculated doses, risks, or hazard indices to one, or possibly two significant digits.

The next sections describe the exposure scenarios selected for the Hanford tank waste risk assessments. Each description includes the basic formulas used to calculate the radiation dose, incremental cancer risk, or hazard quotient. The input data for the calculations are developed in Appendix A. Additional detail about the time dependence of the calculations for radionuclides is provided in Appendix B. Each description also includes the unit dose or risk or hazard quotient factors for each radionuclide and chemical of concern. These unit factors are simply the radiation dose, incremental cancer risk, or hazard quotient based on a unit amount in the medium of interest. For example, the unit risk factors for groundwater are based on a unit concentration in the water. The unit factors are multiplied by the amount of each contaminant and summed to give the total dose or risk or hazard index for the mixture.

**Table 6. Exposure Pathway Summary for HSRAM and MTCA Scenarios**

| | | Hanford Site Risk Assessment Methodology (HSRAM) | | | | | | | WAC 173-340 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Exposure Scenarios → | Indus-trial | Recreational | | Residential | | Agricultural | | MTCA B & C | |
| | Exposure Pathways | | GW | River | GW | River | GW | River | GW | River |
| Water | Ingestion | • | • | • | • | • | • | • | • | • |
| | Vapor Inhalation | • | • | • | • | • | • | • | | |
| | Shower, dermal | • | • | • | • | • | • | • | | |
| | Swimming, dermal | | | • | | • | | • | | |
| | Sweat Lodge, inhalation | | | | | | | | | |
| Shore Sediments | Ingestion | | | • | | • | | • | | |
| | Inhalation | | | | | | | | | |
| | Dermal Contact | | | • | | • | | • | | |
| | External Radiation Dose | | | • | | • | | • | | |
| Soil | Ingestion | • | • | • | • | • | • | • | | |
| | Inhalation | • | • | • | • | • | • | • | | |
| | Dermal Contact | • | • | • | • | • | • | • | | |
| | External Radiation Dose | • | • | • | • | • | • | • | | |
| | Tritium Vapor Inhalation | • | • | • | • | • | • | • | | |
| Food Chain | Garden Produce | | | | • | • | • | • | | |
| | Grains | | | | | | | | | |
| | Beef & Milk | | | | | | • | • | | |
| | Poultry & Egg | | | | | | | | | |
| | Fish | | | • | | • | | • | | • |
| | Wild Game | | | • | | | | • | | |

The annual effective dose equivalent (in mrem) is not calculated for the exposure scenarios shown on this table. The risk quantifiers for these scenarios are incremental cancer risk from a lifetime exposure for both radionuclides and chemicals, and hazard quotient for chemicals.

## 3.1 WELL DRILLER

In this exposure scenario the restrictions and warnings are lost or not effective and someone drills a well that passes through the buried waste to obtain groundwater. Radiation dose is the only hazard considered for this individual because it is a short-duration exposure rather than a lifetime exposure. The intrusion occurs before the radioactivity has migrated significantly from the waste site. The exposure occurs during a drilling operation that lasts 40 hours spread over 5 days. Most of the material removed from the hole is uncontaminated soil. As an example, if the waste thickness is about 10% of the distance to the water table, the well driller's actual exposure to the waste takes place over a period of about 4 hours.

During the period that the buried waste is coming out of the hole, the driller is exposed to airborne particulate and elevated dose rates. If the borehole cuttings are placed in one pile, the waste is covered with uncontaminated soil that lies below the buried waste, which reduces or eliminates the exposures. If the borehole cuttings are spread around, the exhumed waste may lie exposed on the surface for some time. Water may or may not be present to control dust at the work site. Thus, there are a variety of possible cases. A representative situation is selected.

The driller is assumed to be exposed to average concentrations in soil and air for the entire 40 hour drilling operation. In this way, the challenge of estimating actual exposure rates and times during a future drilling operation can be avoided. The average concentration in the borehole cuttings (activity per unit mass) is the activity exhumed divided by the total mass of the cuttings.

Two methods for calculating this average concentration will be discussed. The first may apply when the total inventory in all or part of the disposal site is known. The second may apply if the average waste concentration is known. In both cases, it turns out that the borehole diameter has no effect.

If the waste site, or a portion of the site, is known to have a particular number of curies distributed over a given area, then the average radionuclide concentration in the borehole cuttings is calculated as shown below. This method assumes the waste has a uniform thickness. It should not be applied to a trench with sloping walls, for example.

$$C_{CUT} = \frac{A_{WELL}\, Q_{SITE}/A_{SITE}}{A_{WELL}\left[\rho_{WASTE} L_{WASTE} + \rho_{WELL}\left(L_{WELL} - L_{WASTE}\right)\right]}$$

$$= \frac{Q_{SITE}/A_{SITE}}{\rho_{WASTE} L_{WASTE} + \rho_{WELL}\left(L_{WELL} - L_{WASTE}\right)}$$

where,

$A_{SITE}$ = horizontal area occupied by the disposal site, in $m^2$

$A_{WELL}$ = cross-sectional area of the borehole, in $m^2$. Note that $A_{WELL} < A_{SITE}$

$C_{CUT}$ = average radionuclide concentration in the borehole cuttings, in Ci/kg

$L_{WELL}$ = depth of the borehole from surface to groundwater, in m

$L_{WASTE}$ = thickness of the waste intercepted by the borehole, in m

$Q_{SITE}$ = total activity of a radionuclide in the disposal site, in Ci
$\rho_{WELL}$ = average density of the soil in the borehole, in kg/m$^3$
$\rho_{WASTE}$ = average density of the waste, in kg/m$^3$

If the waste density and soil density in the borehole are nearly the same, then the average concentration in the borehole cuttings can be written in the simpler form shown below. The soil concentration depends on the activity per unit area in the site, the well depth, and the density of the compacted soil. It does not depend on the borehole diameter.

$$C_{CUT} \cong \frac{Q_{SITE}}{A_{SITE}\,\rho_{WELL} L_{WELL}} \qquad \text{if } \rho_{WASTE} \cong \rho_{WELL}$$

As an alternative, the activity concentration in the waste may be known. In this case, the average radionuclide concentration in the borehole cuttings is calculated as shown below. The approximate form when the waste density and soil density are nearly the same is also shown. The approximate formula shows that the average concentration in the borehole cuttings is the waste concentration multiplied by the ratio of the waste thickness to the well depth. It does not depend on the borehole diameter.

$$\begin{aligned} C_{CUT} &= \frac{A_{WELL} L_{WASTE} \rho_{WASTE} C_{WASTE}}{A_{WELL}\left[\rho_{WASTE} L_{WASTE} + \rho_{WELL}\left(L_{WELL} - L_{WASTE}\right)\right]} \\ &= \frac{\rho_{WASTE} L_{WASTE} C_{WASTE}}{\rho_{WASTE} L_{WASTE} + \rho_{WELL}\left(L_{WELL} - L_{WASTE}\right)} \\ &\cong C_{WASTE} \frac{L_{WASTE}}{L_{WELL}} \qquad \text{if } \rho_{WASTE} \cong \rho_{WELL} \end{aligned}$$

where,

$A_{WELL}$ = cross-sectional area of the borehole, in m$^2$
$C_{CUT}$ = average radionuclide concentration in the borehole cuttings, in Ci/kg
$C_{WASTE}$ = concentration of a radionuclide in the disposal site, in Ci/kg
$L_{WELL}$ = depth of the borehole from surface to groundwater, in m
$L_{WASTE}$ = thickness of the waste intercepted by the borehole, in m
$\rho_{WELL}$ = average density of the soil in the borehole, in kg/m$^3$
$\rho_{WASTE}$ = average density of the waste, in kg/m$^3$

Note that the contaminant concentration in the borehole cuttings is independent of the borehole diameter. Thus, for the well driller, the borehole diameter has no effect on the estimated doses.

The total radiation dose to the individual drilling the well is the sum of external and internal doses. The external dose comes from being near the contaminated soil. The internal dose comes from inhaling and ingesting small amounts of contaminated soil. In addition, some contamination may be absorbed through the skin. Each of these pathways will be described next.

External Dose to the Driller

The driller is exposed to external radiation from the average concentration in the borehole cuttings. The borehole cuttings are assumed to be spread around enough to be represented by a layer of contaminated soil that surrounds the worker. It is assumed that this layer is about 5 cm thick. To put this in perspective, if the volume of soil taken from the borehole is about 4 $m^3$, then the borehole cuttings are spread over an area of 80 $m^2$. The external dose to the driller is calculated using external dose rate factors for a layer 5 cm thick and of very great extent in all directions. These values are shown in Appendix A, Section A3.6.1. The equation used to calculate the external dose is shown below. Note that the assumed density of the borehole cuttings (1,500 $kg/m^3$) is lower than typically found underground due to the loosening of the soil during drilling. The conversion from pCi to Ci is not explicitly shown in the equation.

$$H_{X,K} = C_{CUT,K}\, \rho_{CUT}\, L_{CUT}\, D_{X,5,K}\, T$$

where,

$C_{CUT,K}$ = average concentration of the $K^{th}$ radionuclide in the borehole cuttings, in Ci/kg

$L_{CUT}$ = average thickness of the borehole cuttings, 0.05 m

$D_{X,5,K}$ = external dose rate factor for the $K^{th}$ radionuclide to a person standing on a layer 0.05 m thick and of great extent in all directions, in mrem/h per $Ci/m^2$. Values from EPA Federal Guidance Report Number 12 for a 5 cm thickness are listed in Table A28.

$H_{X,K}$ = external dose to the driller from the $K^{th}$ radionuclide, mrem

T = time of exposure from Table A18, 40 h

$\rho_{CUT}$ = average density of the borehole cuttings, 1,500 $kg/m^3$

Inhalation Dose to the Driller

The driller is exposed to airborne particulate during the 40-hour drilling period as described in Appendix AA, Section A3.2. The average air concentration of respirable particulate is 0.1 $mg/m^3$ based on moderately dusty conditions. The concentration of radionuclides in the suspended particulate is assumed to be the same as the average concentration of radionuclides in the borehole cuttings. The driller breathes at the outdoor activity rate of 1.21 $m^3/h$ (ICRP 66, 1994) and thus inhales 4.84 mg soil.

$$H_{B,K} = C_{CUT,K}\, M_B\, D_{B,K}$$

where,

$C_{CUT,K}$ = average concentration of the $K^{th}$ radionuclide in the borehole cuttings, in Ci/kg

$D_{B,K}$ = inhalation dose factor from Table A25, in mrem/pCi inhaled

$H_{B,K}$ = inhalation dose to the driller from the $K^{th}$ radionuclide, mrem

$M_B$ = total mass of borehole cuttings inhaled during the well-drilling from Table A10, namely, $4.84 \times 10^{-6}$ kg

Ingestion Dose to the Driller

The driller ingests small amounts of soil in the course of his work, as described in Appendix A, Section A3.1.3. The soil ingestion occurs as a result of occasional hand-to-face contact, licking the lips, and similar motions. The typical adult soil ingestion rate is 100 mg/d, as recommended in the EPA Exposure Factors Handbook (EPA/600/P-95/002Fa). Thus the driller ingests 500 mg in the course of drilling the well.

$$H_{G,K} = C_{CUT,K}\, M_G\, D_{G,K}$$

where,

$C_{CUT,K}$ = average concentration of the $K^{th}$ radionuclide in the borehole cuttings, in Ci/kg

$D_{G,K}$ = ingestion dose factor from Table A24, in mrem/pCi ingested

$H_{G,K}$ = ingestion dose to the driller from the $K^{th}$ radionuclide, mrem

$M_G$ = total mass of borehole cuttings ingested during the well-drilling from Table A8, namely, 0.0005 kg

Dermal Absorption Dose to the Driller

The absorption of material on the skin into the body is shown to be a minor contributor for radionuclides in Section A3.4.1. In this section, the dose from radionuclides absorbed through the skin is compared with the soil ingestion dose. Because the radionuclides of interest are likely to be present as inorganic compounds, the dermal absorption is small compared to the other pathways. Thus, the dose from dermal absorption is not calculated for radionuclides.

Total Dose to the Driller

Scenario dose factors for the driller are presented in Table 7 as the dose per unit concentration in the borehole cuttings. To calculate the actual dose, these unit dose factors must be multiplied by the average concentration in the borehole cuttings. As discussed above, this average concentration is calculated as the activity exhumed divided by the total mass of the cuttings. Other formulas are possible, as shown in the discussion above.

In the event that the chemical form of the waste at the time of intrusion allows only a fraction of the exhumed material to be inhaled or ingested, the internal doses must be reduced. An example of this is vitrified waste material. After site closure, the radionuclides are decaying and the waste is slowly releasing trapped activity. Thus, the activity concentration in the cuttings and the fraction available depend on the elapsed time since closure. The external dose will be delivered regardless of the waste form. The total dose to the driller can be written as shown below.

$$H_{DRILLER} = \sum_K \left[H_{X,K} + F_{AVAIL}\left(H_{B,K} + H_{G,K}\right)\right]$$

where,

$F_{AVAIL}$ = fraction of the waste that is available for ingestion and inhalation at the time of intrusion by the well driller (Table 7 assumes $F_{AVAIL}$=1 in the "Total" columns)

$H_{DRILLER}$ = total effective dose equivalent received by the driller from all radionuclides in the waste at the time of intrusion, in mrem

$H_{B,K}$ = inhalation dose to the driller from the $K^{th}$ radionuclide, in mrem

$H_{G,K}$ = ingestion dose to the driller from the $K^{th}$ radionuclide, in mrem

$H_{X,K}$ = external dose to the driller from the $K^{th}$ radionuclide, in mrem

The fraction of exhumed waste that is available for inhalation and ingestion ($F_{AVAIL}$) depends on the nature of the waste matrix at the time of drilling. Organic materials in low level waste may be fully decomposed, so that $F_{AVAIL}$=100%. Grouted waste may be exhumed as chunks that still contain much of the waste embedded in the grout matrix. The fraction of finely ground material is expected to be minimized by drilling practices, so that a reasonable estimate for $F_{AVAIL}$ is 10%. Finally, waste that is contained in a glass matrix (vitrified) should have the smallest fraction available because even fine particles will chemically contain the waste. For vitrified waste, a reasonable estimate for $F_{AVAIL}$ is 1%.

The scenario dose factors for the driller are calculated assuming the average concentration in the borehole cuttings is 1 Ci/kg. Values listed in Table 7 are separated into the external component and the internal component. The column labeled "Total" is the sum of the internal and external in the event that 100% of the exhumed waste is available for inhalation and ingestion.

**Table 7. Unit Dose Factors for the Well Drilling Intruder (mrem per Ci/kg)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| H-3 | 3.25E+01 | 0.00E+00 | 3.25E+01 | Eu-155 | 6.78E+05 | 6.77E+05 | 9.65E+02 |
| Be-10 | 7.84E+03 | 3.79E+03 | 4.05E+03 | Gd-152 | 1.26E+06 | 0.00E+00 | 1.26E+06 |
| C-14 | 1.11E+03 | 5.76E+01 | 1.05E+03 | Tb-157 | 1.32E+04 | 1.30E+04 | 1.07E+02 |
| Na-22 | 3.37E+07 | 3.37E+07 | 5.77E+03 | Ho-166m | 2.69E+07 | 2.69E+07 | 7.78E+03 |
| Al-26 | 4.04E+07 | 4.04E+07 | 7.64E+03 | Re-187 | 5.02E+00 | 0.00E+00 | 5.02E+00 |
| Si-32+D | 4.70E+04 | 3.66E+04 | 1.05E+04 | Tl-204 | 1.71E+04 | 1.54E+04 | 1.69E+03 |
| Cl-36 | 9.17E+03 | 7.56E+03 | 1.62E+03 | Pb-205 | 8.67E+02 | 3.22E+01 | 8.35E+02 |
| K-40 | 2.38E+06 | 2.37E+06 | 9.35E+03 | Pb-210+D | 2.77E+06 | 2.28E+04 | 2.75E+06 |
| Ca-41 | 6.43E+02 | 0.00E+00 | 6.43E+02 | Bi-207 | 2.34E+07 | 2.34E+07 | 2.83E+03 |
| Ti-44+D | 3.44E+07 | 3.44E+07 | 1.45E+04 | Po-209 | 1.29E+06 | 5.17E+04 | 1.24E+06 |
| V-49 | 3.24E+01 | 0.00E+00 | 3.24E+01 | Po-210 | 9.93E+05 | 1.31E+02 | 9.92E+05 |
| Mn-53 | 5.64E+01 | 0.00E+00 | 5.64E+01 | Ra-226+D | 2.75E+07 | 2.68E+07 | 7.04E+05 |
| Mn-54 | 1.29E+07 | 1.29E+07 | 1.42E+03 | Ra-228+D | 1.55E+07 | 1.48E+07 | 7.42E+05 |
| Fe-55 | 3.10E+02 | 0.00E+00 | 3.10E+02 | Ac-227+D | 1.96E+07 | 5.89E+06 | 1.37E+07 |
| Fe-60+D | 1.39E+05 | 6.16E+04 | 7.75E+04 | Th-228+D | 2.51E+07 | 2.31E+07 | 2.07E+06 |
| Co-60 | 3.80E+07 | 3.79E+07 | 1.36E+04 | Th-229+D | 1.50E+07 | 4.56E+06 | 1.05E+07 |
| Ni-59 | 1.09E+02 | 0.00E+00 | 1.09E+02 | Th-230 | 1.54E+06 | 4.45E+03 | 1.54E+06 |
| Ni-63 | 3.00E+02 | 0.00E+00 | 3.00E+02 | Th-232 | 6.94E+06 | 2.01E+03 | 6.93E+06 |
| Se-79 | 4.46E+03 | 7.92E+01 | 4.38E+03 | Pa-231 | 1.00E+07 | 5.51E+05 | 9.45E+06 |
| Rb-87 | 3.03E+03 | 5.51E+02 | 2.48E+03 | U-232 | 7.30E+05 | 3.30E+03 | 7.27E+05 |
| Sr-90+D | 1.51E+05 | 7.34E+04 | 7.78E+04 | U-233 | 1.88E+05 | 4.52E+03 | 1.83E+05 |

**Table 7. Unit Dose Factors for the Well Drilling Intruder (mrem per Ci/kg)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| Zr-93 | 1.23E+03 | 0.00E+00 | 1.23E+03 | U-234 | 1.81E+05 | 1.55E+03 | 1.80E+05 |
| Nb-91 | 3.29E+04 | 3.27E+04 | 2.76E+02 | U-235+D | 2.56E+06 | 2.40E+06 | 1.69E+05 |
| Nb-93m | 7.51E+02 | 4.75E+02 | 2.76E+02 | U-236 | 1.71E+05 | 8.61E+02 | 1.70E+05 |
| Nb-94 | 2.44E+07 | 2.44E+07 | 3.75E+03 | U-238+D | 5.37E+05 | 3.68E+05 | 1.68E+05 |
| Mo-93 | 3.51E+03 | 2.69E+03 | 8.11E+02 | Np-237+D | 8.11E+06 | 3.28E+06 | 4.84E+06 |
| Tc-97 | 3.78E+03 | 3.69E+03 | 9.05E+01 | Pu-236 | 1.28E+06 | 9.38E+02 | 1.28E+06 |
| Tc-99 | 1.26E+03 | 4.89E+02 | 7.71E+02 | Pu-238 | 3.50E+06 | 6.48E+02 | 3.50E+06 |
| Ru-106+D | 3.37E+06 | 3.35E+06 | 1.43E+04 | Pu-239 | 3.85E+06 | 9.81E+02 | 3.85E+06 |
| Pd-107 | 1.37E+02 | 0.00E+00 | 1.37E+02 | Pu-240 | 3.85E+06 | 6.34E+02 | 3.85E+06 |
| Ag-108m+D | 2.52E+07 | 2.52E+07 | 3.93E+03 | Pu-241+D | 7.42E+04 | 6.50E+01 | 7.42E+04 |
| Cd-109+D | 1.11E+05 | 1.04E+05 | 6.79E+03 | Pu-242 | 3.67E+06 | 5.48E+02 | 3.67E+06 |
| Cd-113m | 9.02E+04 | 2.31E+03 | 8.79E+04 | Pu-244+D | 8.78E+06 | 5.17E+06 | 3.61E+06 |
| In-115 | 9.84E+04 | 1.47E+03 | 9.69E+04 | Am-241 | 4.16E+06 | 1.86E+05 | 3.97E+06 |
| Sn-121m+D | 1.07E+04 | 9.53E+03 | 1.18E+03 | Am-242m+D | 4.04E+06 | 2.20E+05 | 3.82E+06 |
| Sn-126+D | 3.09E+07 | 3.09E+07 | 1.10E+04 | Am-243+D | 6.88E+06 | 2.94E+06 | 3.94E+06 |
| Sb-125 | 6.53E+06 | 6.53E+06 | 1.46E+03 | Cm-242 | 1.42E+05 | 7.33E+02 | 1.41E+05 |
| Te-125m | 6.98E+04 | 6.80E+04 | 1.87E+03 | Cm-243 | 4.57E+06 | 1.82E+06 | 2.74E+06 |
| I-129 | 1.98E+05 | 5.90E+04 | 1.39E+05 | Cm-244 | 2.21E+06 | 5.75E+02 | 2.21E+06 |
| Cs-134 | 2.42E+07 | 2.41E+07 | 3.69E+04 | Cm-245 | 5.24E+06 | 1.17E+06 | 4.07E+06 |
| Cs-135 | 3.71E+03 | 1.58E+02 | 3.56E+03 | Cm-246 | 4.04E+06 | 5.30E+02 | 4.03E+06 |
| Cs-137+D | 8.80E+06 | 8.78E+06 | 2.51E+04 | Cm-247+D | 8.92E+06 | 5.21E+06 | 3.72E+06 |
| Ba-133 | 5.66E+06 | 5.66E+06 | 1.74E+03 | Cm-248 | 1.48E+07 | 4.01E+02 | 1.48E+07 |
| Ce-144+D | 8.54E+05 | 8.42E+05 | 1.16E+04 | Cm-250+D | 8.85E+07 | 4.21E+06 | 8.43E+07 |
| Pm-147 | 9.09E+02 | 1.95E+02 | 7.13E+02 | Bk-247 | 6.54E+06 | 1.42E+06 | 5.13E+06 |
| Sm-147 | 4.54E+05 | 0.00E+00 | 4.54E+05 | Cf-248 | 3.83E+05 | 5.69E+02 | 3.82E+05 |
| Sm-151 | 3.44E+02 | 4.49E+00 | 3.39E+02 | Cf-249 | 1.03E+07 | 5.17E+06 | 5.16E+06 |
| Eu-150 | 2.29E+07 | 2.29E+07 | 4.48E+03 | Cf-250 | 2.33E+06 | 5.41E+02 | 2.33E+06 |
| Eu-152 | 1.73E+07 | 1.73E+07 | 4.31E+03 | Cf-251 | 6.98E+06 | 1.71E+06 | 5.27E+06 |
| Eu-154 | 1.89E+07 | 1.88E+07 | 6.16E+03 | Cf-252 | 1.21E+06 | 7.37E+02 | 1.20E+06 |

Notes:

- These scenario dose factors for the intruder must be multiplied by the average radionuclide concentration in the borehole cuttings. This concentration is the activity exhumed divided by the total mass of the cuttings.
- The "Total" column is the sum of the "Internal" and "External" columns. External and internal doses are separated because the waste matrix may prevent a portion of the exhumed activity from giving an internal dose.

## 3.2 POST-INTRUSION SUBURBAN GARDEN

This scenario assumes that an individual lives near the borehole cuttings and manages to spread the cuttings in his garden. The individual obtains one-fourth of his fruit and vegetable (but not grain) supply each year from the garden. In addition, he inhales resuspended garden soil and ingests small amounts of it each day. His external dose comes from spending time in or near

the garden. The radiation dose to this individual is the 50 year committed effective dose equivalent from the first year of exposure after the well was drilled.

The descriptions below include the factors that take into account radioactive decay and leaching from the garden soil. They do not show the method used to represent decay chains. The treatment of decay chains is presented in Appendix B.

Contaminant Concentration in Garden Soil

The garden area is 100 $m^2$ based on the discussion in Section 2.1.2. A more detailed derivation of the garden area is given in Appendix A, Section A3.1.2. The depth of soil contaminated is 0.15 m, a traditional representation of the tilling depth. Thus the volume of soil in the garden is 15 $m^3$. The density of the garden soil is assumed to be 1,500 $kg/m^3$. Thus, the mass of the garden soil is 22,500 kg. The exhumed waste is distributed over this amount of soil. The concentration of radionuclides in the garden is the concentration in the waste (activity per unit mass) multiplied by the ratio of the volume of waste exhumed by the well-drilling operation divided by the volume of soil in the garden, 15 $m^3$. Equivalently, the garden soil concentration is the activity exhumed divided by the mass of soil in the garden. The soil concentration in this scenario clearly depends on the diameter of the borehole. If the total activity and the horizontal area of the disposal site are known, then the activity exhumed is just the site inventory of one nuclide times the ratio of the borehole cross-sectional area to the site horizontal area. This is summarized in the equations below.

$$Q_{EXHUMED} = A_{WELL}\, L_{WASTE}\, \rho_{WASTE}\, C_{WASTE}$$

or

$$Q_{EXHUMED} = Q_{SITE} \frac{A_{WELL}}{A_{SITE}}$$

and

$$C_{GARDEN} = \frac{Q_{EXHUMED}}{A_{GARDEN}\, L_{GARDEN}\, \rho_{GARDEN}}$$

where,

$A_{GARDEN}$ = cultivated area of a garden, 100 $m^2$
$A_{SITE}$ = horizontal area occupied by the disposal site, in $m^2$
$A_{WELL}$ = cross-sectional area of the borehole, in $m^2$
$C_{GARDEN}$ = initial concentration of a radionuclide in the garden, in Ci/kg
$C_{WASTE}$ = concentration of a radionuclide in the disposal site, in Ci/kg
$L_{GARDEN}$ = thickness of the contaminated layer of surface soil in the garden, 0.15 m
$L_{WASTE}$ = thickness of the waste intercepted by the borehole, in m
$Q_{EXHUMED}$ = activity of a radionuclide brought to the surface by the well-drilling, in Ci
$Q_{SITE}$ = total activity of a radionuclide in the disposal site, in Ci
$\rho_{GARDEN}$ = average density of the soil in the garden, 1,500 $kg/m^3$
$\rho_{WASTE}$ = average density of the waste, in $kg/m^3$

During the year, the concentration of each isotope in the garden decreases due to leaching from the surface layer and radioactive decay. The first half of the year the garden is irrigated, so both processes are in effect. The second half of the year the garden is not irrigated and the precipitation is matched by evaporation, so only radioactive decay occurs. This is represented mathematically during the first year using the formulas below.

$$C_{GRDN,K}(t) = C_{GARDEN,K}\, F_{NS,K}(t)$$

$$F_{NS,K}(t) = \mathrm{Exp}(-\lambda_K t) = \mathrm{Exp}(-\lambda_{S,K} t - \lambda_{R,K} t) \qquad \text{for } 0 \le t \le T_{irr}$$

$$F_{NS,K}(t) = \mathrm{Exp}(-\lambda_K T_{irr})\,\mathrm{Exp}[-\lambda_{R,K}(t - T_{irr})] \qquad \text{for } T_{irr} < t \le 1\,\mathrm{y}$$

$$\text{or} \quad F_{NS,K}(t) = \mathrm{Exp}(-\lambda_{S,K} T_{irr} - \lambda_{R,K} t)$$

where,

$C_{GARDEN,K}$ = initial average concentration of the $K^{th}$ radionuclide in the garden soil, in Ci/kg

$C_{GRDN,K}(t)$ = concentration of the $K^{th}$ radionuclide in garden soil as a function of time (t) during the year, in Ci/kg.

Exp = the exponential function (e raised to some power)

$F_{NS,K}(t)$ = fraction of the initial soil concentration of the $K^{th}$ radionuclide that remains in the surface layer at time "t" given that the irrigation water adds no contaminants

$T_{irr}$ = irrigation period (the $1^{st}$ half of the year), 0.5 y

$\lambda_K$ = total fractional removal rate for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

The function $F_{NS}(t)$ is graphed in Figure 1. The graph shows the time dependence of the soil concentration during the first year. No contaminants are added to the surface during the year.

The first isotope (Th-232) illustrates the case with little decay and little leaching. Th-232 has a very long half life ($1.405 \times 10^{10}$ years) and a very large retardation in the surface soil ($K_d$=600,000 ml/g). The Th-232 concentration is therefore constant during the year. The second isotope (Cl-36) has a long half life (301,000 years) but is only slightly retarded in garden soil ($K_d$=1.0 ml/g). The Cl-36 concentration decreases during the irrigation season, but is constant during the non-irrigation season. The third isotope (Po-210) has a short half life (138.38 days) but is significantly retarded in the soil ($K_d$=1,100 ml/g). It shows only the effect of radioactive decay during the year.

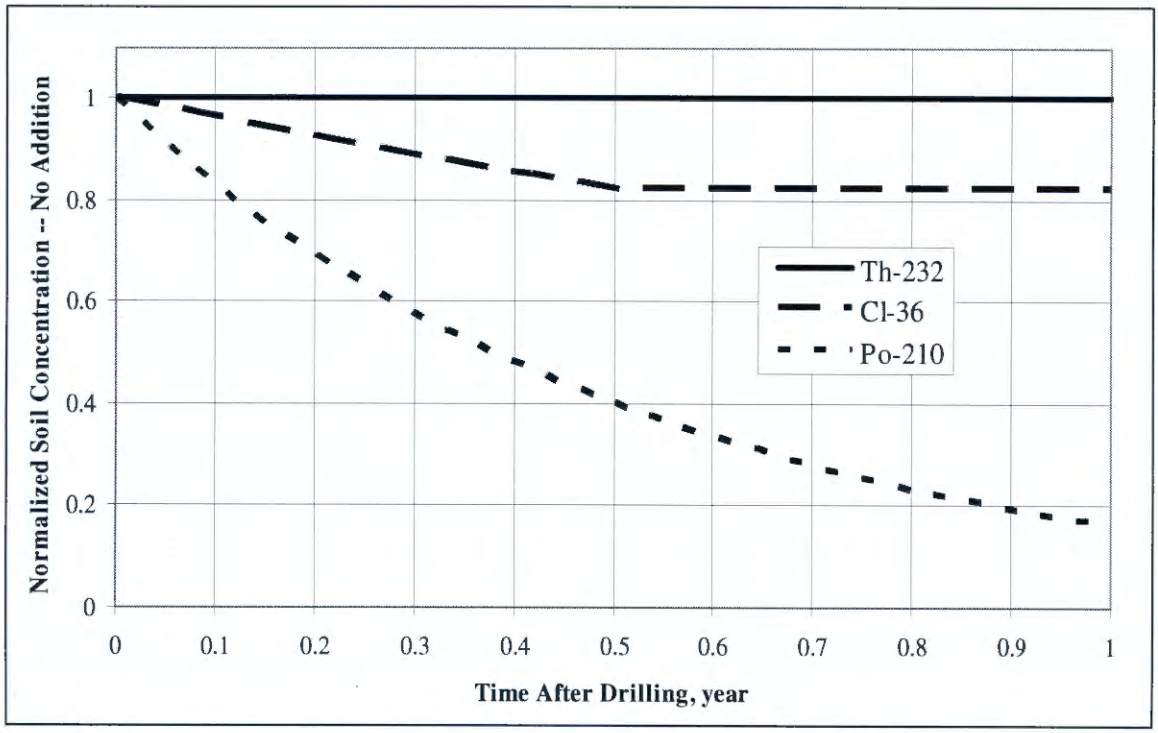


**Figure 1. Fraction of Garden Soil Concentration Remaining During the Year**

After the first year, the equation is written in terms of two factors. The first represents the previous years of decay and leaching ($T_{NY}$). The second is the function $F_{NS}$ during the remaining fraction of a year ($t-T_{NY}$). In later years the function $F_{NS}(t)$ becomes smaller and smaller due to radioactive decay and leaching from the surface layer. Thus the soil concentration and the annual dose are largest for the first year after the borehole is drilled.

$$\text{for } t > 1\,y \qquad F_{NS,K}(t) = F_{NS,K}(t - T_{PY})\,\left[F_{NS,K}(1\,y)\right]^{N_{PY}}$$

$$\text{where} \quad T_{PY} = \text{Trunc}(t) \qquad \text{and} \qquad N_{PY} = \frac{T_{PY}}{1\,y}$$

$$\text{and} \qquad F_{NS,K}(1\,y) = \text{Exp}\left[-\lambda_{S,K}T_{irr} - \lambda_{R,K}(1\,y)\right]$$

where,

$F_{NS,K}(t)$ = fraction of the initial soil concentration of the $K^{th}$ radionuclide that remains in the surface layer at time "t" given that the irrigation water adds no contaminants

$N_{PY}$ = number of years of leaching and decay prior to the year of interest, unitless.

$T_{PY}$ = period of leaching and decay prior to the year of interest, years. This is an integer number of years. Thus, the term ($t - T_{PY}$) is the fractional part of the elapsed time, t.

Trunc(t) = spreadsheet function that removes the fractional part of t to calculate the number of years prior to the current year. For example, Trunc(9.9 y) = 9 y and Trunc(30 y) = 30 y

$T_{irr}$ = irrigation period (the 1st half of the year), 0.5 y

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

The total radiation dose to the individual drilling the well is the sum of external and internal doses. The external dose comes from being near the exhumed waste in the garden. The internal dose comes from eating contaminated garden produce in addition to inhaling and ingesting small amounts of contaminated soil. Finally, some contamination may be absorbed through the skin. Each of these pathways will be described next. Note that the doses are calculated for the first year after the well is drilled. The first year has the largest doses.

External Dose to the Suburban Gardener

External exposure only occurs when the individual is in or near the garden. The limited size of the garden means the external exposure is limited to an effective exposure time of 180 hours per year. The derivation of this exposure time is presented in Section A3.3.

The external exposure period is spread evenly over the first half of the year while the garden is in use, with no exposure in the second half. The radiation dose accumulates during the exposure period. Because the external dose rate is proportional to the soil concentration, the average dose rate decreases during the exposure period. To calculate the total dose received during the year it is necessary to carry out a time integration of the daily dose during the first half of the year. Mathematically this is described using the formula shown below.

$$H_{X,K} = C_{GARDEN,K}\, \rho_{GARDEN}\, L_{GARDEN}\, D_{X,K}\, T_X\, F_{X,N,K}$$

$$F_{X,N,K} = \frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}$$

where,

$C_{GARDEN,K}$ = initial average concentration of the $K^{th}$ radionuclide in the garden soil, in Ci/kg

$L_{GARDEN}$ = thickness of the contaminated layer of surface soil in the garden, 0.15 m

$D_{X,K}$ = external dose rate factor for the $K^{th}$ radionuclide to a person standing on a layer 0.15 m thick and of great extent in all directions, in mrem/h per Ci/m$^2$. Values from EPA Federal Guidance Report Number 12 for a 15 cm thickness are listed in Table A28.

Exp = the exponential function (e raised to some power)

$F_{X,N,K}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the first half of the year (X=external calculation, N=the irrigation water adds no contaminants, and K=radionuclide index)

$H_{X,K}$ = external dose to the suburban gardener from the $K^{th}$ radionuclide during the first year after the well is drilled, mrem/y

$T_X$ = time of exposure from Table A18, 180 h/y. All of this occurs during the first half of the year.

$T_{irr}$ = irrigation period, 0.5 y (the first half of the year)

$\lambda_K$ = total fractional removal rate for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

$\rho_{GARDEN}$ = average density of the garden soil, 1,500 kg/m$^3$

Inhalation Dose to the Suburban Gardener

As the resident works in the garden, he is exposed to airborne particulate (dust) that contains some of the exhumed waste. As described in Section A3.2.1, the suburban gardener inhales 87 mg of garden soil over the course of a year. Most of the inhalation intake occurs during the first half of the year while the resident is working in the garden. A fraction of the total is inhaled during the non-irrigating half of the year as small amounts of soil are carried into the house. To simplify the calculation of the total amount inhaled, it is assumed that the resident inhales the same amount each day for the entire year.

The concentration of radionuclides in the suspended particulate is assumed to be the same as the average concentration of radionuclides in the garden. The inhalation dose to the gardener is calculated using the formula below. The decay and leaching factor ($F_{B,N,K}$) is the sum of two terms. The first is the time integral during the irrigation period. The second is the product of the factor representing soil concentration at the end of the irrigation period and the time integral during the non-irrigation period.

$$H_{B,K} = C_{GARDEN,K}\, M_B\, D_{B,K}\, F_{B,N,K}$$

$$F_{B,N,K} = \frac{1-\mathrm{Exp}(-\lambda_K T_{irr})}{(1\,y)\lambda_K} + \mathrm{Exp}(-\lambda_K T_{irr})\frac{1-\mathrm{Exp}(-\lambda_{R,K} T_{no})}{(1\,y)\lambda_{R,K}}$$

where,

$C_{GARDEN,K}$ = initial average concentration of the $K^{th}$ radionuclide in the garden soil, in Ci/kg

$D_{B,K}$ = inhalation dose factor for the $K^{th}$ radionuclide from Table A25, in mrem/pCi inhaled

$F_{B,N,K}$ = factor that results from the time integral of the inhalation dose rate for the $K^{th}$ radionuclide over the full year (B=inhalation calculation, N=the irrigation water adds no contaminants, and K=radionuclide index)

$H_{B,K}$ = inhalation dose to the suburban gardener from the $K^{th}$ radionuclide, mrem/y

$M_B$ = total mass of garden soil inhaled during the year from Table A10, $8.7 \times 10^{-5}$ kg/y

$T_{irr}$ = irrigation period (the 1$^{st}$ half of the year), 0.5 y

$T_{no}$ = no irrigation period (the 2$^{nd}$ half of the year), $T_{irr} + T_{no} = 1$ y

$\lambda_K$ = Total fractional removal rate for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

A special model for tritium emanation from the soil and subsequent inhalation is based on the water evaporation rates estimated for the Hanford Site. The tritium model is derived in Section A3.2.1. Due to the relative complexity of the model, it is not repeated here. The interested reader should go to Appendix A. Note that all of the tritium exhumed is regarded as tritiated water in this model.

Ingestion Dose to the Suburban Gardener

In addition to the small amounts of soil that are ingested during the irrigation season, the gardener also eats fruits and vegetables from his garden. The garden supplies 25% of the fruit and vegetable intake (Section A3.11). Grains are obtained from uncontaminated sources. The ingestion dose for the $K^{th}$ radionuclide due to the garden produce intakes is shown below.

Note that there are four types of garden produce that must be calculated individually and summed. These four types are leafy vegetables, other vegetables, fruit, and grains. Consumption amounts are shown in Table A5 in the column labeled "All Pathways Farmer". It is assumed that no grains are grown in a home garden. Both scenarios (All Pathways Farmer and Suburban Garden) use the same garden vegetable consumption amounts.

$$H_{G,K} = \left( C_{GARDEN,K}\, M_G\, F_{X,N,K} + \sum_p C_{V,p,K}\, M_{V,p} \right) D_{G,K}$$

where,

$C_{GARDEN,K}$ = initial average concentration of the $K^{th}$ radionuclide in the garden soil, in Ci/kg

$C_{V,p,K}$ = time-integrated radionuclide concentration in garden produce type p, in Ci/kg wet weight

$D_{G,K}$ = ingestion dose factor for the $K^{th}$ radionuclide from Table A24, in mrem/pCi ingested

$F_{X,N,K}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the first half of the year (X=external calculation, N=the irrigation water adds no contaminants, and K=radionuclide index)

$H_{G,K}$ = ingestion dose to the suburban gardener from the $K^{th}$ radionuclide, mrem/y

$M_G$ = total mass of garden soil ingested during the irrigation season from Table A8, 0.018 kg/y

$M_{V,p}$ = mass of garden produce type p eaten during the year, in kg/y. These amounts are shown in Table A5 under the heading "All Pathways Farmer".

p = index to the four types of garden produce, i.e., fruit, protected vegetables, exposed vegetables, and grains

The garden produce becomes contaminated by root uptake from the soil and by soil adhering to the foliage. The concentration of a radionuclide in a garden food item is shown in the equation below. Leafy vegetables are produced in the garden and eaten continuously during the first half of the year. Leafy vegetables eaten during the second half of the year are obtained from uncontaminated sources. Thus, the entire ingestion dose from leafy vegetables accumulates during the irrigation season. The other items are harvested midway through the irrigation season (0.25 year after the well is finished). The plant concentrations are proportional to the soil

concentration at this time. They are then consumed over a 90-day period. The ingestion dose accumulates during the consumption period. Note that some parameters depend on the food type, while others are the same for all types. Similarly, some parameters depend on the radionuclide while others are the same for all radionuclides.

$$C_{V,p,K} = C_{GARDEN,K}\left(F_{DRY,p}\, B_{V,p,K} + \frac{J_{SPLASH}\, F_{INT,p}\, F_{TRANS,p}\, T_{W,p}}{Y_{V,p}}\right) F_{V,N,K,p}$$

$$T_{W,p} = \frac{1 - \mathrm{Exp}\left(-\lambda_W T_{GROW,p}\right)}{\lambda_W}$$

$$F_{V,N,K,Leafy} = \frac{1 - \mathrm{Exp}\left(-\lambda_K T_{irr}\right)}{\lambda_K T_{irr}}$$

$$F_{V,N,K,Other} = \mathrm{Exp}\left(-\lambda_K T_{harvest}\right)\frac{1 - \mathrm{Exp}\left(-\lambda_{R,K} T_{veg}\right)}{\lambda_{R,K} T_{veg}}$$

where,

$B_{V,p,K}$ = soil-to-plant transfer factor for the $K^{th}$ radionuclide in garden produce type p from Table A40

$C_{GARDEN,K}$ = initial average concentration of the $K^{th}$ radionuclide in the garden soil, in Ci/kg

$C_{V,p,K}$ = time-integrated radionuclide concentration in garden produce type p, in Ci/kg wet weight

$F_{DRY,p}$ = dry-to-wet ratio for garden produce type p from Table A42

$F_{INT,p}$ = interception fraction for airborne dust on exposed surfaces of garden produce type p, from Table A42

$F_{TRANS,p}$ = translocation factor from exposed surfaces to the edible portion of garden produce type p, from Table A42

$F_{V,N,K,p}$ = factor that results from the time integral of the daily dose from garden produce for the $K^{th}$ radionuclide (V=garden produce calculation, N=the irrigation water adds no contaminants, K=radionuclide index, and p= plant index). Specific cases are shown for leafy vegetables and all other types of garden produce.

$J_{SPLASH}$ = average soil deposition rate due to rain splash (see Section A5.2), $2.7 \times 10^{-4}$ kg/m$^2$ per day

p = index to the four types of garden produce, i.e., fruit, protected vegetables, exposed vegetables, and grains

$T_{GROW,p}$ = growing period of garden produce type p from Table A42

$T_{harvest}$ = time at which harvest occurs (midway through the irrigation season), 0.25 y after the well is drilled

$T_{irr}$ = irrigation period (the 1$^{st}$ half of the year), 0.5 y

$T_{veg}$ = consumption period for all garden produce except leafy vegetables, 90 d (0.2466 y)

$T_{W,p}$ = effective exposure time for garden produce type p, days. Calculated values are listed in Table B1.

$Y_{V,p}$ = yield of garden produce type p, from Table A42, in kg(wet)/m$^2$

$\lambda_K$ = total removal constant for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

$\lambda_W$ = weathering constant for all type of garden produce, 0.04951 per day. This is based on a weathering half time of 14 days.

An equilibrium model is used to estimate tritium concentrations in plants. It assumes the tritium exhumed is in the form of tritiated water (HTO). The concentration of tritium in the surface moisture is assumed the same as the tritium concentration in the water contained in the plant. The tritium concentration in garden produce is shown in the equation below. The product of the soil concentration and the first ratio gives the tritium concentration in the soil water. The factor 8.94 is calculated from the ratio of the atomic weights of water and hydrogen. It converts the hydrogen fractions ($F_{H,p}$) from Table A37 to water fractions. Because the hydrogen fractions include organically bound hydrogen, the water fraction calculated is an upper bound. Note also that the tritium concentration in the plants follows the tritium concentration in the soil, which is decreasing rapidly due to applied irrigation water and evaporation.

$$C_{V,p,H\text{-}3} = C_{GARDEN,H\text{-}3}\left(\frac{\rho_{GARDEN}}{\theta\ \rho_W}\right)\left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right)F_{H,p}\ F_{V,N,H\text{-}3,p}$$

where,

$C_{GARDEN,H\text{-}3}$ = initial average concentration of tritium (H-3) in the garden soil, in Ci/kg

$C_{V,p,H\text{-}3}$ = time-integrated tritium concentration in garden produce type p, in Ci/kg wet weight

$F_{H,p}$ = mass fraction of hydrogen in garden produce type p from Table A37, in kg hydrogen per kg plant (wet)

$F_{V,N,H\text{-}3,p}$ = factor that results from the time integral of the daily dose from garden produce for tritium (V=garden produce calculation, N=the irrigation water adds no contaminants, H-3=tritium, and p= plant index).

p = index to the four types of garden produce, i.e., fruit, protected vegetables, exposed vegetables, and grains

$\rho_{GARDEN}$ = average density of the garden soil, 1.5 kg soil per liter of soil

$\rho_W$ = density of water, 1.0 kg water per liter of water

$\theta$ = volumetric water content of the surface soil, liters of water per liter of soil. A value of 0.2 is assumed. Because the total soil porosity is about 0.4, the saturation ratio is about 50%.

Dermal Absorption Dose to the Suburban Gardener

The absorption of material on the skin into the body is shown to be a minor contributor for radionuclides in Section A3.4.1. In this section, the dose from radionuclides absorbed through the skin is compared with the soil ingestion dose. The dose from dermal absorption is not calculated for radionuclides.

Total Dose to the Suburban Gardener

Scenario dose factors for the suburban gardener are presented in Table 8 as the dose received during the first year per curie that is exhumed. These unit dose factors must be multiplied by the activity exhumed to calculate the first year dose. The radiation dose to this individual is the 50 year committed effective dose equivalent from one year of exposure.

The internal doses must be reduced in the event that the chemical form of the waste at the time of intrusion allows only a fraction of the material to be inhaled, ingested, or absorbed by plants. An example of this is vitrified waste material. After site closure, the radionuclides are decaying and the waste is releasing trapped activity. Thus, the cuttings activity concentration and the fraction available depend on the elapsed time since closure. The external dose will be delivered regardless of the waste form. The total dose to the suburban gardener can be written as shown below.

$$H_{GARDNER} = \sum_{K} \left[ H_{X,K} + F_{AVAIL} \left( H_{B,K} + H_{G,K} \right) \right]$$

where,

$F_{AVAIL}$ = fraction of the waste that is available for ingestion, inhalation, and absorption by plants at the time of suburban gardener exposures (Table 8 assumes $F_{AVAIL}$=1 in the "Total" columns)

$H_{GARDNER}$ = total effective dose equivalent received by the suburban gardener from all radionuclides in the exhumed waste material, in mrem/y

$H_{B,K}$ = inhalation dose to the suburban gardener from the $K^{th}$ radionuclide, in mrem/y

$H_{G,K}$ = ingestion dose to the suburban gardener from the $K^{th}$ radionuclide, in mrem/y

$H_{X,K}$ = external dose to the suburban gardener from the $K^{th}$ radionuclide, in mrem/y

The scenario dose factors for the suburban gardener assume that 1 Ci of each isotope comes out of the borehole. Values listed in Table 8 are separated into the external component and the internal component. The column labeled "Total" is the sum of the internal and external in the event that 100% of the exhumed waste is available for inhalation and ingestion.

**Table 8. Unit Dose Factors for the Suburban Gardener (mrem/y per Ci exhumed)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| H-3 | 3.04E+00 | 0.00E+00 | 3.04E+00 | Eu-155 | 1.65E+02 | 1.60E+02 | 4.79E+00 |
| Be-10 | 1.24E+01 | 9.67E-01 | 1.14E+01 | Gd-152 | 1.45E+03 | 0.00E+00 | 1.45E+03 |
| C-14 | 6.21E+02 | 1.21E-02 | 6.21E+02 | Tb-157 | 3.07E+00 | 2.64E+00 | 4.29E-01 |
| Na-22 | 1.14E+04 | 1.01E+04 | 1.35E+03 | Ho-166m | 8.38E+03 | 8.35E+03 | 2.87E+01 |
| Al-26 | 1.32E+04 | 1.32E+04 | 2.50E+01 | Re-187 | 1.64E+00 | 0.00E+00 | 1.64E+00 |
| Si-32+D | 4.11E+02 | 1.02E+01 | 4.01E+02 | Tl-204 | 8.59E+00 | 3.50E+00 | 5.09E+00 |
| Cl-36 | 8.25E+04 | 1.89E+00 | 8.25E+04 | Pb-205 | 7.48E+00 | 6.45E-03 | 7.47E+00 |
| K-40 | 5.28E+03 | 7.71E+02 | 4.51E+03 | Pb-210+D | 2.70E+04 | 5.38E+00 | 2.70E+04 |
| Ca-41 | 2.61E+02 | 0.00E+00 | 2.61E+02 | Bi-207 | 7.38E+03 | 7.36E+03 | 2.21E+01 |
| Ti-44+D | 1.08E+04 | 1.08E+04 | 6.76E+01 | Po-209 | 7.46E+03 | 1.61E+01 | 7.45E+03 |
| V-49 | 1.30E-01 | 0.00E+00 | 1.30E-01 | Po-210 | 3.33E+03 | 2.74E-02 | 3.33E+03 |

**Table 8. Unit Dose Factors for the Suburban Gardener (mrem/y per Ci exhumed)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| Mn-53 | 1.23E+01 | 0.00E+00 | 1.23E+01 | Ra-226+D | 1.41E+04 | 8.61E+03 | 5.45E+03 |
| Mn-54 | 3.60E+03 | 3.36E+03 | 2.36E+02 | Ra-228+D | 1.09E+04 | 5.20E+03 | 5.71E+03 |
| Fe-55 | 1.72E+00 | 0.00E+00 | 1.72E+00 | Ac-227+D | 2.96E+04 | 1.72E+03 | 2.79E+04 |
| Fe-60+D | 9.13E+02 | 4.15E+02 | 4.97E+02 | Th-228+D | 9.11E+03 | 6.92E+03 | 2.19E+03 |
| Co-60 | 1.25E+04 | 1.19E+04 | 5.86E+02 | Th-229+D | 1.40E+04 | 1.34E+03 | 1.26E+04 |
| Ni-59 | 5.70E+00 | 0.00E+00 | 5.70E+00 | Th-230 | 1.82E+03 | 2.02E+00 | 1.81E+03 |
| Ni-63 | 1.56E+01 | 0.00E+00 | 1.56E+01 | Th-232 | 8.82E+03 | 1.52E+02 | 8.67E+03 |
| Se-79 | 9.99E+01 | 1.61E-02 | 9.99E+01 | Pa-231 | 1.97E+04 | 1.78E+02 | 1.95E+04 |
| Rb-87 | 1.91E+03 | 1.28E-01 | 1.91E+03 | U-232 | 7.54E+03 | 6.39E+02 | 6.90E+03 |
| Sr-90+D | 3.58E+04 | 2.10E+01 | 3.58E+04 | U-233 | 1.48E+03 | 1.25E+00 | 1.47E+03 |
| Zr-93 | 3.36E+00 | 1.01E-03 | 3.35E+00 | U-234 | 1.45E+03 | 3.59E-01 | 1.45E+03 |
| Nb-91 | 1.49E+01 | 1.03E+01 | 4.53E+00 | U-235+D | 2.03E+03 | 6.62E+02 | 1.36E+03 |
| Nb-93m | 4.55E+00 | 9.39E-02 | 4.46E+00 | U-236 | 1.37E+03 | 1.91E-01 | 1.37E+03 |
| Nb-94 | 7.78E+03 | 7.72E+03 | 6.20E+01 | U-238+D | 1.47E+03 | 1.07E+02 | 1.37E+03 |
| Mo-93 | 4.59E+02 | 5.32E-01 | 4.58E+02 | Np-237+D | 3.44E+04 | 9.47E+02 | 3.35E+04 |
| Tc-97 | 5.94E+02 | 7.01E-01 | 5.93E+02 | Pu-236 | 2.17E+03 | 1.25E+00 | 2.17E+03 |
| Tc-99 | 5.06E+03 | 1.09E-01 | 5.06E+03 | Pu-238 | 6.35E+03 | 1.37E-01 | 6.35E+03 |
| Ru-106+D | 1.35E+03 | 8.89E+02 | 4.64E+02 | Pu-239 | 7.02E+03 | 2.59E-01 | 7.02E+03 |
| Pd-107 | 3.11E+00 | 0.00E+00 | 3.11E+00 | Pu-240 | 7.02E+03 | 1.34E-01 | 7.02E+03 |
| Ag-108m+D | 7.87E+03 | 7.86E+03 | 1.39E+01 | Pu-241+D | 1.37E+02 | 3.29E-02 | 1.37E+02 |
| Cd-109+D | 8.10E+02 | 2.12E+01 | 7.88E+02 | Pu-242 | 6.68E+03 | 1.17E-01 | 6.68E+03 |
| Cd-113m | 1.15E+04 | 5.75E-01 | 1.15E+04 | Pu-244+D | 8.22E+03 | 1.63E+03 | 6.59E+03 |
| In-115 | 2.66E+02 | 3.62E-01 | 2.66E+02 | Am-241 | 7.24E+03 | 3.99E+01 | 7.20E+03 |
| Sn-121m+D | 1.17E+01 | 1.92E+00 | 9.82E+00 | Am-242m+D | 7.08E+03 | 5.90E+01 | 7.02E+03 |
| Sn-126+D | 9.74E+03 | 9.65E+03 | 9.21E+01 | Am-243+D | 7.96E+03 | 7.95E+02 | 7.17E+03 |
| Sb-125 | 1.92E+03 | 1.89E+03 | 2.85E+01 | Cm-242 | 1.58E+02 | 1.08E-01 | 1.57E+02 |
| Te-125m | 9.20E+00 | 5.57E+00 | 3.63E+00 | Cm-243 | 5.39E+03 | 5.12E+02 | 4.88E+03 |
| I-129 | 2.89E+03 | 1.17E+01 | 2.87E+03 | Cm-244 | 3.90E+03 | 1.14E-01 | 3.90E+03 |
| Cs-134 | 1.21E+04 | 7.02E+03 | 5.10E+03 | Cm-245 | 7.62E+03 | 3.07E+02 | 7.31E+03 |
| Cs-135 | 5.55E+02 | 3.50E-02 | 5.55E+02 | Cm-246 | 7.24E+03 | 1.06E-01 | 7.24E+03 |
| Cs-137+D | 6.63E+03 | 2.74E+03 | 3.89E+03 | Cm-247+D | 8.25E+03 | 1.57E+03 | 6.68E+03 |
| Ba-133 | 1.71E+03 | 1.65E+03 | 5.44E+01 | Cm-248 | 2.66E+04 | 8.02E-02 | 2.66E+04 |
| Ce-144+D | 4.28E+02 | 2.08E+02 | 2.20E+02 | Cm-250+D | 1.53E+05 | 1.33E+03 | 1.52E+05 |
| Pm-147 | 3.23E+00 | 4.26E-02 | 3.19E+00 | Bk-247 | 9.69E+03 | 3.85E+02 | 9.30E+03 |
| Sm-147 | 8.79E+02 | 0.00E+00 | 8.79E+02 | Cf-248 | 1.62E+03 | 9.56E-02 | 1.62E+03 |
| Sm-151 | 1.35E+00 | 8.97E-04 | 1.35E+00 | Cf-249 | 3.06E+04 | 1.57E+03 | 2.90E+04 |
| Eu-150 | 7.12E+03 | 7.09E+03 | 2.12E+01 | Cf-250 | 1.28E+04 | 1.07E-01 | 1.28E+04 |
| Eu-152 | 5.44E+03 | 5.42E+03 | 2.11E+01 | Cf-251 | 3.01E+04 | 4.71E+02 | 2.97E+04 |
| Eu-154 | 5.91E+03 | 5.88E+03 | 3.07E+01 | Cf-252 | 6.06E+03 | 1.50E-01 | 6.06E+03 |

Notes:

- The radiation dose to this individual is the 50 year committed effective dose equivalent from the first year of exposure.
- These scenario dose factors must be multiplied by the activity exhumed by the well drilling, in curies.
- The "Total" column is the sum of the "Internal" and "External" columns. External and internal doses are separated because the waste matrix may prevent a portion of the exhumed activity from giving an internal dose.

Comparison of the Driller and Suburban Gardener Doses. To compare the driller and the suburban gardener, note that the dose depends on both the effective annual intake and the soil concentration. The effective annual intakes are discussed in Appendix A, Section A3.1. For the well-driller, the soil concentration is the average concentration in the borehole cuttings. For the suburban gardener the soil concentration is the average concentration in the garden.

For a few nuclides there are additional differences due to radioactive decay and leaching from the garden soil. These processes are not included in the driller scenario due to the short exposure time (5 days). The factors that adjust the garden doses for decay and leaching have values between 0 and 1, with most nuclides very close to 1 due to the high organic content of the garden soil. These factors are not included in this comparison so that the results do not depend on the specific radionuclide. The equations below show the dose ratios, assuming the waste density is similar to the density of the compacted soil in the borehole.

$$\frac{C_{GARDEN,K}}{C_{CUT,K}} = \frac{A_{WELL}\, L_{WELL}\, \rho_{WELL}}{A_{GARDEN}\, L_{GARDEN}\, \rho_{GARDEN}}$$

$$\text{Internal Dose Ratio} = \left(\frac{M_{GARDEN}}{M_{CUT}}\right)\left(\frac{C_{GARDEN,K}}{C_{CUT,K}}\right)$$

$$\text{External Dose Ratio} = \left(\frac{L_{GARDEN}\, T_{GARDEN}\, D_{X,K}}{L_{CUT}\, T_{WELL}\, D_{X,5,K}}\right)\left(\frac{C_{GARDEN,K}}{C_{CUT,K}}\right)$$

where,

$A_{GARDEN}$ = cultivated area of a garden, 100 $m^2$

$A_{WELL}$ = cross-sectional area of the borehole, in $m^2$

$C_{GARDEN,K}$ = initial average concentration of the $K^{th}$ radionuclide in the garden soil, in Ci/kg

$C_{CUT,K}$ = average concentration of the $K^{th}$ radionuclide in the borehole cuttings, in Ci/kg

$D_{X,K}$ = external dose rate factor for the $K^{th}$ radionuclide to a person standing on a layer 0.15 m thick and of great extent in all directions, in mrem/h per Ci/$m^2$. Values from EPA Federal Guidance Report Number 12 for a 15 cm thickness are listed in Table A28.

$D_{X,5,K}$ = external dose rate factor for the $K^{th}$ radionuclide to a person standing on a layer 0.05 m thick and of great extent in all directions, in mrem/h per Ci/$m^2$. Values from EPA Federal Guidance Report Number 12 for a 5 cm thickness are listed in Table A28.

$L_{GARDEN}$ = depth of the contaminated soil layer in the suburban garden, 0.15 m

$L_{CUT}$ = depth of the contaminated soil layer in the well-drilling scenario, 0.05 m

$L_{WELL}$ = depth of the borehole from surface to groundwater, in m

$M_{GARDEN}$ = mass of contaminated soil inhaled (0.087 g) or ingested (18 g) in the suburban garden

$M_{CUT}$ = mass of contaminated soil inhaled (0.00484 g) or ingested (0.5 g) in the well-drilling scenario

Ratio = the dose to the suburban gardener divided by the dose to the well-driller

$T_{GARDEN}$ = external exposure time in the suburban garden, 180 h

$T_{WELL}$ = external exposure time in the well-drilling scenario, 40 h

$\rho_{GARDEN}$ = average density of the soil in the garden, 1,500 kg/m$^3$

$\rho_{WELL}$ = average density of the soil in the borehole, 1,700 kg/m$^3$

Notice that the gardener-to-driller dose ratios do not depend on the waste thickness, provided that the waste density is about the same as the soil density in the borehole. The internal dose ratios are essentially independent of the radionuclide because the dose from garden vegetables is not included. The external dose ratios do contain an explicit reference to the radionuclide in the external dose rate factors from Federal Guidance Report Number 12. However, the ratio of 5 cm to 15 cm dose rate factors shown in Table A28 ranges from 1.8 to 3.0. Nearly all of the dose rate factors that are greater than 1,000 mrem/h per Ci/m$^2$ have ratios less than 2.0. Thus, for the sake of the comparison, the ratio of dose rate factors can be replaced with 1/2.

Assuming the borehole is 100 m (328 ft) deep, has a diameter of 0.165 m (6.5 in.), and the compacted soil density in the borehole is 1,700 kg/m$^3$, then the soil concentration ratio (gardener/driller) is 0.162. The mass of soil inhaled or ingested is from Tables A8 and A10. The external exposure times are shown in Table A18. The ratio of the post-intrusion dose to the well-driller dose is shown in Table 9 for each exposure pathway. Ingestion of contaminated garden vegetables is not shown because the driller does not consume any.

Also shown in Table 9 is the borehole depth at which the dose to the driller equals the dose to the suburban gardener, assuming the borehole diameter is 0.165 m (6.5 in.). The general conclusion is that wells shallower than about 90 m may have driller doses larger than the suburban gardener dose (excluding vegetables). The actual depth depends on the combination of radionuclides present in the waste, and must include the garden produce contribution, as well.

For other post-intrusion scenarios, the borehole diameters are larger. This increases the dose to the post-intrusion resident but has no effect on the well driller dose. However, the increased amount exhumed is offset by the larger area of the pasture and farm. Thus for the other post-intrusion cases, the ratio with the driller dose is smaller, and the borehole depths to reach equal doses are greater.

**Table 9. Comparison of the Well Driller and Suburban Gardener**

| Pathway | Gardener to Driller Dose Ratio | Borehole Depth for Driller Dose Equal to Suburban Gardener Dose |
|---|---|---|
| Soil Ingestion | 5.8 | 17 m |
| Soil Inhalation | 2.9 | 35 m |
| External Exposure | 1.1 | 92 m |

Notes:
- The Gardener to Driller Dose Ratio ignores differences in density between the buried waste and the soil in the borehole. Both are assumed to be 1,700 kg/m$^3$.
- Ingestion of garden vegetables is not included in this comparison because the well driller does not consume any.
- The internal dose is the 50 year committed effective dose equivalent from intakes during the first year of exposure. The external dose is the effective dose equivalent accumulated during the year of exposure.
- The assumed borehole is 0.165 m (6.5 inches) diameter and 100 m deep.
- The minimum well depths shown in the last column assume a 0.165 m diameter borehole, in addition to an in situ density of 1,700 kg/m$^3$.

## 3.3 POST-INTRUSION RURAL PASTURE

This scenario assumes that an individual lives near the borehole cuttings and spreads the cuttings in his pasture and hay field. The individual obtains half of his annual intake of milk from the cow. In addition, he inhales resuspended soil and ingests small amounts of it each day. His external dose comes from spending time in or near the pasture and hay field. The radiation dose to this individual is the 50 year committed effective dose equivalent from the first year of exposure after the well was drilled.

The pasture and hay field areas are discussed in Section A4.1. The total pasture and hay field area is about 5,000 m$^2$. This total area will be used as the averaging area. Realistically, the borehole cuttings will not be spread in both the pasture and hay field. Only one will receive the contaminated soil. Since the two areas are about half the total, the average soil concentration would double. Thus, either the pasture grass or the stored hay would have twice the concentration, while the other crop would be uncontaminated. The net effect on the cow's milk is small. Hence, the total area will be used, and all of the cow's solid food will be contaminated based on an averaging area of 5,000 m$^2$.

The depth of soil contaminated is 0.15 m, a traditional representation of the tilling depth. Thus the volume of soil used for the average soil concentration is 750 m$^3$. Since the density of the surface soil is assumed to be 1,500 kg/m$^3$, the mass of soil is 1,125 MT. When calculating the average doses, the exhumed waste is distributed over this amount of soil. Assuming 1 Curie of a radionuclide is exhumed, the average soil concentration in the pasture and hay field is 889 pCi/g.

The descriptions for the external, inhalation, and soil ingestion routes are very similar to those presented earlier for the Suburban Gardener. Instead of garden vegetables, there is a pasture and milk cow. The equations for the milk dose include the effects of decay and leaching,

but do not show the method used to represent decay chains. The treatment of decay chains is presented in Appendix B.

External and Inhalation Dose in the Rural Pasture Scenario

The external and inhalation doses are calculated using the same equations given for the suburban gardener. The external exposure time has increased to 360 h/y, and the annual soil inhalation has increased to 169 mg/y. Both of these are approximately twice the values used for the suburban gardener. Since the soil concentration is a factor of 50 smaller, the rural pasture external and inhalation doses are a factor of 25 smaller than for the suburban garden.

Ingestion Dose in the Rural Pasture Scenario

In addition to the small amounts of soil that are ingested during the irrigation season, the pasture owner also consumes milk from his cow. From recent USDA estimates of per capita food consumption (Putnam and Allshouse, 1999), the total milk equivalent is 263 kg/y. Deducting cheeses and other milk products unlikely to be produced at home leaves 116 kg/y. The owner of the cow is assumed to obtain 58 L of milk from his cow during the year. This amount is 22% of the total milk equivalent and 50% of the home milk consumption. These fractions are derived from the EPA Exposure Factors Handbook (EPA/600-P-95/002Fa), which shows 20% to 25% for all dairy products in Table 13-71 under "Questionnaire Response". The ingestion dose for one nuclide that results from these intakes is shown below. Note that the formula shown applies to all animal products. The rural pasture scenario only uses the milk. The other formulas will be needed when calculating lifetime intakes for the All Pathways Farmer scenario.

$$H_{G,K} = \left( C_{Pasture,K}\, M_G\, F_{X,N,K} + \sum_q C_{A,q,K}\, M_{A,q} \right) D_{G,K}$$

where,

$C_{A,q,K}$ = time-integrated concentration of the $K^{th}$ radionuclide in animal product type q, in Ci/kg

$C_{Pasture,K}$ = initial average concentration of the $K^{th}$ radionuclide in the soil in the pasture and hay field, in Ci/kg

$D_{G,K}$ = ingestion dose factor for the $K^{th}$ radionuclide from Table A24, in mrem/pCi ingested

$F_{X,N,K}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the first half of the year (X=external calculation, N=the irrigation water adds no contaminants, and K=radionuclide index)

$H_{G,K}$ = ingestion dose for the rural pasture scenario from the $K^{th}$ radionuclide, mrem/y

$M_{A,q}$ = mass of animal product type q eaten during the year, in kg/y. These amounts are shown in Table A5.

$M_G$ = total mass of soil ingested during the irrigation season from Table A8, 0.018 kg/y

q = index to the four types of animal products, i.e., beef, milk, poultry, and eggs

Animal products (beef, milk, poultry, and eggs) become contaminated when some portion of the animal's diet is contaminated. All of the animals modeled are assumed to ingest soil, water, and fodder. Both the soil and the fodder are contaminated. The fodder is either fresh pasture grass or stored hay and grain. The fresh pasture grass is assumed to be eaten throughout the year because animals forage during most of the year. The hay and grain are harvested at various times throughout the irrigation season, stored for a period of time and then consumed. The simplified model to represent this assumes harvest midway through the irrigation season (0.25 year after the well is drilled). The plant concentrations are proportional to the soil concentration at this time. They are stored for 90 days and then consumed over a 90-day period. The ingestion dose accumulates during the consumption period.

The beef cow is slaughtered midway through the irrigation season (at 0.25 year) and consumed over a period of time ($T_{beef}$). The milk and the chickens (poultry and eggs) are consumed throughout the year with little storage time. The concentration in the animal product is therefore calculated using the equations below. The animal products are divided into beef and other. "Other" refers to milk, poultry, and eggs.

$$C_{A,q,K} = B_{A,q,K}\left(C_{Pasture,K}\, M_{S,q}\, F_{V,N,K,q(fresh)} + \sum_p C_{V,p,K}\, M_{V,p,q}\right) F_{A,K,q}$$

$$C_{V,p,K} = C_{Pasture,K}\left(F_{DRY,p}\, B_{V,p,K} + \frac{J_{SPLASH}\, F_{INT,p}\, F_{TRANS,p}\, T_{W,p}}{Y_{V,p}}\right) F_{V,N,K,p}$$

$$F_{A,K,Beef} = \frac{1-\mathrm{Exp}(-\lambda_{R,K} T_{beef})}{\lambda_{R,K} T_{beef}} \quad \text{and} \quad F_{A,K,Other} = 1$$

$$F_{V,N,K,Beef(fresh)} = \mathrm{Exp}(-\lambda_K T_{harvest}) \quad \text{and} \quad F_{V,N,K,Other(fresh)} = F_{B,N,K}$$

$$F_{V,N,K,Beef(stored)} = \mathrm{Exp}(-\lambda_K T_{harvest})\,\mathrm{Exp}(-\lambda_{R,K} T_{sto}) \quad \text{and}$$

$$F_{V,N,K,Other(stored)} = \mathrm{Exp}(-\lambda_K T_{harvest})\,\mathrm{Exp}(-\lambda_{R,K} T_{sto})\frac{1-\mathrm{Exp}(-\lambda_{R,K} T_{an})}{\lambda_{R,K} T_{an}}$$

where,

$B_{A,q,K}$ = animal transfer factor for the $K^{th}$ radionuclide into animal product type q from Table A36, in day/kg

$B_{V,p,K}$ = soil-to-plant transfer factor for the $K^{th}$ radionuclide in animal fodder type p from Table A40

$C_{A,q,K}$ = time-integrated concentration of the $K^{th}$ radionuclide in animal product type q, in Ci/kg

$C_{Pasture,K}$ = initial average concentration of the $K^{th}$ radionuclide in the soil in the pasture and hay field, in Ci/kg

$C_{V,p,K}$ = time-integrated radionuclide concentration in animal fodder of type p, in Ci/kg wet weight

$F_{B,N,K}$ = factor that results from the time integral of the inhalation dose rate for the $K^{th}$ radionuclide over the full year (B=inhalation calculation, N=the irrigation water adds no contaminants, and K=radionuclide index)

$F_{DRY,p}$ = dry-to-wet ratio for animal fodder type p from Table A42

$F_{INT,p}$ = interception fraction for airborne dust on exposed surfaces of animal fodder type p, from Table A42

$F_{TRANS,p}$ = translocation factor from exposed surfaces to the edible portion of animal fodder type p, from Table A42

$F_{V,N,K,p}$ = factor that results from the time integral of the daily dose from milk due to the cow's consumption of animal fodder type p for the $K^{th}$ radionuclide (V=animal fodder calculation, N=the irrigation water adds no contaminants, K=radionuclide index, and p= plant index). Specific cases are shown for fresh pasture grass and stored feed (i.e., hay and grain).

$J_{SPLASH}$ = average soil deposition rate due to rain splash (see Section A5.2), $2.7 \times 10^{-4}$ $kg/m^2$ per day

$M_{S,q}$ = daily mass of soil ingested by animal type q in Table A35, in kg/d

$M_{V,p,q}$ = daily mass of animal fodder type p eaten by animal type q, in kg (wet)/d. These amounts are shown in Table A35.

p = index to the types of animal fodder, fresh pasture grass and stored hay and grain for beef, milk, poultry and eggs

$T_{an}$ = consumption period for the animal fodder, 90 d (0.2466 y)

$T_{beef}$ = consumption period for beef, 120 d (0.3288 y)

$T_{harvest}$ = time at which harvest occurs, 0.25 y (midway through the irrigation season)

$T_{irr}$ = irrigation period (the $1^{st}$ half of the year), 0.5 y

$T_{sto}$ = storage period for stored fodder, 90 d (0.2466 y)

$T_{W,p}$ = effective exposure time for garden produce type p, days. Calculated values are listed in Table B1.

$Y_{V,p}$ = yield of garden produce type p, from Table A42, in $kg(wet)/m^2$

$\lambda_K$ = total removal constant for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

The concentration of tritium in animal products is calculated from an equilibrium model. The concentration of tritium in the animal is based on the assumption that the ratio of contaminated water in the animal product to total water in the animal product is proportional to the ratio of contaminated water in the animal's diet to the total water in the diet. The formula below reflects this. The first four terms in the first equation calculate the tritium concentration in the animal product, just as was done for garden produce. The mass ratio adjusts this concentration for the fraction of the animal's diet that is contaminated. The time-integration factors are the same as shown above.

$$C_{A,q,H\text{-}3} = C_{Pasture,H\text{-}3}\left(\frac{\rho_{Pasture}}{\theta\ \rho_W}\right)\left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right)F_{H,q}\left(\frac{M_{W,C,q}}{M_{W,T,q}}\right)F_{A,H\text{-}3,q}$$

$$M_{W,C,q} = \left(\frac{\theta\ \rho_W}{\rho_{Pasture}}\right)M_{S,q}\ F_{V,N,H\text{-}3,q(fresh)} + \sum_p\left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right)F_{H,p}\ F_{V,N,H\text{-}3,p}\ M_{V,p,q}$$

$$M_{W,T,q} = \left(\frac{\theta\ \rho_W}{\rho_{Pasture}}\right)M_{S,q} + \sum_p\left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right)F_{H,p}\ M_{V,p,q} + \rho_W\ V_{W,q}$$

where,

$C_{A,q,H\text{-}3}$ = time-integrated tritium concentration in animal product type q, in Ci/kg

$C_{Pasture,K}$ = initial average concentration of the $K^{th}$ radionuclide in the pasture and hay field, in Ci/kg

$F_{A,H\text{-}3,q}$ = factor that results from the time integral of the dose rate for tritium over the full year (A=animal calculation, H-3=tritium, and q=animal type).

$F_{H,p}$ = mass fraction of hydrogen in animal fodder type p from Table A37, in kg hydrogen per kg plant (wet)

$F_{H,q}$ = mass fraction of hydrogen in animal product type q from Table A37, in kg hydrogen per kg of the animal product

$F_{V,N,H\text{-}3,p}$ = factor that results from the time integral of the daily dose from animal products for tritium (V=garden produce calculation, N=the irrigation water adds no contaminants, H-3=tritium, and p= plant index).

$M_{S,q}$ = daily mass of soil ingested by animal type q in Table A35, in kg/d

$M_{V,p,q}$ = daily mass of animal fodder type p eaten by animal type q, in kg (wet)/d. These amounts are shown in Table A35.

$M_{W,C,q}$ = mass of contaminated water ingested daily by the animal, in kg/d

$M_{W,T,q}$ = total mass of water ingested daily by the animal, in kg/d

p = index to the types of animal fodder, i.e., fresh pasture grass and stored hay and grain for beef, milk, poultry, and eggs

q = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

$V_{W,q}$ = daily volume of water ingested by animal type q from Table A35, in L/d

$\rho_{Pasture}$ = average density of the soil in the pasture and hay field, 1.5 kg soil per liter of soil

$\rho_W$ = density of water, 1.0 kg water per liter of water

$\theta$ = volumetric water content of the surface soil, liters of water per liter of soil. A value of 0.2 is assumed.

Note that the equation for the concentration of tritium in the animal product can be rearranged to indicate an equilibrium concentration ratio for tritium in the animal product. This equation has the same form as the equation used for all the other radionuclides. The equilibrium transfer factor is calculated from the tritium equilibrium model.

$$C_{A,q,H\text{-}3} = B_{A,q,H\text{-}3}\left(C_{Pasture,H\text{-}3}\, M_{S,q}\, F_{V,N,H\text{-}3,q(fresh)} + \sum_{p} C_{V,p,H\text{-}3}\, M_{V,p}\right) F_{A,H\text{-}3,q}$$

$$B_{A,q,H\text{-}3} = \left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right)\left(\frac{F_{H,q}}{M_{W,T,q}}\right)$$

$$C_{V,p,H\text{-}3} = C_{Pasture,H\text{-}3}\left(\frac{\rho_{Pasture}}{\theta\ \rho_W}\right)\left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right) F_{H,p}\, F_{V,N,H\text{-}3,p}$$

Dermal Absorption Dose in the Rural Pasture Scenario

The absorption of material on the skin into the body is shown to be a minor contributor for radionuclides in Section A3.4.1. In this section, the dose from radionuclides absorbed through the skin is compared with the soil ingestion dose. The dose from dermal absorption is not calculated for radionuclides.

Total Dose in the Rural Pasture Scenario

Scenario dose factors from the rural pasture scenario are presented in Table 10 as the dose received during the first year per curie that is exhumed. These unit dose factors must be multiplied by the activity exhumed to calculate the first year dose. The radiation dose to this individual is the 50 year committed effective dose equivalent from one year of exposure.

The internal doses must be reduced in the event that the chemical form of the waste at the time of intrusion allows only a fraction of the material to be inhaled, ingested, or absorbed by plants. An example of this is vitrified waste material. After site closure, the radionuclides are decaying and the waste is releasing trapped activity. Thus, the activity concentration in the borehole cuttings and the fraction available depend on the elapsed time since closure. The external dose will be delivered regardless of the waste form. The total dose to the rural resident with a cow can be written as shown below.

$$H_{RURAL} = \sum_{K}\left[H_{X,K} + F_{AVAIL}\left(H_{B,K} + H_{G,K}\right)\right]$$

where,

$F_{AVAIL}$ = fraction of the waste that is available for ingestion, inhalation, and absorption by plants at the time of rural pasture scenario exposures (Table 10 assumes $F_{AVAIL}$=1 in the "Total" columns)

$H_{RURAL}$ = total effective dose equivalent received in the rural pasture scenario from all radionuclides in the exhumed waste material, in mrem/y

$H_{B,K}$ = inhalation dose to the rural pasture scenario from the $K^{th}$ radionuclide, in mrem/y

$H_{G,K}$ = ingestion dose to the rural pasture scenario from the $K^{th}$ radionuclide, in mrem/y

$H_{X,K}$ = external dose to the rural pasture scenario from the $K^{th}$ radionuclide, in mrem/y

The scenario dose factors for the rural pasture assume that 1 Ci of each isotope comes out of the borehole. Values listed in Table 10 are separated into the external component and the internal component. The column labeled "Total" is the sum of the internal and external in the event that 100% of the exhumed waste is available for inhalation and ingestion.

**Table 10. Unit Dose Factors for the Rural Pasture Scenario (mrem/y per Ci exhumed)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| H-3 | 1.33E-01 | 0.00E+00 | 1.33E-01 | Eu-155 | 6.44E+00 | 6.41E+00 | 3.09E-02 |
| Be-10 | 1.67E-01 | 3.87E-02 | 1.28E-01 | Gd-152 | 3.93E+01 | 0.00E+00 | 3.93E+01 |
| C-14 | 1.36E+01 | 4.84E-04 | 1.36E+01 | Tb-157 | 1.09E-01 | 1.05E-01 | 3.49E-03 |
| Na-22 | 4.50E+02 | 4.03E+02 | 4.73E+01 | Ho-166m | 3.34E+02 | 3.34E+02 | 2.54E-01 |
| Al-26 | 5.28E+02 | 5.27E+02 | 3.93E-01 | Re-187 | 1.71E-02 | 0.00E+00 | 1.71E-02 |
| Si-32+D | 8.05E-01 | 4.09E-01 | 3.96E-01 | Tl-204 | 5.04E-01 | 1.40E-01 | 3.63E-01 |
| Cl-36 | 2.65E+03 | 7.56E-02 | 2.65E+03 | Pb-205 | 4.97E-02 | 2.58E-04 | 4.94E-02 |
| K-40 | 1.41E+02 | 3.08E+01 | 1.11E+02 | Pb-210+D | 1.90E+02 | 2.15E-01 | 1.89E+02 |
| Ca-41 | 1.00E+01 | 0.00E+00 | 1.00E+01 | Bi-207 | 2.95E+02 | 2.94E+02 | 2.91E-01 |
| Ti-44+D | 4.44E+02 | 4.31E+02 | 1.32E+01 | Po-209 | 7.95E+01 | 6.43E-01 | 7.89E+01 |
| V-49 | 8.96E-04 | 0.00E+00 | 8.96E-04 | Po-210 | 3.47E+01 | 1.10E-03 | 3.47E+01 |
| Mn-53 | 3.70E-03 | 0.00E+00 | 3.70E-03 | Ra-226+D | 5.14E+02 | 3.44E+02 | 1.70E+02 |
| Mn-54 | 1.35E+02 | 1.35E+02 | 6.86E-02 | Ra-228+D | 3.88E+02 | 2.08E+02 | 1.80E+02 |
| Fe-55 | 1.01E-02 | 0.00E+00 | 1.01E-02 | Ac-227+D | 5.11E+02 | 6.87E+01 | 4.42E+02 |
| Fe-60+D | 1.95E+01 | 1.66E+01 | 2.84E+00 | Th-228+D | 3.32E+02 | 2.77E+02 | 5.55E+01 |
| Co-60 | 4.80E+02 | 4.78E+02 | 2.00E+00 | Th-229+D | 3.81E+02 | 5.36E+01 | 3.27E+02 |
| Ni-59 | 3.22E-01 | 0.00E+00 | 3.22E-01 | Th-230 | 4.83E+01 | 8.09E-02 | 4.82E+01 |
| Ni-63 | 8.83E-01 | 0.00E+00 | 8.83E-01 | Th-232 | 2.34E+02 | 6.10E+00 | 2.28E+02 |
| Se-79 | 2.36E+00 | 6.45E-04 | 2.36E+00 | Pa-231 | 3.13E+02 | 7.11E+00 | 3.06E+02 |
| Rb-87 | 4.70E+01 | 5.12E-03 | 4.70E+01 | U-232 | 8.52E+01 | 2.56E+01 | 5.97E+01 |
| Sr-90+D | 9.68E+02 | 8.39E-01 | 9.67E+02 | U-233 | 1.19E+01 | 4.99E-02 | 1.19E+01 |
| Zr-93 | 3.92E-02 | 4.05E-05 | 3.92E-02 | U-234 | 1.16E+01 | 1.44E-02 | 1.16E+01 |
| Nb-91 | 4.22E-01 | 4.13E-01 | 8.83E-03 | U-235+D | 3.74E+01 | 2.65E+01 | 1.09E+01 |
| Nb-93m | 1.25E-02 | 3.76E-03 | 8.74E-03 | U-236 | 1.10E+01 | 7.66E-03 | 1.10E+01 |
| Nb-94 | 3.09E+02 | 3.09E+02 | 1.20E-01 | U-238+D | 1.52E+01 | 4.27E+00 | 1.09E+01 |
| Mo-93 | 1.65E+00 | 2.13E-02 | 1.63E+00 | Np-237+D | 1.91E+02 | 3.79E+01 | 1.53E+02 |
| Tc-97 | 3.01E+00 | 2.81E-02 | 2.98E+00 | Pu-236 | 3.72E+01 | 5.01E-02 | 3.71E+01 |
| Tc-99 | 2.55E+01 | 4.34E-03 | 2.55E+01 | Pu-238 | 1.10E+02 | 5.49E-03 | 1.10E+02 |
| Ru-106+D | 3.60E+01 | 3.56E+01 | 3.97E-01 | Pu-239 | 1.21E+02 | 1.04E-02 | 1.21E+02 |
| Pd-107 | 2.46E-01 | 0.00E+00 | 2.46E-01 | Pu-240 | 1.21E+02 | 5.35E-03 | 1.21E+02 |
| Ag-108m+D | 3.14E+02 | 3.14E+02 | 1.49E-01 | Pu-241+D | 2.37E+00 | 1.32E-03 | 2.37E+00 |
| Cd-109+D | 5.60E+00 | 8.48E-01 | 4.76E+00 | Pu-242 | 1.16E+02 | 4.67E-03 | 1.16E+02 |
| Cd-113m | 7.59E+01 | 2.30E-02 | 7.59E+01 | Pu-244+D | 1.79E+02 | 6.51E+01 | 1.14E+02 |
| In-115 | 3.90E+00 | 1.45E-02 | 3.89E+00 | Am-241 | 1.27E+02 | 1.60E+00 | 1.25E+02 |
| Sn-121m+D | 2.72E-01 | 7.68E-02 | 1.95E-01 | Am-242m+D | 1.24E+02 | 2.36E+00 | 1.22E+02 |
| Sn-126+D | 3.88E+02 | 3.86E+02 | 1.84E+00 | Am-243+D | 1.56E+02 | 3.18E+01 | 1.24E+02 |
| Sb-125 | 7.58E+01 | 7.57E+01 | 8.22E-02 | Cm-242 | 2.88E+00 | 4.31E-03 | 2.87E+00 |
| Te-125m | 2.68E-01 | 2.23E-01 | 4.55E-02 | Cm-243 | 1.08E+02 | 2.05E+01 | 8.79E+01 |
| I-129 | 2.23E+02 | 4.69E-01 | 2.22E+02 | Cm-244 | 7.04E+01 | 4.55E-03 | 7.04E+01 |
| Cs-134 | 4.70E+02 | 2.81E+02 | 1.89E+02 | Cm-245 | 1.44E+02 | 1.23E+01 | 1.32E+02 |

**Table 10. Unit Dose Factors for the Rural Pasture Scenario (mrem/y per Ci exhumed)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| Cs-135 | 2.19E+01 | 1.40E-03 | 2.19E+01 | Cm-246 | 1.31E+02 | 4.24E-03 | 1.31E+02 |
| Cs-137+D | 2.62E+02 | 1.10E+02 | 1.53E+02 | Cm-247+D | 1.83E+02 | 6.29E+01 | 1.20E+02 |
| Ba-133 | 6.65E+01 | 6.62E+01 | 3.08E-01 | Cm-248 | 4.79E+02 | 3.21E-03 | 4.79E+02 |
| Ce-144+D | 8.65E+00 | 8.32E+00 | 3.24E-01 | Cm-250+D | 2.78E+03 | 5.33E+01 | 2.73E+03 |
| Pm-147 | 2.36E-02 | 1.71E-03 | 2.19E-02 | Bk-247 | 1.77E+02 | 1.54E+01 | 1.62E+02 |
| Sm-147 | 1.44E+01 | 0.00E+00 | 1.44E+01 | Cf-248 | 9.99E+00 | 3.82E-03 | 9.99E+00 |
| Sm-151 | 1.11E-02 | 3.59E-05 | 1.11E-02 | Cf-249 | 2.25E+02 | 6.26E+01 | 1.63E+02 |
| Eu-150 | 2.84E+02 | 2.84E+02 | 1.48E-01 | Cf-250 | 7.21E+01 | 4.27E-03 | 7.21E+01 |
| Eu-152 | 2.17E+02 | 2.17E+02 | 1.42E-01 | Cf-251 | 1.85E+02 | 1.88E+01 | 1.66E+02 |
| Eu-154 | 2.36E+02 | 2.35E+02 | 2.01E-01 | Cf-252 | 3.44E+01 | 6.01E-03 | 3.44E+01 |

Notes:
- The radiation dose to this individual is the 50 year committed effective dose equivalent from the first year of exposure.
- These scenario dose factors must be multiplied by the activity exhumed by the well drilling, in curies.
- The "Total" column is the sum of the "Internal" and "External" columns. External and internal doses are separated because the waste matrix may prevent a portion of the exhumed activity from giving an internal dose.

## 3.4 POST-INTRUSION COMMERCIAL FARM

This scenario assumes that an individual lives near the borehole cuttings and spreads the cuttings in a field used for growing a food crop for market. The individual inhales resuspended soil and ingests small amounts of it each day. His external dose comes from spending time in or near the field. The radiation dose to this individual is the 50 year committed effective dose equivalent from the first year of exposure after the well was drilled.

The field is assumed to have an area of 160 acres, or 647,000 $m^2$. This total area will be used as the averaging area. The depth of soil contaminated is 0.15 m, a traditional representation of the tilling depth. Thus the volume of soil used for the average soil concentration is 97,000 $m^3$. Since the density of the surface soil is assumed to be 1,500 $kg/m^3$, the mass of soil is 146,000 MT. When calculating the average doses, the exhumed waste is distributed over this amount of soil. Assuming a unit activity is exhumed, the average concentration in the field is 6.87 pCi/g soil.

External, Inhalation, and Ingestion Dose

The external and inhalation doses are calculated using the same equations given for the suburban gardener. The external exposure time has increased to 8 h/d or 1,440 h/y, and the annual soil inhalation has increased to 321 mg/y. Both of these are approximately four times larger than the values used for the suburban gardener. Since the soil concentration is a factor of 6,470 smaller, the commercial farm external and inhalation doses are a factor of 1,620 smaller than for the suburban garden.

The only item ingested is trace amounts of soil. The usual exposure of 100 mg/d for 180 days is assumed. Thus, the annual ingestion of contaminated soil is 18 g. This is the same

as used in the suburban garden and rural pasture scenarios. Hence, the ingestion dose is lower than the suburban garden dose by a factor of 6,470.

Dermal absorption of radionuclides is not considered, based on the discussion in Section A3.4.1.

Total Dose in the Commercial Farm Scenario

Scenario dose factors from the commercial farm scenario are presented in Table 11 as the dose received during the first year per curie that is exhumed. These unit dose factors must be multiplied by the activity exhumed to calculate the first year dose. The radiation dose to this individual is the 50 year committed effective dose equivalent from one year of exposure.

The internal doses must be reduced in the event that the chemical form of the waste at the time of intrusion allows only a fraction of the material to be inhaled, ingested, or absorbed by plants. An example of this is vitrified waste material. After site closure, the radionuclides are decaying and the waste is releasing trapped activity. Thus, the activity concentration in the borehole cuttings and the fraction available depend on the elapsed time since closure. The external dose will be delivered regardless of the waste form. The total dose to the rural resident with a cow can be written as shown below.

$$H_{FARM} = \sum_{K} \left[ H_{X,K} + F_{AVAIL} \left( H_{B,K} + H_{G,K} \right) \right]$$

where,

$F_{AVAIL}$ = fraction of the waste that is available for ingestion, inhalation, and absorption by plants at the time of commercial farm scenario exposures (Table 11 assumes $F_{AVAIL}$=1 in the "Total" columns)

$H_{FARM}$ = total effective dose equivalent received in the commercial farm scenario from all radionuclides in the exhumed waste material, in mrem/y

$H_{B,K}$ = inhalation dose to the commercial farm scenario from the $K^{th}$ radionuclide, in mrem/y

$H_{G,K}$ = ingestion dose to the commercial farm scenario from the $K^{th}$ radionuclide, in mrem/y

$H_{X,K}$ = external dose to the commercial farm scenario from the $K^{th}$ radionuclide, in mrem/y

The scenario dose factors for the commercial farm assume that 1 Ci of each isotope comes out of the borehole. Unit factors listed in Table 11 are separated into the external component and the internal component. The column labeled "Total" is the sum of the internal and external in the event that 100% of the exhumed waste is available for inhalation and ingestion.

**Table 11. Unit Dose Factors for the Commercial Farm Scenario (mrem/y per Ci exhumed)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| H-3 | 1.89E-03 | 0.00E+00 | 1.89E-03 | Eu-155 | 9.94E-02 | 9.91E-02 | 2.67E-04 |
| Be-10 | 1.95E-03 | 5.98E-04 | 1.36E-03 | Gd-152 | 5.57E-01 | 0.00E+00 | 5.57E-01 |
| C-14 | 2.66E-04 | 7.47E-06 | 2.59E-04 | Tb-157 | 1.67E-03 | 1.63E-03 | 3.55E-05 |
| Na-22 | 6.22E+00 | 6.22E+00 | 1.34E-03 | Ho-166m | 5.17E+00 | 5.16E+00 | 2.70E-03 |
| Al-26 | 8.15E+00 | 8.15E+00 | 1.96E-03 | Re-187 | 1.29E-06 | 0.00E+00 | 1.29E-06 |
| Si-32+D | 9.92E-03 | 6.32E-03 | 3.60E-03 | Tl-204 | 2.57E-03 | 2.17E-03 | 4.02E-04 |
| Cl-36 | 1.55E-03 | 1.17E-03 | 3.82E-04 | Pb-205 | 2.14E-04 | 3.99E-06 | 2.10E-04 |
| K-40 | 4.79E-01 | 4.77E-01 | 2.30E-03 | Pb-210+D | 7.83E-01 | 3.33E-03 | 7.79E-01 |
| Ca-41 | 1.58E-04 | 0.00E+00 | 1.58E-04 | Bi-207 | 4.55E+00 | 4.55E+00 | 7.17E-04 |
| Ti-44+D | 6.66E+00 | 6.66E+00 | 4.02E-03 | Po-209 | 3.26E-01 | 9.94E-03 | 3.16E-01 |
| V-49 | 6.83E-06 | 0.00E+00 | 6.83E-06 | Po-210 | 1.63E-01 | 1.69E-05 | 1.63E-01 |
| Mn-53 | 1.45E-05 | 0.00E+00 | 1.45E-05 | Ra-226+D | 5.51E+00 | 5.32E+00 | 1.89E-01 |
| Mn-54 | 2.08E+00 | 2.08E+00 | 2.91E-04 | Ra-228+D | 3.52E+00 | 3.22E+00 | 3.09E-01 |
| Fe-55 | 7.31E-05 | 0.00E+00 | 7.31E-05 | Ac-227+D | 5.71E+00 | 1.06E+00 | 4.65E+00 |
| Fe-60+D | 2.76E-01 | 2.57E-01 | 1.96E-02 | Th-228+D | 5.01E+00 | 4.28E+00 | 7.30E-01 |
| Co-60 | 7.39E+00 | 7.39E+00 | 3.29E-03 | Th-229+D | 5.17E+00 | 8.28E-01 | 4.34E+00 |
| Ni-59 | 2.80E-05 | 0.00E+00 | 2.80E-05 | Th-230 | 6.46E-01 | 1.25E-03 | 6.45E-01 |
| Ni-63 | 7.63E-05 | 0.00E+00 | 7.63E-05 | Th-232 | 2.98E+00 | 9.43E-02 | 2.89E+00 |
| Se-79 | 1.04E-03 | 9.97E-06 | 1.03E-03 | Pa-231 | 3.37E+00 | 1.10E-01 | 3.26E+00 |
| Rb-87 | 6.93E-04 | 7.91E-05 | 6.14E-04 | U-232 | 7.14E-01 | 3.95E-01 | 3.19E-01 |
| Sr-90+D | 3.23E-02 | 1.30E-02 | 1.94E-02 | U-233 | 5.34E-02 | 7.71E-04 | 5.26E-02 |
| Zr-93 | 3.90E-04 | 6.26E-07 | 3.89E-04 | U-234 | 5.17E-02 | 2.22E-04 | 5.15E-02 |
| Nb-91 | 6.45E-03 | 6.38E-03 | 7.15E-05 | U-235+D | 4.58E-01 | 4.09E-01 | 4.83E-02 |
| Nb-93m | 1.29E-04 | 5.81E-05 | 7.07E-05 | U-236 | 4.88E-02 | 1.18E-04 | 4.87E-02 |
| Nb-94 | 4.77E+00 | 4.77E+00 | 9.62E-04 | U-238+D | 1.14E-01 | 6.60E-02 | 4.79E-02 |
| Mo-93 | 5.55E-04 | 3.29E-04 | 2.26E-04 | Np-237+D | 2.32E+00 | 5.85E-01 | 1.73E+00 |
| Tc-97 | 4.56E-04 | 4.34E-04 | 2.21E-05 | Pu-236 | 4.21E-01 | 7.74E-04 | 4.20E-01 |
| Tc-99 | 2.56E-04 | 6.71E-05 | 1.89E-04 | Pu-238 | 1.26E+00 | 8.49E-05 | 1.26E+00 |
| Ru-106+D | 5.53E-01 | 5.50E-01 | 3.06E-03 | Pu-239 | 1.38E+00 | 1.60E-04 | 1.38E+00 |
| Pd-107 | 4.65E-05 | 0.00E+00 | 4.65E-05 | Pu-240 | 1.38E+00 | 8.27E-05 | 1.38E+00 |
| Ag-108m+D | 4.86E+00 | 4.86E+00 | 9.97E-04 | Pu-241+D | 2.71E-02 | 2.03E-05 | 2.71E-02 |
| Cd-109+D | 1.46E-02 | 1.31E-02 | 1.49E-03 | Pu-242 | 1.32E+00 | 7.22E-05 | 1.32E+00 |
| Cd-113m | 2.33E-02 | 3.56E-04 | 2.29E-02 | Pu-244+D | 2.31E+00 | 1.01E+00 | 1.30E+00 |
| In-115 | 2.80E-02 | 2.24E-04 | 2.77E-02 | Am-241 | 1.45E+00 | 2.47E-02 | 1.43E+00 |
| Sn-121m+D | 1.49E-03 | 1.19E-03 | 3.03E-04 | Am-242m+D | 1.43E+00 | 3.64E-02 | 1.39E+00 |
| Sn-126+D | 5.97E+00 | 5.96E+00 | 2.82E-03 | Am-243+D | 1.91E+00 | 4.91E-01 | 1.42E+00 |
| Sb-125 | 1.17E+00 | 1.17E+00 | 4.12E-04 | Cm-242 | 3.20E-02 | 6.66E-05 | 3.20E-02 |
| Te-125m | 3.63E-03 | 3.45E-03 | 1.87E-04 | Cm-243 | 1.29E+00 | 3.17E-01 | 9.78E-01 |
| I-129 | 4.15E-02 | 7.25E-03 | 3.43E-02 | Cm-244 | 7.83E-01 | 7.04E-05 | 7.83E-01 |
| Cs-134 | 4.35E+00 | 4.34E+00 | 8.43E-03 | Cm-245 | 1.66E+00 | 1.90E-01 | 1.47E+00 |
| Cs-135 | 9.05E-04 | 2.16E-05 | 8.84E-04 | Cm-246 | 1.45E+00 | 6.56E-05 | 1.45E+00 |
| Cs-137+D | 1.70E+00 | 1.69E+00 | 6.21E-03 | Cm-247+D | 2.31E+00 | 9.72E-01 | 1.34E+00 |
| Ba-133 | 1.02E+00 | 1.02E+00 | 4.29E-04 | Cm-248 | 5.33E+00 | 4.96E-05 | 5.33E+00 |
| Ce-144+D | 1.31E-01 | 1.29E-01 | 2.43E-03 | Cm-250+D | 3.12E+01 | 8.25E-01 | 3.03E+01 |

**Table 11. Unit Dose Factors for the Commercial Farm Scenario (mrem/y per Ci exhumed)**

| Nuclide | Total | External | Internal | Nuclide | Total | External | Internal |
|---|---|---|---|---|---|---|---|
| Pm-147 | 2.24E-04 | 2.64E-05 | 1.97E-04 | Bk-247 | 2.08E+00 | 2.38E-01 | 1.85E+00 |
| Sm-147 | 1.88E-01 | 0.00E+00 | 1.88E-01 | Cf-248 | 1.13E-01 | 5.91E-05 | 1.13E-01 |
| Sm-151 | 1.14E-04 | 5.54E-07 | 1.14E-04 | Cf-249 | 2.82E+00 | 9.68E-01 | 1.86E+00 |
| Eu-150 | 4.39E+00 | 4.39E+00 | 1.37E-03 | Cf-250 | 8.23E-01 | 6.60E-05 | 8.23E-01 |
| Eu-152 | 3.35E+00 | 3.35E+00 | 1.26E-03 | Cf-251 | 2.19E+00 | 2.91E-01 | 1.90E+00 |
| Eu-154 | 3.64E+00 | 3.64E+00 | 1.76E-03 | Cf-252 | 3.91E-01 | 9.29E-05 | 3.91E-01 |

Notes:
- The radiation dose to this individual is the 50 year committed effective dose equivalent from the first year of exposure.
- These scenario dose factors must be multiplied by the activity exhumed by the well drilling, in curies.
- The "Total" column is the sum of the "Internal" and "External" columns. External and internal doses are separated because the waste matrix may prevent a portion of the exhumed activity from giving an internal dose.

## 3.5 ALL PATHWAYS FARMER

This scenario assumes that some of the waste materials have migrated into the groundwater. A subsistence farm located down gradient from the disposal site uses groundwater for domestic needs (drinking, cooking, showering), for irrigation (garden and pasture), and for watering livestock. The individual obtains one-fourth of his fruit and vegetable intake each year from a garden, and half of his meat, milk, poultry, and egg intake from his livestock. In addition, he inhales resuspended garden soil and ingests small amounts of it each day. His external dose comes from the contaminated soil near his dwelling.

The radiation dose to this individual is the 50 year committed effective dose equivalent from one year of exposure. No prior irrigation is assumed. Thus, the calculated annual doses are the lifetime dose that results from exposure during the first year of irrigation with contaminated water. In effect, the individual drills the well, uses it for one year, and then moves to another location. Alternate strategies for estimating dose allow contaminants to accumulate in the soil. The two leading methods are to calculate the doses after some period of accumulation, or to calculate the average annual dose during some period of exposure. Neither of these alternate methods is employed when calculating radiation dose factors. A comparison of the alternate method dose factors with the first year dose factors is shown in Appendix C.

The number of equations presented in this section is very large. It includes the pathways used for the post-intrusion residents. The intrusion equations are modified to reflect the contaminated irrigation water source. An additional version of this scenario assumes the contaminated water comes from the Columbia River and adds doses from shoreline external exposure and fish. Finally, the increased cancer risks that result from 30 years of continuous exposure are calculated. The various exposure amounts and other parameters are presented in Appendix A.

Soil Concentration for the All Pathways Farmer

In the irrigation scenarios, the garden and pasture are contaminated by the application of irrigation water. The soil contamination is averaged over the tilling depth, 0.15 m. The land surface area that is contaminated does not enter into the dose calculations. The important quantity is the amount of contaminated irrigation water that falls on the soil. The soil concentration is summarized in the equations below. The first equation is the average contaminant deposition rate during the irrigation period. The second equation is the soil concentration at the end of the first year of irrigation assuming no loss from the surface layer.

$$ID_K = \left(\frac{C_{W,K}\, I}{T_{irr}}\right)\left(\frac{10\,L}{m^2\,cm}\right)$$

$$C_{S,K} = \left(\frac{C_{W,K}\, I}{L_{Garden}\, \rho_{Garden}}\right)\left(\frac{10\,L}{m^2\,cm}\right)$$

where,

| | | |
|---|---|---|
| $10\ L/m^2cm$ | = | unit conversion factor. When 10 L of water is spread over an area of 1 $m^2$, it will have a depth of 1 cm. |
| $C_{S,K}$ | = | concentration of the $K^{th}$ radionuclide in irrigated soil at the end of the year with no decay or leaching, in Ci/kg |
| $C_{W,K}$ | = | concentration of the $K^{th}$ radionuclide in the irrigation water, in Ci/L |
| $L_{Garden}$ | = | thickness of the contaminated layer of surface soil in the garden, 0.15 m |
| I | = | amount of irrigation water applied to plants during the irrigation season, cm. For the Columbia River population, this is 63.5 cm. For all other scenarios this is 82.3 cm. (see Section A6.0) |
| $ID_K$ | = | average contaminant deposition rate for the $K^{th}$ radionuclide during the irrigation season, $Ci/m^2$ per year |
| $T_{irr}$ | = | length of irrigation season, 0.5 y |
| $\rho_{Garden}$ | = | average density of the surface soil, 1,500 $kg/m^3$ |

During the year, the concentration of each isotope in the garden and pasture first increases due to irrigation deposition, then decreases due to radioactive decay. During the non-irrigation half of the year, the precipitation is matched by evaporation, hence, there is no leaching. The contaminant deposition by irrigation water occurs only during the first half of the year. The surface soil concentration as a function of time during the first year is described mathematically using the equations below. The formula for later times is described next. Should the contaminant become airborne by evaporation, then both $\lambda_T$ and $\lambda_D$ are increased by a rate coefficient for surface emanation ($\lambda_E$).

$$C_{Soil,K}(t) = C_{S,K}\, F_{IS,K}(t)$$

$$F_{IS,K}(t) = \frac{1-\mathrm{Exp}(-\lambda_K t)}{\lambda_K T_{irr}} \qquad \text{for } 0 \le t \le T_{irr}$$

$$F_{IS,K}(t) = \frac{1-\mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}\mathrm{Exp}\left[-\lambda_{R,K}(t-T_{irr})\right] \qquad \text{for } T_{irr} < t \le 1\,y$$

$$\text{or} \quad F_{IS,K}(t) = \frac{\mathrm{Exp}(\lambda_{R,K}T_{irr}) - \mathrm{Exp}(-\lambda_{S,K}T_{irr})}{\lambda_K T_{irr}}\mathrm{Exp}(-\lambda_{R,K}t)$$

where,

$C_{S,K}$ = concentration of the $K^{th}$ radionuclide in irrigated soil at the end of the year with no decay or leaching, in Ci/kg

$C_{Soil,K}(t)$ = concentration of the $K^{th}$ radionuclide in irrigated soil as a function of time (t) during the year, in Ci/kg.

$F_{IS,K}(t)$ = fraction at time "t" of the total activity of the $K^{th}$ radionuclide deposited on the soil by 1 year of contaminated irrigation water that remains in the surface layer

Exp = the exponential function (e raised to some power)

$T_{irr}$ = irrigation period (the $1^{st}$ half of the year), 0.5 y

$\lambda_K$ = total removal constant for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

The soil concentration as a function of time for three radionuclides is shown in Figure 2. The soil concentration is normalized by the end-of-year soil concentration in the absence of decay and leaching ($C_{S,K}$). The first isotope (Th-232) illustrates the case with little decay and little leaching. Th-232 has a very long half life ($1.405 \times 10^{10}$ years) and a very large retardation in the surface soil ($K_d$=600,000 ml/g). Note that radioactive decay half lives are listed in Table A1, while the soil distribution coefficients ($K_d$) are listed in Table A43. The Th-232 concentration increases linearly during the irrigation season and is constant the remainder of the year.

The second isotope (Cl-36) has a long half life (300,992 years) but is only slightly retarded in the soil ($K_d$=1.0 ml/g). The Cl-36 concentration increases during the irrigation season, but not as much as Th-232 due to the loss from leaching. The Cl-36 concentration is constant during the non-irrigation season. The third isotope (Po-210) has a very short half life (138.38 days) but is significantly retarded in the soil ($K_d$=1,100 ml/g). The loss of Po-210 from the surface layer during the year is due almost entirely to its radioactive decay.

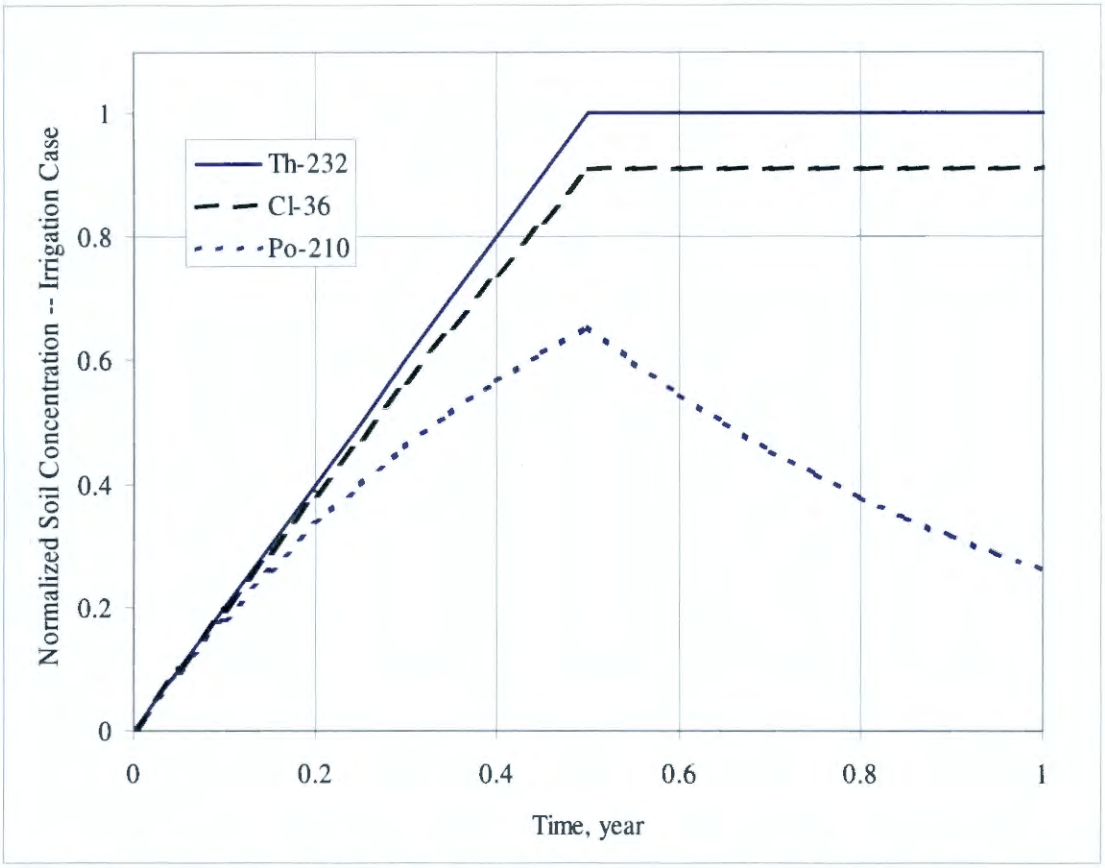


**Figure 2. Fraction of Irrigation-Deposited Contamination Present in Surface Soil**

After the first year, the equation for $F_{IS}$ is written as the sum of two contributions. The first is the previous years of irrigation ($T_{NY}$) after decay and leaching. The second is the function $F_{IS}$ during the remaining fraction of a year ($t-T_{NY}$). The equations are shown below. In later years the value of the function $F_{IS}(t)$ at the end of the year increases less and less. Conceptually, the amount that leaches and decays each year increases as the soil concentration increases. The amount that is added by irrigation each year remains fixed. The soil concentration and the annual dose are smallest in the first year after the irrigation begins because the year of intake begins with clean soil.

$$F_{IS,K}(t) = F_{IS,K}(t-T_{PY}) + F_{NS,K}(t-T_{PY})\, F_{IS,K}(1\,y)\, \frac{1-\left[F_{NS,K}(1\,y)\right]^{N_{PY}}}{1-F_{NS,K}(1\,y)}$$

$$\text{where} \quad t > 1\,y \quad \text{and} \quad T_{PY} = \text{Trunc}(t) \quad \text{and} \quad N_{PY} = \frac{T_{PY}}{1\,y}$$

where,

$F_{IS,K}(t)$ = fraction at time "t" of the total activity of the $K^{th}$ radionuclide deposited on the soil by 1 year of contaminated irrigation water that remains in the surface layer

$F_{NS,K}(t)$ = fraction at time "t" of the initial soil concentration of the $K^{th}$ radionuclide that remains in the surface layer given that the irrigation water adds no contaminants

$N_{PY}$ = number of years of leaching and decay prior to the year of interest, unitless.

$T_{PY}$ = period of leaching and decay prior to the year of interest, years.

Trunc(t) = spreadsheet function that removes the fractional part of t to calculate the number of years prior to the current year. For example, Trunc(9.9 y) = 9 y and Trunc(30 y) = 30 y

The concentration of tritium (regarded here as tritiated water) in the soil is based on the water content of the surface soil layer. Thus, the tritium concentration in the soil is constant during the irrigation season and decreases rapidly after that due to evaporation. Section A6.2 discusses the soil removal constants for tritium. The concentration of tritium in the soil during the irrigation season is shown below. The final ratio in the formula accounts for a small amount of dilution by natural precipitation.

$$C_{S,H\text{-}3} = C_{W,H\text{-}3}\left(\frac{\theta}{\rho_{Garden}}\right)\left(\frac{I}{I+P}\right)$$

Where,

$C_{S,H\text{-}3}$ = concentration of tritium in irrigated soil during the irrigation season, in Ci/kg

$C_{W,H\text{-}3}$ = tritium concentration in the irrigation water, in Ci/L

I = total irrigation water applied during the irrigation season, in cm. For the all pathways farmer it is 82.3 cm (32.4 inches). Nearly all of this is deposited during the 6 month period from April to September.

P = total precipitation, in centimeters, during the irrigation period. Over the period 1971 to 2000, the precipitation during the 6 month irrigation season (April to September) has been 5.766 cm (PNNL-15160).

$\rho_{Garden}$ = average density of the surface soil, 1.5 kg soil per liter of soil

$\theta$ = volumetric water content of the surface soil, liters of water per liter of soil. A value of 0.2 is assumed. Because the total soil porosity is about 0.4, the saturation ratio is about 50%.

External Dose to the All Pathways Farmer

The external dose received by the farmer each day during the irrigation season increases as radionuclides accumulate in the surface soil. During the non-irrigation season the dose rate decreases slowly because the soil contamination is undergoing radioactive decay without leaching. Note that the effective external exposure time is greater than in the intruder scenarios because the contamination is more widespread. In addition, the farmer is exposed throughout the year. Section A3.3 discusses external exposure times. The external dose is calculated using the equation shown below. The decay and leaching factor ($F_{X,I,K}$) is the time-integral of the soil concentration fraction shown in Figure 2. The formula has two parts corresponding to the irrigation and non-irrigation seasons. The first part of the formula is the time integral during the irrigation period. The second part is the product of the factor representing soil concentration at the end of the irrigation period and the time integral during the non-irrigation period.

$$H_{X,K} = C_{S,K}\, \rho_{GARDEN}\, L_{GARDEN}\, D_{X,K}\, T_X\, F_{X,I,K}$$

$$F_{X,I,K} = \frac{\lambda_K T_{irr} - 1 + \mathrm{Exp}(-\lambda_K T_{irr})}{(1\ \mathrm{y})\lambda_K^2\, T_{irr}} + \left(\frac{1-\mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}\right)\left(\frac{1-\mathrm{Exp}(-\lambda_{R,K} T_{no})}{(1\ \mathrm{y})\lambda_{R,K}}\right)$$

where,

$C_{S,K}$ = concentration of the $K^{th}$ radionuclide in irrigated soil at the end of the year with no decay or leaching, in Ci/kg

$D_{X,K}$ = external dose rate factor for the $K^{th}$ radionuclide to a person standing on a layer 0.15 m thick and of great extent in all directions, in mrem/h per Ci/m$^2$. Values are listed in Table A28.

$F_{X,I,K}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the full year (X=external calculation, I=the irrigation water is contaminated, and K=radionuclide index). If $\lambda_K$ is very small, $F_{X,I,K}$=0.75.

$H_{X,K}$ = external dose to the all pathways farmer from the $K^{th}$ radionuclide, mrem/y

$L_{GARDEN}$ = thickness of the contaminated layer of surface soil in the garden, 0.15 m

$T_{irr}$ = irrigation period (the 1$^{st}$ half of the year), 0.5 y

$T_{no}$ = no irrigation period (the 2$^{nd}$ half of the year), $T_{irr} + T_{no} = 1$ y

$T_X$ = time of exposure each year from Table A18, 4,120 h/y

$\lambda_K$ = total removal constant for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

$\rho_{GARDEN}$ = average density of the garden, 1,500 kg/m$^3$

Inhalation Dose to the All Pathways Farmer

The gardener is exposed to airborne particulate during the year, as described in Section A3.2. Some of the material inhaled is contaminated soil (539 mg/y from Table A10) while the rest is from the water becoming airborne (0.0011 L/y from Table A16). The inhalation intakes occur over the course of one year. The concentration of radionuclides in the suspended particulate is assumed to be the same as the average concentration of radionuclides in the soil. The total inhalation dose to the farmer is calculated using the formula below. Tritium is not calculated using this formula. Since the tritium is in the form of tritiated water (HTO), the water inhalation calculation for tritium includes all soil contributions.

$$H_{B,K} = \left(C_{S,K}\, M_B\, F_{X,I,K} + C_{W,K}\, V_B\right) D_{B,K}$$

where,

$C_{S,K}$ = concentration of the $K^{th}$ radionuclide in irrigated soil at the end of the year with no decay or leaching, in Ci/kg

$C_{W,K}$ = concentration of the $K^{th}$ radionuclide in the irrigation water, in Ci/L

$D_{B,K}$ = inhalation dose factor for the $K^{th}$ radionuclide from Table A25, in mrem/pCi inhaled

$F_{X,I,K}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the full year (X=external calculation, I=the irrigation water is contaminated, and K=radionuclide index). If $\lambda_K$ is very small, $F_{X,I,K}$=0.75.

$H_{B,K}$ = inhalation dose to the all pathways farmer from the $K^{th}$ radionuclide, mrem/y

$M_B$ = total mass of soil inhaled during the year from Table A10, $5.39 \times 10^{-4}$ kg/y

$V_B$ = total volume of water inhaled during the year from Table A16, 0.0011 L/y

Ingestion Dose to the All Pathways Farmer

In addition to the small amounts of soil that are ingested in the course of the year, the farmer also eats fruits and vegetables from his garden, and meat, milk, poultry, and eggs from his livestock. The ingestion dose for one nuclide from these intakes is shown below. Note the summations over plant types and animal types. The decay and leaching factors for plants and animals are not shown in this equation because the direct deposition from overhead irrigation portion has a different factor than the root uptake and rain splash terms. These decay and leaching factors for the ingestion dose are included in the description of the plant and animal concentration (next equations).

$$H_{G,K} = \left( C_{S,K}\, M_G\, F_{X,I,K} + \sum_p C_{V,p,K}\, M_{V,p} + \sum_q C_{A,q,K}\, M_{A,q} + C_{W,K}\, V_G \right) D_{G,K}$$

where,

$C_{A,q,K}$ = concentration of the $K^{th}$ radionuclide in animal product type q, in Ci/kg

$C_{S,K}$ = concentration of the $K^{th}$ radionuclide in irrigated soil at the end of the year with no decay or leaching, in Ci/kg

$C_{V,p,K}$ = time-integrated concentration of the $K^{th}$ radionuclide in garden produce type p, in Ci/kg wet weight

$C_{W,K}$ = concentration of the $K^{th}$ radionuclide in the irrigation water, in Ci/L

$D_{G,K}$ = ingestion dose factor for the $K^{th}$ radionuclide from Table A24, in mrem/pCi ingested

$F_{X,I,K}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the full year (X=external calculation, I=the irrigation water is contaminated, and K=radionuclide index). If $\lambda_K$ is very small, $F_{X,I,K}$=0.75.

$H_{G,K}$ = ingestion dose to the all pathways farmer from the $K^{th}$ radionuclide, mrem/y

p = index to the four types of garden produce, i.e., fruit, protected vegetables, exposed vegetables, and grains

q = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

$M_{A,q}$ = mass of animal product type q eaten during the year, in kg/y. These amounts are 50% of the values shown in Table A4 under the heading "USDA".

$M_G$ = total mass of soil ingested during the year from Table A8, 0.0365 kg/y

$M_{V,p}$ = mass of garden produce type p eaten by the farmer during the year, in kg/y. These amounts are 25% of the values shown in Table A4 under the heading "USDA". Because grains consumed are not typically irrigated, the mass of grains is set to zero.

$V_G$ = total volume of water ingested during the year from Table A4, 545 L/y

Concentration in Garden Produce

The garden produce becomes contaminated by root uptake from the soil and by soil adhering to the foliage. In addition, overhead irrigation puts some contamination directly on the foliage. All three mechanisms of contamination also apply to the plants grown to feed the livestock. The concentration of a radionuclide in garden produce or animal fodder is shown in the equations below. Note that some parameters depend on the food type, while others are the same for all types. Leafy vegetables are consumed throughout the irrigation season, while other garden produce is harvested at the end of the growing season and consumed over a 90 day period. Vegetation fed to beef cattle has a decay and leaching factor based on slaughter at the end of the irrigation season. Vegetation fed to milk cows has a decay and leaching factor based on continuous consumption throughout the year. Stored feed for all the animals is harvested at the end of the growing season to maximize contamination levels. Note that the conversion of time units for $T_{W,p}$ and $ID_K$ is not explicitly shown in the first equation.

$$C_{V,p,K} = F_{V,I,K,p}\, C_{S,K}\left(F_{DRY,p}\, B_{V,p,K} + \frac{J_{SPLASH}\, F_{INT,p}\, F_{TRANS,p}\, T_{W,p}}{Y_{V,p}}\right) + \frac{ID_K\, F_{Direct,p}\, F_{TRANS,p}\, T_{W,p}}{Y_{V,p}}$$

$$F_{V,I,K,Leafy} = \frac{\lambda_K T_{irr} - 1 + \mathrm{Exp}(-\lambda_K T_{irr})}{(\lambda_K T_{irr})^2} \quad \text{and} \quad T_{W,p} = \frac{1 - \mathrm{Exp}(-\lambda_W T_{GROW,p})}{\lambda_W}$$

$$F_{V,I,K,Other} = \left(\frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}\right)\left(\frac{1 - \mathrm{Exp}(-\lambda_{R,K} T_{veg})}{\lambda_{R,K} T_{veg}}\right)$$

$$F_{V,I,K,Fresh(beef)} = \frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}$$

$$F_{V,I,K,Fresh(other)} = \frac{\lambda_K T_{irr} - 1 + \mathrm{Exp}(-\lambda_K T_{irr})}{(1\,y)\lambda_K^2\, T_{irr}} + \left(\frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}\right)\left(\frac{1 - \mathrm{Exp}(-\lambda_{R,K} T_{no})}{(1\,y)\lambda_{R,K}}\right)$$

$$F_{V,I,K,Stored(beef)} = \left(\frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}\right)\mathrm{Exp}(-\lambda_{R,K} T_{sto})$$

$$F_{V,I,K,Stored(other)} = \left(\frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}}\right)\mathrm{Exp}(-\lambda_{R,K} T_{sto})\left(\frac{1 - \mathrm{Exp}(-\lambda_{R,K} T_{an})}{\lambda_{R,K} T_{an}}\right)$$

where,

$B_{V,p,K}$ = soil-to-plant transfer factor for the $K^{th}$ radionuclide in plant type p from Table A40

$C_{S,K}$ = concentration of the $K^{th}$ radionuclide in irrigated soil at the end of the year with no decay or leaching, in Ci/kg

$C_{V,p,K}$ = time-integrated radionuclide concentration in plant type p, in Ci/kg wet weight

$F_{Direct,p}$ = interception fraction for contaminants in irrigation water on exposed surfaces of garden produce type p, see Table A42

$F_{DRY,p}$ = dry-to-wet ratio for plant type p from Table A42

$F_{INT,p}$ = interception fraction for airborne dust on exposed surfaces of plant type p, from Table A42

$F_{TRANS,p}$ = translocation factor from exposed surfaces to the edible portion of plant type p, from Table A42

$F_{V,I,K,p}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the full year (V=plant calculation, I=the irrigation water is contaminated, K=radionuclide index, and p=plant index). Specific cases are shown for leafy vegetables, all other vegetables, fresh fodder for beef cattle and other animal products (milk, poultry, and eggs), and stored feed for beef and the other products.

$ID_K$ = irrigation deposition rate for the $K^{th}$ radionuclide during the irrigation season, $Ci/m^2$ per year (1 y = 365 d)

$J_{SPLASH}$ = average soil deposition rate due to rain splash (see Section A5.2), $2.7 \times 10^{-4}$ $kg/m^2$ per day

p = index to the various types of garden produce (leafy, protected, fruit and grain) and animal fodder (fresh and stored fodder for beef, milk, poultry and egg) listed in Table A42

$T_{an}$ = consumption period for the animal fodder, 90 d (0.2466 y)

$T_{GROW,p}$ = growing period of plant type p from Table A42

$T_{irr}$ = irrigation period (the $1^{st}$ half of the year), 0.5 y

$T_{no}$ = no irrigation period (the $2^{nd}$ half of the year), $T_{irr} + T_{no} = 1$ y

$T_{sto}$ = storage period for stored fodder, 90 d (0.2466 y)

$T_{veg}$ = consumption period for all garden produce except leafy vegetables, 90 d (0.2466 y)

$T_{W,p}$ = effective exposure time for plant type p, in days

$Y_{V,p}$ = yield of plant type p, from Table A42, in $kg(wet)/m^2$

$\lambda_K$ = total removal constant for the $K^{th}$ radionuclide, per year, $\lambda_K = \lambda_{S,K} + \lambda_{R,K}$

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ radionuclide, fraction removed from the surface layer of soil, per year (see Table A43)

$\lambda_W$ = weathering constant for all type of plants, 0.04951 per day. This is based on a weathering half time of 14 days.

The tritium concentration in garden produce and animal fodder is calculated using the equilibrium model equation shown below. The first ratio expresses the water concentration in Ci/kg water. The factor 8.94 is calculated from the ratio of the atomic weights of water and hydrogen. It is used to convert the hydrogen fractions ($F_{H,p}$) to water fractions. Since the hydrogen fractions include organically bound hydrogen as well as water, the produce concentration is a bounding value. The ratio containing the natural precipitation amount (P) adjusts for the presence of uncontaminated water in the environment.

$$C_{V,p,H\text{-}3} = \left(\frac{C_{W,H\text{-}3}}{\rho_W}\right)\left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right)F_{H,p}\left(\frac{1}{P+I}\right)F_{V,I,H\text{-}3,p}$$

$$F_{V,I,H\text{-}3,Leafy} = 1 \quad \text{and} \quad F_{V,I,H\text{-}3,Other} = \frac{1-\text{Exp}\left(-\lambda_{R,H\text{-}3}\,T_{veg}\right)}{\lambda_{R,H\text{-}3}\,T_{veg}}$$

$$F_{V,I,H\text{-}3,Fresh(beef)} = 1 \quad \text{and} \quad F_{V,I,H\text{-}3,Fresh(other)} = 0.5 + \left(\frac{1-\text{Exp}\left(-\lambda_{N,H\text{-}3}\,T_{no}\right)}{(1\text{ y})\lambda_{N,H\text{-}3}}\right)$$

$$F_{V,I,H\text{-}3,Stored(beef)} = \text{Exp}\left(-\lambda_{R,K}\,T_{sto}\right)$$

$$F_{V,I,H\text{-}3,Stored(other)} = \text{Exp}\left(-\lambda_{R,K}\,T_{sto}\right)\left(\frac{1-\text{Exp}\left(-\lambda_{N,H\text{-}3}\,T_{an}\right)}{\lambda_{N,H\text{-}3}\,T_{an}}\right)$$

where,

$C_{V,p,H\text{-}3}$ = time-integrated tritium concentration in garden produce type p, in Ci/kg wet weight

$C_{W,H\text{-}3}$ = tritium concentration in the irrigation water, in Ci/L

$F_{H,p}$ = mass fraction of hydrogen in garden produce type p from Table A37, in kg hydrogen per kg plant (wet)

$F_{V,I,H\text{-}3,p}$ = factor that results from the time integral of the dose rate for tritium over the full year (V=plant calculation, I=the irrigation water is contaminated, H-3=tritium, and p=plant type). Specific cases are shown for leafy vegetables, all other vegetables, fresh fodder for beef cattle, fresh fodder for all other animal products, and stored feed for beef and all other animal products.

I = total irrigation water applied during the irrigation season, in cm. For the all pathways farmer it is 82.3 cm (32.4 inches). Nearly all of this is deposited during the 6 month period from April to September.

P = total precipitation, in centimeters, during the irrigation period. Over the period 1971 to 2000, the precipitation during the 6 month irrigation season (April to September) has been 5.766 cm (PNNL-15160).

p = index to the various types of garden produce (leafy, protected, fruit and grain) and animal fodder (fresh and stored for beef, milk, poultry and egg) listed in Table A42

$T_{an}$ = consumption period for the animal fodder, 90 d (0.2466 y)

$T_{no}$ = no-irrigation period (the 2nd half of the year), $T_{no}$ = 0.5 y

$T_{sto}$ = storage period for stored fodder, 90 d (0.2466 y)

$T_{veg}$ = consumption period for all garden produce except leafy vegetables, 90 d (0.2466 y)

$\lambda_{N,H\text{-}3}$ = total removal constant for tritium during the no-irrigation period, 8.032 per year

$\lambda_{R,H\text{-}3}$ = radioactive decay constant for tritium, 0.05622 per year. This is calculated as ln(2)=0.6931472 divided by the material half life, 12.33 years.

$\rho_W$ = density of water, 1.0 kg/L

Concentration in Animal Products

Animal products (meat, milk, poultry, and eggs) become contaminated when the animals ingest soil, water, and fodder. The soil ingested by the animal uses the same decay and leaching factor as the fresh fodder. The beef cow is slaughtered at the end of the irrigation period and consumed over a period of time ($T_{beef}$). However, the milk and the chickens (meat and eggs) are consumed throughout the year with little storage time. The concentration in the animal product is calculated using the equations below.

$$C_{A,q,K} = B_{A,q,K}\left(C_{S,K}\, M_{S,q}\, F_{V,I,K,q(fresh)} + \sum_p C_{V,p,K}\, M_{V,p,q} + C_{W,K}\, V_{W,q}\right) F_{A,K,q}$$

$$F_{A,K,Beef} = \frac{1 - \mathrm{Exp}\left(-\lambda_{R,K} T_{beef}\right)}{\lambda_{R,K} T_{beef}} \quad \text{and} \quad F_{A,K,Other} = 1$$

where,

$B_{A,q,K}$ = animal transfer factor for the $K^{th}$ radionuclide into animal product type q from Table A36, in day/kg

$C_{A,q,K}$ = time-integrated concentration of the $K^{th}$ radionuclide in animal product type q, in Ci/kg

$C_{S,K}$ = concentration of the $K^{th}$ radionuclide in irrigated soil at the end of the year with no decay or leaching, in Ci/kg

$C_{V,p,K}$ = time-integrated radionuclide concentration in plant type p, in Ci/kg wet weight

$C_{W,K}$ = concentration of the $K^{th}$ radionuclide in the irrigation water, in Ci/L

$F_{A,K,q}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the full year (A=animal calculation, K=radionuclide index, and q=animal type).

$F_{V,I,K,q(fresh)}$ = factor that results from the time integral of the dose rate for the $K^{th}$ radionuclide over the full year (V=fodder calculation, I=the irrigation water is contaminated, K=radionuclide index, and q(fresh)=fresh fodder for animal type q). The soil ingested by beef cattle uses the same decay and leaching factor ($F_{V,I,K,Fresh(beef)}$) as the fresh fodder used by beef cattle. The soil ingested by other animals uses the same decay and leaching factor ($F_{V,I,K,Fresh(milk)}$) as the fresh fodder used by the other animals.

$M_{S,q}$ = daily mass of soil ingested by animal type q in Table A35, in kg/d

$M_{V,p,q}$ = daily mass of animal fodder type p eaten by animal type q, in kg (wet)/d. These amounts are shown in Table A35.

p = index to the various types of animal fodder shown in Table A42

q = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

$T_{beef}$ = consumption period for beef, 120 d (0.3288 y)

$V_{W,q}$ = daily volume of water ingested by animal type q from Table A35, in L/d

$\lambda_{R,K}$ = radioactive decay constant for the $K^{th}$ radionuclide, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

The concentration of tritium in animal products is calculated from an equilibrium model very similar to the one shown in Section 3.3. The ratio of contaminated water mass ingested per day to total mass of water ingested per day is closer to 1.0 in the irrigation cases because the animal's drinking water is contaminated. The drinking water is the bulk of the total water ingested each day. The equation below shows the calculation of tritium concentration in animal products. The time-integration factors are the same as shown above for tritium concentration in vegetation.

$$C_{A,q,H\text{-}3} = \left(\frac{C_{W,H\text{-}3}}{\rho_W}\right)\left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right) F_{H,q} \left(\frac{M_{W,C,q}}{M_{W,T,q}}\right) F_{A,H\text{-}3,q}$$

$$M_{W,C,q} = \rho_W\, V_{W,q} + \left(\frac{I}{P+I}\right)\left(\frac{\theta\, \rho_W}{\rho_{Garden}}\right) M_{S,q}\, F_{V,I,H\text{-}3,q(fresh)}$$

$$+ \left(\frac{I}{P+I}\right)\sum_p \left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right) F_{H,p}\, F_{V,I,H\text{-}3,p}\, M_{V,p,q}$$

$$M_{W,T,q} = \rho_W\, V_{W,q} + \left(\frac{\theta\, \rho_W}{\rho_{Garden}}\right) M_{S,q} + \sum_p \left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right) F_{H,p}\, M_{V,p}$$

where,

$C_{A,q,H\text{-}3}$ = time-integrated tritium concentration in animal product type q, in Ci/kg

$C_{W,K}$ = concentration of the $K^{th}$ radionuclide in the irrigation water, in Ci/L

$F_{A,H\text{-}3,q}$ = factor that results from the time integral of the dose rate for tritium over the full year (A=animal calculation, H-3=tritium, and q=animal type).

$F_{H,p}$ = mass fraction of hydrogen in animal fodder type p from Table A37, in kg hydrogen per kg plant (wet)

$F_{H,q}$ = mass fraction of hydrogen in animal product type q from Table A37, in kg hydrogen per kg of the animal product

$F_{V,I,H\text{-}3,p}$ = factor that results from the time integral of the dose rate for tritium over the full year (V=plant calculation, I=the irrigation water is contaminated, H-3=tritium, and p=plant type). Equations are given in the preceding pages for calculating tritium concentration in vegetation.

I = total irrigation water applied during the irrigation season, in cm. For the all pathways farmer it is 82.3 cm (32.4 inches). Nearly all of this is deposited during the 6 month period from April to September.

$M_{S,q}$ = daily mass of soil ingested by animal type q in Table A35, in kg/d

$M_{V,p,q}$ = daily mass of animal fodder type p eaten by animal type q, in kg (wet)/d. These amounts are shown in Table A35.

$M_{W,C,q}$ = mass of contaminated water ingested daily by the animal, in kg/d

$M_{W,T,q}$ = total mass of water ingested daily by the animal, in kg/d

$P$ = total precipitation, in centimeters, during the irrigation period. Over the period 1971 to 2000, the precipitation during the 6 month irrigation season (April to September) has been 5.766 cm (PNNL-15160).

$p$ = index to the types of animal fodder, i.e., fresh pasture grass and stored hay and grain for beef, milk, poultry, and eggs

$q$ = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

$V_{W,q}$ = daily volume of water ingested by animal type q from Table A35, in L/d

$\rho_{Garden}$ = average density of the surface soil, 1.5 kg soil per liter of soil

$\rho_W$ = density of water, 1.0 kg water per liter of water

$\theta$ = volumetric water content of the surface soil, liters of water per liter of soil. A value of 0.2 is assumed.

Note that the equation for the concentration of tritium in the animal product can be rearranged to indicate an equilibrium concentration ratio for tritium in the animal product. This equation has the same form as the equation used for all the other radionuclides. The equilibrium transfer factors ($B_{A,q,H\text{-}3}$) are identical to the ones shown for the rural pasture scenario in Section 3.3.

$$C_{A,q,H\text{-}3} = B_{A,q,H\text{-}3}\left(C_{S,H\text{-}3}\, M_{S,q}\, F_{V,I,H\text{-}3,q(fresh)} + \sum_p C_{V,p,H\text{-}3}\, M_{V,p,q} + C_{W,H\text{-}3}\, V_{W,q}\right) F_{A,H\text{-}3,q}$$

$$B_{A,q,H\text{-}3} = \left(\frac{8.94\text{ kg water}}{\text{kg hydrogen}}\right)\left(\frac{F_{H,q}}{M_{W,T,q}}\right)$$

The simplified model for the milk cow and chicken has them foraging throughout the year. In reality, most of the fresh forage is consumed during the irrigation season, with a heavier emphasis on stored feed and grain during the non-irrigation season. Supposing that some fraction, say 80% of the fresh forage was consumed during the irrigation season. Then the direct deposition portion of $C_{V,p,K}$ would need to be multiplied by this fraction because the plants consumed by the animals during the non-irrigation season would not receive direct deposition. This would lower $C_{V,p,K}$. However, the integration factor, $F_{V,I,K,Fresh(other)}$, would need to be adjusted to move more of the fresh fodder consumption into the first half of the year. This would lower the integration factor (except for tritium, which rapidly disappears from the soil during the non-irrigation season). Thus the simplified milk cow and chicken model tends to overestimate the resulting ingestion doses.

Total Dose to the All Pathways Farmer -- Well Water

The total dose to the all pathways farmer is the sum of the external (from soil), inhalation (from dust and showers), and ingestion doses (from water, soil, vegetables, and animal products). With the exception of tritium (H-3), absorption of radionuclides through the skin is not a significant pathway, as discussed in Section A3.4.1. The source of contaminated water is a well to groundwater. Scenario dose factors for the all pathways farmer who uses well water are presented in Table 12 in the "Total" column. This column shows the first year effective dose equivalent per pCi/L in the groundwater. These unit dose factors must be multiplied by the

groundwater concentration to calculate the first year dose. The radiation dose to this individual is the 50 year committed effective dose equivalent from one year of exposure.

Table 12 also shows the dose from only the drinking water consumed by the all pathways farmer (545 L/y, from Table A4). The third column shows the ratio of the total dose to the drinking water dose. Large ratios indicate that most of the dose comes from pathways other than drinking water. For most radionuclides, the drinking water pathway contributes the bulk of the total dose.

**Table 12. Unit Dose Factors for the All Pathway Farmer (mrem/y per pCi/L) Using Well Water**

| Nuclide | Total | Drinking Water | Ratio | Nuclide | Total | Drinking Water | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 4.75E-05 | 3.49E-05 | 1.36 | Eu-155 | 1.24E-03 | 8.33E-04 | 1.49 |
| Be-10 | 2.95E-03 | 2.54E-03 | 1.16 | Gd-152 | 1.05E-01 | 8.75E-02 | 1.20 |
| C-14 | 3.68E-03 | 1.14E-03 | 3.23 | Tb-157 | 8.58E-05 | 6.76E-05 | 1.27 |
| Na-22 | 3.83E-02 | 6.25E-03 | 6.12 | Ho-166m | 1.71E-02 | 4.40E-03 | 3.90 |
| Al-26 | 2.81E-02 | 7.95E-03 | 3.54 | Re-187 | 7.54E-06 | 5.18E-06 | 1.46 |
| Si-32+D | 6.90E-03 | 5.97E-03 | 1.16 | Tl-204 | 3.78E-03 | 1.83E-03 | 2.06 |
| Cl-36 | 2.33E-02 | 1.65E-03 | 14.1 | Pb-205 | 1.04E-03 | 8.89E-04 | 1.17 |
| K-40 | 2.32E-02 | 1.01E-02 | 2.29 | Pb-210+D | 3.49E+00 | 2.93E+00 | 1.19 |
| Ca-41 | 1.03E-03 | 6.94E-04 | 1.48 | Bi-207 | 1.39E-02 | 2.98E-03 | 4.66 |
| Ti-44+D | 4.80E-02 | 1.34E-02 | 3.59 | Po-209 | 1.83E+00 | 1.29E+00 | 1.41 |
| V-49 | 3.95E-05 | 3.35E-05 | 1.18 | Po-210 | 1.41E+00 | 1.04E+00 | 1.36 |
| Mn-53 | 6.80E-05 | 5.89E-05 | 1.15 | Ra-226+D | 9.08E-01 | 7.22E-01 | 1.26 |
| Mn-54 | 6.02E-03 | 1.51E-03 | 3.99 | Ra-228+D | 9.76E-01 | 7.84E-01 | 1.25 |
| Fe-55 | 5.16E-04 | 3.31E-04 | 1.56 | Ac-227+D | 9.05E+00 | 8.04E+00 | 1.13 |
| Fe-60+D | 1.33E-01 | 8.31E-02 | 1.60 | Th-228+D | 5.05E-01 | 4.42E-01 | 1.14 |
| Co-60 | 3.75E-02 | 1.47E-02 | 2.56 | Th-229+D | 2.47E+00 | 2.19E+00 | 1.13 |
| Ni-59 | 2.74E-04 | 1.14E-04 | 2.40 | Th-230 | 3.36E-01 | 2.98E-01 | 1.13 |
| Ni-63 | 7.53E-04 | 3.15E-04 | 2.39 | Th-232 | 1.68E+00 | 1.49E+00 | 1.13 |
| Se-79 | 1.06E-02 | 4.74E-03 | 2.25 | Pa-231 | 6.48E+00 | 5.77E+00 | 1.12 |
| Rb-87 | 6.60E-03 | 2.68E-03 | 2.46 | U-232 | 8.72E-01 | 7.14E-01 | 1.22 |
| Sr-90+D | 1.34E-01 | 8.35E-02 | 1.60 | U-233 | 1.92E-01 | 1.57E-01 | 1.22 |
| Zr-93 | 1.01E-03 | 9.03E-04 | 1.12 | U-234 | 1.88E-01 | 1.54E-01 | 1.22 |
| Nb-91 | 3.34E-04 | 2.84E-04 | 1.18 | U-235+D | 1.78E-01 | 1.46E-01 | 1.22 |
| Nb-93m | 3.20E-04 | 2.84E-04 | 1.12 | U-236 | 1.78E-01 | 1.46E-01 | 1.22 |
| Nb-94 | 1.53E-02 | 3.89E-03 | 3.93 | U-238+D | 1.78E-01 | 1.46E-01 | 1.22 |
| Mo-93 | 1.02E-03 | 7.34E-04 | 1.38 | Np-237+D | 2.77E+00 | 2.42E+00 | 1.15 |
| Tc-97 | 2.01E-04 | 9.34E-05 | 2.16 | Pu-236 | 7.12E-01 | 6.35E-01 | 1.12 |
| Tc-99 | 1.71E-03 | 7.97E-04 | 2.15 | Pu-238 | 1.96E+00 | 1.74E+00 | 1.12 |
| Ru-106+D | 3.09E-02 | 1.49E-02 | 2.07 | Pu-239 | 2.17E+00 | 1.93E+00 | 1.12 |
| Pd-107 | 1.58E-04 | 8.15E-05 | 1.94 | Pu-240 | 2.17E+00 | 1.93E+00 | 1.12 |

**Table 12. Unit Dose Factors for the All Pathway Farmer (mrem/y per pCi/L) Using Well Water**

| Nuclide | Total | Drinking Water | Ratio | Nuclide | Total | Drinking Water | Ratio |
|---|---|---|---|---|---|---|---|
| Ag-108m+D | 1.64E-02 | 4.15E-03 | 3.95 | Pu-241+D | 4.19E-02 | 3.73E-02 | 1.12 |
| Cd-109+D | 8.88E-03 | 7.16E-03 | 1.24 | Pu-242 | 2.06E+00 | 1.83E+00 | 1.12 |
| Cd-113m | 1.10E-01 | 8.77E-02 | 1.25 | Pu-244+D | 2.04E+00 | 1.81E+00 | 1.12 |
| In-115 | 1.13E-01 | 8.59E-02 | 1.32 | Am-241 | 2.23E+00 | 1.98E+00 | 1.12 |
| Sn-121m+D | 3.47E-03 | 1.23E-03 | 2.83 | Am-242m+D | 2.16E+00 | 1.92E+00 | 1.12 |
| Sn-126+D | 4.61E-02 | 1.15E-02 | 4.03 | Am-243+D | 2.22E+00 | 1.98E+00 | 1.13 |
| Sb-125 | 4.37E-03 | 1.53E-03 | 2.85 | Cm-242 | 6.95E-02 | 6.25E-02 | 1.11 |
| Te-125m | 2.57E-03 | 2.00E-03 | 1.29 | Cm-243 | 1.54E+00 | 1.37E+00 | 1.13 |
| I-129 | 4.00E-01 | 1.50E-01 | 2.66 | Cm-244 | 1.24E+00 | 1.10E+00 | 1.12 |
| Cs-134 | 1.19E-01 | 3.99E-02 | 2.97 | Cm-245 | 2.29E+00 | 2.04E+00 | 1.13 |
| Cs-135 | 1.10E-02 | 3.85E-03 | 2.86 | Cm-246 | 2.27E+00 | 2.02E+00 | 1.13 |
| Cs-137+D | 8.14E-02 | 2.72E-02 | 2.99 | Cm-247+D | 2.10E+00 | 1.86E+00 | 1.13 |
| Ba-133 | 4.50E-03 | 1.85E-03 | 2.43 | Cm-248 | 8.35E+00 | 7.42E+00 | 1.12 |
| Ce-144+D | 1.31E-02 | 1.15E-02 | 1.14 | Cm-250+D | 4.76E+01 | 4.23E+01 | 1.13 |
| Pm-147 | 6.94E-04 | 5.71E-04 | 1.22 | Bk-247 | 2.88E+00 | 2.56E+00 | 1.12 |
| Sm-147 | 1.24E-01 | 1.01E-01 | 1.23 | Cf-248 | 2.19E-01 | 1.82E-01 | 1.20 |
| Sm-151 | 2.60E-04 | 2.12E-04 | 1.23 | Cf-249 | 3.16E+00 | 2.58E+00 | 1.23 |
| Eu-150 | 1.42E-02 | 3.47E-03 | 4.11 | Cf-250 | 1.42E+00 | 1.16E+00 | 1.22 |
| Eu-152 | 1.19E-02 | 3.53E-03 | 3.38 | Cf-251 | 3.24E+00 | 2.64E+00 | 1.23 |
| Eu-154 | 1.46E-02 | 5.20E-03 | 2.80 | Cf-252 | 7.18E-01 | 5.91E-01 | 1.22 |

Notes:

- The radiation dose to this individual is the 50 year committed effective dose equivalent from one year of exposure.
- These scenario dose factors must be multiplied by the groundwater concentration.
- The "Total" column is for the full scenario. The column "Drinking Water" shows only the drinking water dose. The "Ratio" column is the "Total" divided by the "Drinking Water" doses. Large ratios mean that drinking water is a minor contributor to the total dose.

Additional Pathways for the All Pathways Farmer Using Columbia River Water

If the all pathways farmer obtains all of his water from the Columbia River there are additional dose pathways due to the contamination of fish taken from the river, and exposure to shoreline sediments. All of the pathways discussed previously still apply. The additional pathways make the unit dose factors larger. The sediments add ingestion of trace amounts of soil (shoreline sediment), and external dose from proximity to the shoreline sediments.

The ingestion dose from fish consumption is the product of the river water concentration for a radionuclide, the bioaccumulation factor for that radionuclide in fish, the mass of fish consumed annually, and the ingestion dose factor for that radionuclide. Because the farmer eats uncontaminated fish as well as fish from the Columbia River, the contaminated fish intake is half the value shown in Table A4. The dose from contaminated fish is calculated using the equation below.

$$H_{F,K} = C_{W,K}\ B_{F,K}\ M_F\ D_{G,K}$$

where,

$B_{F,K}$ = bioaccumulation factor for the $K^{th}$ radionuclide in fish from Table A36, in units of Ci/kg fish per Ci/L water

$C_{W,K}$ = concentration of the $K^{th}$ radionuclide in the river water, in Ci/L

$D_{G,K}$ = ingestion dose factor for the $K^{th}$ radionuclide from Table A24, in mrem/pCi ingested

$H_{F,K}$ = ingestion dose from eating fish for the $K^{th}$ radionuclide, mrem/y

$M_F$ = total mass of contaminated fish eaten during the year, 3.29 kg/y

The model used for shoreline sediment concentrations is described in Section A6.3. Sediment concentrations are generally larger than those for irrigated land. The ingestion dose from eating trace amounts of sediment is shown in the equation below. Also shown is the external dose from proximity to the shoreline sediment. A preliminary sediment accumulation time of 20 years is assumed. Radionuclides accumulate in the shoreline sediment for 20 years before the farmer begins to irrigate crops from the Columbia River.

$$H_{XD,K} = C_{W,K}\ V_S\ T_{D,K}\ D_{X,K}\ T_{XD}$$

$$H_{GD,K} = C_{W,K}\ V_S\ T_{D,K}\ D_{G,K}\ \frac{M_{GD}}{\rho_{GARDEN}\ L_{GARDEN}}$$

$$T_{D,K} = \frac{\lambda_K T_C\ -\ \mathrm{Exp}(-\lambda_K T_A)\ +\ \mathrm{Exp}[-\lambda_K (T_A + T_C)]}{(1\ \mathrm{y})\,\lambda_K^2}$$

where,

$C_{W,K}$ = concentration of the $K^{th}$ radionuclide in the river water, in Ci/L

$D_{G,K}$ = ingestion dose factor for the $K^{th}$ radionuclide from Table A24, in mrem/pCi ingested

$D_{X,K}$ = external dose rate factor for the $K^{th}$ radionuclide to a person standing on a layer 0.15 m thick and of great extent in all directions, in mrem/h per Ci/m$^2$. Values are listed in Table A28.

$H_{GD,K}$ = ingestion dose to the all pathways farmer from the $K^{th}$ radionuclide in shoreline sediment, mrem/y

$H_{XD,K}$ = external dose to the all pathways farmer from the $K^{th}$ radionuclide in shoreline sediment, mrem/y

$L_{GARDEN}$ = thickness of the contaminated layer of surface soil in the garden, 0.15 m

$M_{GD}$ = mass of shoreline sediment ingested annually from Table A8, 0.0007 kg/y

$T_A$ = preliminary sediment accumulation time, 20 y

$T_C$ = dose accumulation period, 1 y for the all pathways farmer

$T_{D,K}$ = effective sediment accumulation time for the $K^{th}$ radionuclide, in years. If the removal constant is very small, $T_{D,K} = T_C\,(T_A+T_C)\,/\,(2\ \mathrm{y})$. If the removal constant is very large, $T_{D,K} = T_C\,/\,(1\ \mathrm{y})\,/\,\lambda_K$.

$T_{XD}$ = effective time of exposure to shoreline sediments each year from Table A18, 11 h/y. The estimated time of exposure (56 h/y) was reduced by the shoreline width geometry factor, 0.2.

$V_S$ = effective river-to-sediment deposition rate, 25,300 L/m$^2$ per year

$\lambda_K$ = total removal constant (decay plus leaching) for the K$^{th}$ radionuclide, per year

$\rho_{GARDEN}$ = average density of the soil in the garden, 1,500 kg/m$^3$

Total Dose to the All Pathways Farmer -- Columbia River Water

The total dose to the all pathways farmer is the sum of the external (from soil and sediments), inhalation (from soil and water), and ingestion doses (from water, soil, sediments, vegetables, and animal products). With the exception of tritium (H-3), absorption of radionuclides through the skin is not a significant pathway, as discussed in Section A3.4.1. The source of contaminated water is the Columbia River. Scenario dose factors for the all pathways farmer who uses water from the Columbia River are presented in Table 13 in the "Total" column. This column shows the 50 year committed effective dose equivalent from one year of exposure per pCi/L in the Columbia River. These unit dose factors must be multiplied by the river water concentration to calculate the first year dose.

Table 13 also shows the dose from fish consumption for the all pathways farmer. The drinking water doses are the same as shown in Table 12. The third column of Table 13 shows the ratio of the total dose to the fish dose. Large ratios indicate that dose from fish is a small fraction of the total dose. Small ratios indicate that fish is a major share of the total dose. A ratio of 2 means the dose from fish is half the total.

**Table 13. Unit Dose Factors for the All Pathway Farmer (mrem/y per pCi/L) Using Columbia River Water**

| Nuclide | Total | Fish | Ratio | Nuclide | Total | Fish | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 4.77E-05 | 2.11E-07 | 227 | Eu-155 | 1.66E-03 | 2.51E-04 | 6.59 |
| Be-10 | 4.49E-03 | 1.53E-03 | 2.93 | Gd-152 | 1.19E-01 | 1.32E-02 | 9.0 |
| C-14 | 3.47E-01 | 3.43E-01 | | Tb-157 | 1.04E-04 | 1.02E-05 | 10.2 |
| Na-22 | 4.47E-02 | 3.02E-04 | 148 | Ho-166m | 4.37E-02 | 6.63E-04 | 65.8 |
| Al-26 | 9.38E-02 | 2.40E-02 | 3.91 | Re-187 | 1.13E-05 | 3.75E-06 | 3.01 |
| Si-32+D | 7.66E-03 | 7.21E-04 | 10.6 | Tl-204 | 1.14E-01 | 1.11E-01 | |
| Cl-36 | 2.38E-02 | 4.98E-04 | 47.8 | Pb-205 | 2.66E-03 | 1.61E-03 | 1.65 |
| K-40 | 8.60E-02 | 6.11E-02 | 1.41 | Pb-210+D | 8.80E+00 | 5.30E+00 | 1.66 |
| Ca-41 | 1.19E-03 | 1.68E-04 | 7.13 | Bi-207 | 3.31E-02 | 1.80E-04 | 183 |
| Ti-44+D | 1.59E-01 | 8.08E-02 | 1.97 | Po-209 | 2.22E+00 | 3.90E-01 | 5.70 |
| V-49 | 8.00E-05 | 4.04E-05 | 1.98 | Po-210 | 1.72E+00 | 3.13E-01 | 5.49 |
| Mn-53 | 2.10E-04 | 1.42E-04 | 1.48 | Ra-226+D | 1.16E+00 | 2.18E-01 | 5.31 |
| Mn-54 | 1.04E-02 | 3.64E-03 | 2.87 | Ra-228+D | 1.23E+00 | 2.37E-01 | 5.19 |
| Fe-55 | 9.16E-04 | 3.99E-04 | 2.29 | Ac-227+D | 1.03E+01 | 1.21E+00 | 8.47 |
| Fe-60+D | 2.58E-01 | 1.00E-01 | 2.58 | Th-228+D | 7.75E-01 | 2.67E-01 | 2.91 |
| Co-60 | 7.71E-02 | 2.66E-02 | 2.90 | Th-229+D | 3.81E+00 | 1.32E+00 | 2.87 |
| Ni-59 | 3.43E-04 | 6.90E-05 | 4.97 | Th-230 | 5.17E-01 | 1.80E-01 | 2.87 |

**Table 13. Unit Dose Factors for the All Pathway Farmer (mrem/y per pCi/L) Using Columbia River Water**

| Nuclide | Total | Fish | Ratio | Nuclide | Total | Fish | Ratio |
|---|---|---|---|---|---|---|---|
| Ni-63 | 9.44E-04 | 1.90E-04 | 4.97 | Th-232 | 2.60E+00 | 8.98E-01 | 2.90 |
| Se-79 | 1.55E-02 | 4.86E-03 | 3.19 | Pa-231 | 6.86E+00 | 3.48E-01 | 19.7 |
| Rb-87 | 3.90E-02 | 3.24E-02 | 1.20 | U-232 | 9.28E-01 | 4.31E-02 | 21.5 |
| Sr-90+D | 1.64E-01 | 3.02E-02 | 5.43 | U-233 | 2.01E-01 | 9.51E-03 | 21.2 |
| Zr-93 | 2.65E-03 | 1.64E-03 | 1.62 | U-234 | 1.98E-01 | 9.32E-03 | 21.2 |
| Nb-91 | 8.81E-04 | 5.15E-04 | 1.71 | U-235+D | 1.89E-01 | 8.80E-03 | 21.4 |
| Nb-93m | 8.35E-04 | 5.15E-04 | 1.62 | U-236 | 1.87E-01 | 8.84E-03 | 21.2 |
| Nb-94 | 4.61E-02 | 7.05E-03 | 6.55 | U-238+D | 1.87E-01 | 8.82E-03 | 21.2 |
| Mo-93 | 1.06E-03 | 4.43E-05 | 24.0 | Np-237+D | 3.09E+00 | 3.07E-01 | 10.1 |
| Tc-97 | 2.13E-04 | 1.13E-05 | 18.9 | Pu-236 | 7.94E-01 | 8.05E-02 | 9.9 |
| Tc-99 | 1.81E-03 | 9.62E-05 | 18.8 | Pu-238 | 2.19E+00 | 2.21E-01 | 9.9 |
| Ru-106+D | 3.21E-02 | 9.01E-04 | 35.6 | Pu-239 | 2.42E+00 | 2.44E-01 | 9.9 |
| Pd-107 | 1.63E-04 | 4.92E-06 | 33.2 | Pu-240 | 2.42E+00 | 2.44E-01 | 9.9 |
| Ag-108m+D | 3.99E-02 | 1.25E-04 | 318 | Pu-241+D | 4.68E-02 | 4.73E-03 | 9.9 |
| Cd-109+D | 1.75E-02 | 8.64E-03 | 2.03 | Pu-242 | 2.30E+00 | 2.32E-01 | 9.9 |
| Cd-113m | 2.16E-01 | 1.06E-01 | 2.04 | Pu-244+D | 2.28E+00 | 2.30E-01 | 9.9 |
| In-115 | 5.20E+01 | 5.19E+01 | | Am-241 | 2.49E+00 | 2.52E-01 | 9.9 |
| Sn-121m+D | 2.57E-02 | 2.22E-02 | 1.16 | Am-242m+D | 2.40E+00 | 2.43E-01 | 9.9 |
| Sn-126+D | 2.84E-01 | 2.07E-01 | 1.37 | Am-243+D | 2.48E+00 | 2.50E-01 | 9.9 |
| Sb-125 | 6.52E-03 | 9.24E-04 | 7.06 | Cm-242 | 7.75E-02 | 7.92E-03 | 9.8 |
| Te-125m | 7.40E-03 | 4.83E-03 | 1.53 | Cm-243 | 1.72E+00 | 1.74E-01 | 9.9 |
| I-129 | 4.37E-01 | 3.63E-02 | 12.0 | Cm-244 | 1.38E+00 | 1.39E-01 | 9.9 |
| Cs-134 | 6.04E-01 | 4.82E-01 | 1.25 | Cm-245 | 2.56E+00 | 2.58E-01 | 9.9 |
| Cs-135 | 5.75E-02 | 4.65E-02 | 1.24 | Cm-246 | 2.53E+00 | 2.56E-01 | 9.9 |
| Cs-137+D | 4.17E-01 | 3.29E-01 | 1.27 | Cm-247+D | 2.35E+00 | 2.36E-01 | 9.9 |
| Ba-133 | 7.31E-03 | 4.47E-05 | 163 | Cm-248 | 9.31E+00 | 9.41E-01 | 9.9 |
| Ce-144+D | 1.53E-02 | 2.09E-03 | 7 | Cm-250+D | 5.31E+01 | 5.37E+00 | 9.9 |
| Pm-147 | 7.98E-04 | 1.03E-04 | 7.72 | Bk-247 | 3.28E+00 | 3.86E-01 | 8.48 |
| Sm-147 | 1.40E-01 | 1.52E-02 | 9.15 | Cf-248 | 2.47E-01 | 2.75E-02 | 8.98 |
| Sm-151 | 2.92E-04 | 3.20E-05 | 9.14 | Cf-249 | 3.57E+00 | 3.90E-01 | 9.15 |
| Eu-150 | 3.39E-02 | 1.05E-03 | 32.4 | Cf-250 | 1.60E+00 | 1.75E-01 | 9.12 |
| Eu-152 | 2.37E-02 | 1.07E-03 | 22.3 | Cf-251 | 3.64E+00 | 3.99E-01 | 9.14 |
| Eu-154 | 2.54E-02 | 1.57E-03 | 16.2 | Cf-252 | 8.08E-01 | 8.92E-02 | 9.06 |

Notes:

- The radiation dose to this individual is the 50 year committed effective dose equivalent from the first year of exposure.
- These scenario dose factors must he multiplied by the Columbia River concentration.
- The "Total" column is for the full scenario. The column "Fish" shows only the dose from eating fish. The "Ratio" column is the "Total" divided by the "Fish" doses. Large ratios mean that fish is a minor contributor to the total dose. Blank cells mean the dose from fish is within 10% of the total.

Increased Cancer Risk for the All Pathways Farmer -- Radionuclides

The increase in risk of developing some type of cancer due to radioactive contaminants in either groundwater or the Columbia River is calculated using the same equations presented for the radiation dose. The two differences are (1) the use of the risk coefficients from Federal Guidance Report Number 13 rather than internal and external dose factors, and (2) the calculation of the cumulative risk from 30 years of water use.

When calculating the cumulative intakes over several years of irrigation with contaminated water it is convenient to distinguish two components to the intakes. The first component is direct from the water. Examples are drinking water and inhalation of airborne water. The second is indirect from radionuclides that are adsorbed on soil particles. Examples are external exposure, soil inhalation, and soil ingestion. Plant and animal pathways are a mixture of these two components.

The intakes from the direct pathways are the same every year because the water concentration remains constant. Thus, the cumulative intake is the number of years times the intake in one year. However, the intakes from the second component are based on the concentration in the soil. Each year this concentration increases due to the applied irrigation water. The methods used for calculating intakes from residual soil contamination are shown in the discussion of doses in the suburban garden and rural pasture scenarios (Sections 3.2 and 3.3). Thus, the cumulative intake from N years of irrigation is the sum of N years of the direct component plus the cumulative sum of (N-1) years of prior irrigation. Equations for this are described in Section A6.2. The formulas below show how the cumulative total dose (or risk) is calculated. For the shoreline sediment the dose is calculated using the equations presented above with $T_C$=30 y.

$$D_{CUM} = ND_{DIRECT} + \frac{D_{SOIL} F_{IS}}{1 - F_{NS}} \left( N - \frac{1 - (F_{NS})^N}{1 - F_{NS}} \right)$$

$$F_{IS} = \left( \frac{1 - \mathrm{Exp}(-\lambda T_{irr})}{\lambda T_{irr}} \right) \mathrm{Exp}(-\lambda_R T_{no})$$

$$F_{NS} = \mathrm{Exp}(-\lambda T_{irr})\ \mathrm{Exp}(-\lambda_R T_{no})$$

where,

$D_{CUM}$ = cumulative total dose (or risk) from N years of irrigation, excluding doses from shoreline sediments, in mrem

$D_{DIRECT}$ = annual dose (or risk) from direct intakes of contaminated water during one year (excludes doses from shoreline sediments), in mrem

$D_{SOIL}$ = annual dose (or risk) from the soil contamination present at the beginning of the year (excludes doses from shoreline sediments), in mrem

$F_{IS}$ = fraction of the total soil concentration (amount deposited per unit area during the year divided by the area density of the soil) that is present at the end of 1 year when the irrigation water is adding contaminants to the soil

$F_{NS}$ = fraction of the initial soil concentration that is left at the end of 1 year when the irrigation water adds no contaminants

$N$ = number of years of irrigation

$T_{irr}$ = irrigation period, 0.5 y

$T_{no}$ = no irrigation period, 1 y - $T_{irr}$ = 0.5 y

$\lambda$ = total removal constant, per year $\lambda = \lambda_R + \lambda_S$

$\lambda_R$ = radioactive decay or chemical decomposition constant, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_S$ = average soil leaching coefficient, fraction removed from the surface layer of soil, per year

The lifetime increase in the risk of developing some type of cancer from radionuclides is the sum of 30 years of exposure. Each year there is a small amount of the radioactive material in the soil from previous years. The method of calculation uses formulas for the current year of irrigation as well as those for an initial soil concentration presented for the suburban garden and rural pasture. The soil concentration at the start of the year as well as the addition from irrigation determines the intake for that year. This leads to a total risk that is greater than 30 times the first year's risk for many nuclides.

The estimated lifetime increase in the risk of developing some type of cancer in the All Pathways Farmer from radioactive materials in the water is shown in Table 14. The first column of risks shows the 30-year total where all the contaminated water comes from a well. The water concentration of each nuclide is 1 pCi/L for this entire period. The second column of risks shows the 30-year total where all of the contaminated water comes from the Columbia River. Again, the water concentration is constant over the 30-year period. The third column is the ratio of the Columbia River risk factors divided by the groundwater risk factors. If the two numbers are within 10%, they are not shown. Because the only difference is the addition of the fish and sediment pathways, radionuclides with large ratios indicate that the added pathways are major contributors to the total.

**Table 14. Unit Risk Factors for Radionuclides in the All Pathways Farmer Scenario (lifetime risk per pCi/L)**

| Nuclide | Ground-water | River Water | Ratio | Nuclide | Ground-water | River Water | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 2.66E-09 | 2.67E-09 | | Eu-155 | 7.57E-08 | 9.30E-08 | 1.2 |
| Be-10 | 1.45E-07 | 2.48E-07 | 1.7 | Gd-152 | 6.28E-07 | 7.28E-07 | 1.2 |
| C-14 | 1.56E-07 | 1.00E-05 | 64 | Tb-157 | 5.24E-09 | 6.14E-09 | 1.2 |
| Na-22 | 2.57E-06 | 2.74E-06 | | Ho-166m | 6.14E-06 | 7.26E-06 | 1.2 |
| Al-26 | 1.08E-05 | 1.40E-05 | 1.3 | Re-187 | 8.36E-10 | 1.14E-09 | 1.4 |
| Si-32+D | 2.79E-07 | 3.16E-07 | 1.1 | Tl-204 | 2.43E-07 | 8.39E-06 | 35 |
| Cl-36 | 4.64E-06 | 4.66E-06 | | Pb-205 | 1.30E-08 | 3.76E-08 | 2.9 |
| K-40 | 2.34E-06 | 5.79E-06 | 2.5 | Pb-210+D | 2.27E-05 | 5.81E-05 | 2.6 |
| Ca-41 | 1.77E-08 | 1.95E-08 | | Bi-207 | 4.67E-06 | 5.40E-06 | 1.2 |
| Ti-44+D | 8.58E-06 | 1.36E-05 | 1.6 | Po-209 | 3.03E-05 | 4.42E-05 | 1.5 |
| V-49 | 2.53E-09 | 6.06E-09 | 2.4 | Po-210 | 1.93E-05 | 3.04E-05 | 1.6 |

**Table 14. Unit Risk Factors for Radionuclides in the All Pathways Farmer Scenario (lifetime risk per pCi/L)**

| Nuclide | Ground-water | River Water | Ratio | Nuclide | Ground-water | River Water | Ratio |
|---|---|---|---|---|---|---|---|
| Mn-53 | 4.10E-09 | 1.30E-08 | 3.2 | Ra-226+D | 1.61E-05 | 2.00E-05 | 1.2 |
| Mn-54 | 2.84E-07 | 4.27E-07 | 1.5 | Ra-228+D | 2.64E-05 | 3.40E-05 | 1.3 |
| Fe-55 | 2.50E-08 | 4.79E-08 | 1.9 | Ac-227+D | 1.04E-05 | 1.22E-05 | 1.2 |
| Fe-60+D | 1.15E-05 | 1.77E-05 | 1.5 | Th-228+D | 6.80E-06 | 1.11E-05 | 1.6 |
| Co-60 | 4.06E-06 | 5.09E-06 | 1.3 | Th-229+D | 1.13E-05 | 1.86E-05 | 1.7 |
| Ni-59 | 1.49E-08 | 1.88E-08 | 1.3 | Th-230 | 1.80E-06 | 3.00E-06 | 1.7 |
| Ni-63 | 3.61E-08 | 4.56E-08 | 1.3 | Th-232 | 7.63E-06 | 1.05E-05 | 1.4 |
| Se-79 | 3.38E-07 | 5.01E-07 | 1.5 | Pa-231 | 3.84E-06 | 4.24E-06 | 1.1 |
| Rb-87 | 4.96E-07 | 1.89E-06 | 3.8 | U-232 | 1.01E-05 | 1.09E-05 | |
| Sr-90+D | 4.31E-06 | 4.89E-06 | 1.1 | U-233 | 1.58E-06 | 1.68E-06 | |
| Zr-93 | 2.14E-08 | 6.43E-08 | 3.0 | U-234 | 1.55E-06 | 1.65E-06 | |
| Nb-91 | 2.19E-08 | 5.78E-08 | 2.6 | U-235+D | 1.90E-06 | 2.03E-06 | |
| Nb-93m | 1.58E-08 | 5.06E-08 | 3.2 | U-236 | 1.47E-06 | 1.56E-06 | |
| Nb-94 | 5.81E-06 | 7.17E-06 | 1.2 | U-238+D | 1.98E-06 | 2.11E-06 | |
| Mo-93 | 1.31E-07 | 1.35E-07 | | Np-237+D | 1.94E-06 | 2.22E-06 | 1.1 |
| Tc-97 | 6.76E-08 | 6.84E-08 | | Pu-236 | 1.55E-06 | 1.78E-06 | 1.1 |
| Tc-99 | 6.94E-07 | 7.02E-07 | | Pu-238 | 2.53E-06 | 2.90E-06 | 1.1 |
| Ru-106+D | 1.78E-06 | 1.84E-06 | | Pu-239 | 2.61E-06 | 2.99E-06 | 1.1 |
| Pd-107 | 1.11E-08 | 1.15E-08 | | Pu-240 | 2.61E-06 | 2.99E-06 | 1.1 |
| Ag-108m+D | 5.63E-06 | 6.58E-06 | 1.2 | Pu-241+D | 3.45E-08 | 3.97E-08 | 1.2 |
| Cd-109+D | 1.11E-07 | 2.44E-07 | 2.2 | Pu-242 | 2.47E-06 | 2.84E-06 | 1.1 |
| Cd-113m | 7.10E-07 | 1.43E-06 | 2.0 | Pu-244+D | 3.98E-06 | 4.63E-06 | 1.2 |
| In-115 | 8.01E-07 | 4.28E-04 | 534 | Am-241 | 2.04E-06 | 2.33E-06 | 1.1 |
| Sn-121m+D | 2.27E-07 | 1.74E-06 | 7.7 | Am-242m+D | 1.46E-06 | 1.68E-06 | 1.1 |
| Sn-126+D | 8.70E-06 | 2.16E-05 | 2.5 | Am-243+D | 2.60E-06 | 3.00E-06 | 1.2 |
| Sb-125 | 4.13E-07 | 5.04E-07 | 1.2 | Cm-242 | 7.29E-07 | 8.43E-07 | 1.2 |
| Te-125m | 7.63E-08 | 2.62E-07 | 3.4 | Cm-243 | 2.09E-06 | 2.40E-06 | 1.1 |
| I-129 | 9.90E-06 | 1.07E-05 | | Cm-244 | 1.61E-06 | 1.84E-06 | 1.1 |
| Cs-134 | 3.28E-06 | 1.35E-05 | 4.1 | Cm-245 | 2.20E-06 | 2.54E-06 | 1.2 |
| Cs-135 | 3.69E-07 | 1.53E-06 | 4.1 | Cm-246 | 1.98E-06 | 2.27E-06 | 1.1 |
| Cs-137+D | 3.80E-06 | 1.14E-05 | 3.0 | Cm-247+D | 3.01E-06 | 3.50E-06 | 1.2 |
| Ba-133 | 7.71E-07 | 8.51E-07 | | Cm-248 | 1.85E-05 | 2.12E-05 | 1.1 |
| Ce-144+D | 6.92E-07 | 8.47E-07 | 1.2 | Cm-250+D | 4.25E-05 | 4.87E-05 | 1.1 |
| Pm-147 | 3.66E-08 | 4.40E-08 | 1.2 | Bk-247 | 2.64E-06 | 3.10E-06 | 1.2 |
| Sm-147 | 8.10E-07 | 9.34E-07 | 1.2 | Cf-248 | 9.35E-07 | 1.09E-06 | 1.2 |
| Sm-151 | 1.23E-08 | 1.44E-08 | 1.2 | Cf-249 | 3.83E-06 | 4.44E-06 | 1.2 |
| Eu-150 | 4.35E-06 | 5.06E-06 | 1.2 | Cf-250 | 1.86E-06 | 2.15E-06 | 1.2 |
| Eu-152 | 2.77E-06 | 3.17E-06 | 1.1 | Cf-251 | 3.18E-06 | 3.67E-06 | 1.2 |
| Eu-154 | 2.57E-06 | 2.93E-06 | 1.1 | Cf-252 | 1.46E-06 | 1.69E-06 | 1.2 |

**Table 14. Unit Risk Factors for Radionuclides in the All Pathways Farmer Scenario (lifetime risk per pCi/L)**

| Nuclide | Ground-water | River Water | Ratio | Nuclide | Ground-water | River Water | Ratio |
|---|---|---|---|---|---|---|---|

Notes:

- The increase in risk of the All Pathways Farmer developing some type of cancer is calculated using intakes from 30 consecutive years, representing a lifetime. The soil concentration is zero at the start of the exposure.
- These scenario risk factors must be multiplied by the water concentration.
- The "Groundwater" column assumes all of the contaminated water comes from a well. The "River Water" column assumes all of the contaminated water comes from the Columbia River. The "Ratio" column is the "River Water" divided by the "Groundwater" risks. Blank entries indicate the two risks are within 10 percent of each other.

Chemicals in the Water Used by the All Pathways Farmer

At this point the human health risks associated with hazardous chemicals will be included in the discussion. The chemicals that are considered in this report are listed in Table A3. Solubility limits in water solutions are presented in Table A3, although these limits are not used in the calculation of unit hazard quotient and unit risk factors. It is assumed that the chemicals are present in trace amounts that are well below the solubility limits. To simplify the discussion, the decomposition of these chemicals in the environment is not considered. The treatment of chemicals is similar to the methods used for radionuclides. All of the pathways discussed for radionuclides are important for chemicals with the exception of the external exposure pathway. In its place is the dermal absorption of chemicals because many chemicals are readily absorbed into the body by passing through the skin.

The dissolved chemical concentration in well or river water is expressed in mg/L. The well or river water is used for household needs and irrigation. The chemicals are inhaled, ingested and absorbed through the skin. The irrigated soil becomes contaminated during the irrigation season. Leaching occurs only during the irrigation season due to over watering. During the non-irrigation season chemicals are removed from the soil by evaporation or volatilization. The exposure parameters for the All Pathways Farmer are the same for radionuclides and chemicals. Additional detail is needed for chemicals to describe the various dermal absorption pathways. Dermal absorption occurs during showering, and as a result of dermal contact with soil and shoreline sediment.

The relative risk associated with a chemical is characterized by its toxicity factors. There are two kinds, the reference dose and the cancer induction slope factor as described in Section A3.8. The overall risk from a chemical is based on the average daily dose over many years as well as the toxicity factor for the chemical. Average daily dose has units of mg of chemical per kg of body mass per day, or mg/kg per day.

When calculating the average daily dose, the cumulative intake over some exposure period is divided by the number of days in the averaging period as well as the individual body mass. The cumulative intake is calculated using an integration over the exposure period because the daily dose changes during the exposure period. The variation in daily dose is due to the irrigation cycle as well as the accumulation of chemicals in the soil.

In the All Pathways Farmer scenario, the exposure period is 30 years. The averaging period depends on whether the cancer risk or the non-carcinogenic hazard quotient is to be calculated. For calculating the increase in the risk of cancer, the daily dose is averaged over 70 years. When calculating the hazard quotient, the averaging time is the same as the exposure time (30 years).

The hazard quotient and cancer induction risk for a chemical are calculated using the formulas below. Separate calculations are made for inhalation, ingestion, and dermal intakes. The hazard index and/or cancer risk from each route of exposure is then summed.

$$(\text{Hazard Index})_K = \int_0^{T_{EXP}} \frac{W_K(t)\,dt}{T_{AVE,HI}\,D_{REF,K}}$$

$$(\text{Cancer Risk})_K = \int_0^{T_{EXP}} \frac{W_K(t)\,R_{IC,K}\,dt}{T_{AVE,IC}}$$

where,

$D_{REF,K}$ = reference dose for the $K^{th}$ chemical from Table A34, in mg/kg per day

$R_{IC,K}$ = cancer induction slope factor for the $K^{th}$ chemical from Table A34, in risk per unit dose, i.e., risk per (mg/kg per day)

$T_{AVE,HI}$ = averaging period for calculating hazard quotient. This is always the same as the exposure duration, in years, i.e., $T_{AVE,HI}=T_{EXP}$.

$T_{AVE,IC}$ = averaging period for calculating cancer risk, 70 years

$T_{EXP}$ = exposure duration, i.e., the number of years the individual receives the average daily dose. For the All Pathways Farmer scenario this is 30 y.

$W_K$ = average daily dose of the $K^{th}$ chemical, in mg of chemical per kg of body weight per day (mg/kg per day)

As part of this calculation, the concentration of the contaminants in soil is increased each year. The effect of leaching from the surface layer is included using the leaching coefficients shown in Table A41. The effect of volatilization removal from the surface layer is included using the emanation constants shown in Table A44.

The degradation of chemicals into other chemicals due to biotic and abiotic action in the environment is not included in the calculations. Some of the chemicals evaluated (e.g., Xylene) are known to degrade with half lives less than 1 year. Moreover, the chemicals produced by degradation processes (e.g., $Cr^{+6}$) may be more toxic than the original chemical (e.g., $Cr^{+3}$). The omission of degradation is conventional in risk assessments due in part to the dearth of experimental data on this subject for most of the chemicals of interest.

The tables of hazard quotient and cancer risks per unit concentration in the water include the effects of leaching and volatilization from the surface layer of soil. The scenario calculations use decay and leaching factors very similar to the ones for radionuclides. During the irrigation season, the decay and leaching terms are replaced with volatilization and leaching terms. During

the non-irrigation season, the decay terms are replaced with volatilization terms. Thus, the same formulas are used with the redefinition of the $\lambda_K$ and $\lambda_{R,K}$ terms shown below.

$$\lambda_K = \lambda_{Virr,K} + \lambda_{S,K} \qquad \text{and} \qquad \lambda_{R,K} = \lambda_{Vno,K}$$

where,

$\lambda_K$ = total removal coefficient for the $K^{th}$ chemical during the irrigation season, fraction removed from the surface layer of soil, per year

$\lambda_{R,K}$ = total removal coefficient for the $K^{th}$ chemical during the non-irrigation season, fraction removed from the surface layer of soil, per year

$\lambda_{S,K}$ = average soil leaching coefficient for the $K^{th}$ chemical, fraction removed from the surface layer of soil, per year (see Table A41)

$\lambda_{Virr,K}$ = average soil emanation constant for the $K^{th}$ chemical during the irrigation season (see Table A44)

$\lambda_{Vno,K}$ = average soil emanation constant for the $K^{th}$ chemical during the non-irrigation season (see Table A44)

The factors that represent the average soil concentration during the period of interest are shown below. These factors are used in the equations for average daily intake (W) that follow. The $F_{M,K}$ term represents continuous intakes, namely, soil ingestion, soil inhalation, and the portion of the milk, poultry, and egg intakes that come from soil ingested by the animal. The $F_{V,K}$ term represents the intakes that occur following a harvest of garden produce, and animal fodder. It gives the portion of the intake due to indirect ingestion of contaminated soil. The cumulative factor ($F_{CUM,K}$) is the same factor shown earlier for the calculation of lifetime cancer risks from radionuclides. It has been restated to show the more general form that allows calculation of cumulative intakes for any start and ending times ($N_1$ and $N_2$).

$$F_{M,K} = F_{X,I,K} + F_{B,N,K}\, F_{CUM,K}(N_1, N_2)$$

$$F_{V,K} = F_{C,N,K}\left[1 + F_{CUM,K}(N_1, N_2)\right]$$

$$F_{C,N,K} = \frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}} \qquad \text{and} \qquad F_{no,K} = \frac{1 - \mathrm{Exp}(-\lambda_{R,K} T_{no})}{\lambda_{R,K} T_{no}}$$

$$F_{X,I,K} = \frac{\lambda_K T_{irr} - 1 + \mathrm{Exp}(-\lambda_K T_{irr})}{(1\,y)\lambda_K^2\, T_{irr}} + \left(\frac{T_{no}}{1\,y}\right) F_{C,N,K}\, F_{no,K}$$

$$F_{B,N,K} = \left(\frac{T_{irr}}{1\,y}\right) F_{C,N,K} + \left(\frac{T_{no}}{1\,y}\right) \mathrm{Exp}(-\lambda_K T_{irr})\, F_{no,K}$$

$$F_{IS,K} = \frac{1 - \mathrm{Exp}(-\lambda_K T_{irr})}{\lambda_K T_{irr}} \mathrm{Exp}(-\lambda_{R,K} T_{no}) \qquad \text{and} \qquad F_{NS,K} = \mathrm{Exp}(-\lambda_K T_{irr})\mathrm{Exp}(-\lambda_{R,K} T_{no})$$

$$F_{CUM,K}(N_1, N_2) = \frac{F_{IS,K}}{1 - F_{NS,K}}\left[1 - \frac{(F_{NS,K})^{N_2} - (F_{NS,K})^{N_1}}{(N_2 - N_1)(1 - F_{NS,K})}\right]$$

where,

$F_{B,N,K}$ = factor that results from the time integral of the soil intake rate for the $K^{th}$ chemical present in the soil at the start of the year (B=inhalation calculation, N=irrigation water is not contaminated, K=chemical index). The first portion is the sum during the irrigation season, while the second portion is the intake during the no-irrigation season. This is the same formula used earlier for the inhalation dose from radionuclides in soil.

$F_{C,N,K}$ = factor that represents the soil concentration of the $K^{th}$ chemical at the end of the irrigation season, or, equivalently, the accumulated soil intake of the $K^{th}$ chemical during the irrigation season from soil contamination present at the beginning of the year (C=chemical, N=irrigation water is not contaminated, K=chemical index)

$F_{CUM,K}$ = cumulative average soil intake factor from residual soil contamination due to irrigation in prior years for the $K^{th}$ chemical. The intake begins at the end of year $N_1$ and concludes at the end of year $N_2$.

$F_{IS,K}$ = fraction of the soil concentration added by irrigation during one year that is present at the end of that year

$F_{M,K}$ = factor that results from the time integral of the soil intake rate for ingestion, inhalation, and dermal contact for the $K^{th}$ chemical over the years $N_1$ to $N_2$. The intake begins at the end of year $N_1$ and concludes at the end of year $N_2$. Irrigation has been taking place since year zero. The irrigation water concentration is constant. Note that this factor is the average per year.

$F_{no,K}$ = factor that results from the time integral of the soil intake rate for the $K^{th}$ chemical during the non-irrigation period

$F_{NS,K}$ = fraction of the soil concentration present at the beginning of a year that is present at the end of that year

$F_{V,K}$ = factor that results from the time integral of the indirect intake of soil during consumption of vegetation and animal products for the $K^{th}$ chemical over the years $N_1$ to $N_2$. The intake begins at the end of year $N_1$ and concludes at the end of year $N_2$. Irrigation has been taking place since year zero. The irrigation water concentration is constant. The plants are harvested at the end of the irrigation season. Note that this factor is the average per year.

$F_{X,I,K}$ = factor that results from the time integral of the soil intake rate for the $K^{th}$ chemical over the full year (X=external dose, I=irrigation water is contaminated, K=chemical index). The first portion is the sum during the irrigation season, while the second portion is the intake during the no-irrigation season. This is the same formula used earlier for the external dose from radionuclides in soil.

$N_1$, $N_2$ = integers that indicate the start year and end year for the cumulative average soil concentration calculations. The first year of irrigation is specified using $(N_1,N_2)=(0,1)$. The childhood years in certain HSRAM scenarios are specified using $(N_1,N_2)=(0,6)$. The adult years are specified using $(N_1,N_2)=(7,30)$.

$T_{irr}$ = irrigation period (the $1^{st}$ half of the year), 0.5 y

$T_{no}$ = no irrigation period (the $2^{nd}$ half of the year), $T_{irr} + T_{no} = 1$ y

$\lambda_K$ = total removal coefficient for the $K^{th}$ chemical during the irrigation season, fraction removed from the surface layer of soil, per year

$\lambda_{R,K}$ = total removal coefficient for the $K^{th}$ chemical during the non-irrigation season, fraction removed from the surface layer of soil, per year

Inhalation Dose from Chemicals for the All Pathways Farmer

The average daily dose via inhalation is calculated from the sum of resuspended soil and volatilized water. The soil is contaminated by irrigation with contaminated water. Each year the soil concentration is greater than the year before. During the shower, chemicals dissolved in the water are volatilized and become airborne. The annual intakes via inhalation are presented in Appendix A, Section A3.2. The formula used to calculate the average daily dose of the $K^{th}$ chemical from inhalation is shown below.

$$W_{B,K} = \frac{C_{S,K}\, M_B\, F_{M,K} + C_{W,K}\, V_{AIR}\, \mathrm{MIN}\left[0.5\ \mathrm{L/m^3}, F_{SAT}\left(1000\ \mathrm{L/m^3}\right) K_{UNITLESS,K}\right]}{(365\ \mathrm{d/y})\, M_{ADULT}}$$

where,

$C_{S,K}$ = concentration of the $K^{th}$ chemical in the surface soil, in mg/kg. This concentration includes the accumulation from prior years. The surface soil concentration is calculated from the water concentration as shown at the beginning of Section 3.3.

$C_{W,K}$ = concentration of the $K^{th}$ chemical in the water, in mg/L

$F_{M,K}$ = factor that results from the time integral of the soil intake rate for inhalation for the $K^{th}$ chemical from the start of irrigation to the end of the exposure duration, 30 y for the all pathways farmer [$(N_1,N_2)=(0,30)$]. The irrigation water concentration is assumed constant. Note that this factor is the average per year.

$F_{SAT}$ = fraction of the upper limit concentration given by Henry's Law that is likely to be present on the average, 50% is assumed

$K_{UNITLESS,K}$ = unitless Henry's Law constant for the $K^{th}$ chemical. Values are listed in Table A3. Application to volatile chemicals is described in Section A3.2.

$M_{ADULT}$ = mass of an adult, 70 kg

$M_B$ = mass of soil inhaled during the year, $5.39 \times 10^{-4}$ kg/y from Table A10

MIN = function that returns the smaller of the two values. In this case, the air concentration has an upper limit of 0.5 $L/m^3$.

$V_{AIR}$ = volume of air with volatilized chemicals inhaled in a year, 8,094 $m^3/y$ from Table A17

$W_{B,K}$ = average daily dose of the $K^{th}$ chemical from inhalation, in mg/kg per day

0.5 $L/m^3$ = bounding volatile chemical concentration in the air from the HSRAM, in liters of solution per cubic meter of air

Ingestion Dose from Chemicals for the All Pathways Farmer

The average daily dose via ingestion is calculated from the sum of the contaminated soil ingested, the contaminated plant and animal produce ingested, and the contaminated water. The soil is contaminated by irrigation with contaminated water. Each year the soil concentration is greater than the year before. The intake from soil ingestion depends on the age of the individual. The adult soil ingestion rate (0.0365 kg/y) is used for the all pathways farmer the entire 30 years

he is exposed. The garden produce is contaminated by root uptake, rain splash and direct deposition from the overhead irrigation. For chemicals there is only one plant type used as food for both people and animals. This crop is harvested at the end of the irrigation season. The total consumed by the all pathways farmer is 25% of 190 kg/y, or 47.5 kg/y. This excludes grains, which are not irrigated with contaminated water. The animal products (meat, milk, poultry, and eggs) are contaminated by the animal consuming contaminated soil, plants, and drinking water. The animal fodder uses the same model as the garden vegetables. The formula used to calculate the average daily dose of the $K^{th}$ chemical from ingestion is shown below. The contribution from fish only applies when the Columbia River is the source of contaminated water.

$$W_{G,K} = \frac{C_{S,K}\, M_G + C_{V,K}\, M_V + \sum_q C_{A,q,K}\, M_{A,q} + C_{W,K}\left(V_G + B_{F,K} M_F\right)}{(365\ \mathrm{d/y})\, M_{ADULT}}$$

where,

$B_{F,K}$ = transfer factor for the $K^{th}$ chemical from water to fish from Table A38

$C_{A,q,K}$ = concentration of the $K^{th}$ chemical in animal product type q, in mg/kg

$C_{S,K}$ = concentration of the $K^{th}$ chemical in the surface soil, in mg/kg. This concentration includes the accumulation from prior years.

$C_{V,K}$ = concentration of the $K^{th}$ chemical in the plants consumed by both people and animals, in mg/kg wet weight

$C_{W,K}$ = concentration of the $K^{th}$ chemical in the water, in mg/L

$M_{ADULT}$ = mass of an adult, 70 kg

$M_{A,q}$ = mass of animal product type q eaten during the year, in kg/y. These amounts are 50% of the values shown in Table A4 under the heading "USDA".

$M_F$ = total mass of contaminated fish eaten during the year, 3.29 kg/y. Half of the USDA average from Table A4 is used for the All Pathways Farmer when the contaminated water comes from the Columbia River.

$M_G$ = mass of contaminated soil ingested during the year, 0.0365 kg/y from Table A8

$M_V$ = mass of contaminated vegetables ingested during the year, 47.5 kg/y.

q = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

$V_G$ = volume of contaminated drinking water consumed in a year, 545 L/y from Table A4

$W_{G,K}$ = average daily dose of the $K^{th}$ chemical from ingestion, in mg/kg per day

The concentration of the chemical in the plants is calculated using a simplified version of the model for radionuclides. One plant type represents all garden produce as well as the plants consumed by the animals. The root uptake factors are listed in Table A41. The dry-to-wet ratio is 0.2. For the rain splash calculation, the interception fraction is 50% and the transfer from plant surfaces to edible portions of the plant is 100%. For direct deposition by overhead irrigation, the interception fraction is 25%. The standing biomass is 2 kg/m$^2$ and the effective exposure time is calculated using a 60-day growing period. The formula used is shown below.

$$C_{V,K} = F_{V,K}\, C_{S,K}\left(F_{DRY}\, B_{V,K} + \frac{J_{SPLASH}\, F_{INT}\, F_{TRANS}\, T_W}{Y_V}\right) + \frac{F_{Direct}\, ID_K\, F_{TRANS}\, T_W}{Y_V}$$

where,

$B_{V,K}$ = soil-to-plant transfer factor for the $K^{th}$ chemical from Table A41

$C_{S,K}$ = concentration of the $K^{th}$ chemical in irrigated soil at the end of the year with no decay or leaching, in mg/kg

$C_{V,K}$ = chemical concentration in plants, in mg/kg wet weight

$F_{Direct}$ = interception fraction for contaminants in irrigation water on exposed surfaces of garden produce and animal fodder, 0.25 for all plant types from Table A42

$F_{DRY}$ = dry-to-wet ratio for plants, 0.2 for all plant types from Table A42

$F_{INT}$ = interception fraction for airborne particulate on exposed surfaces of plants, 0.5 for all plant types from Table A42

$F_{TRANS}$ = translocation factor from exposed surfaces to the edible portion of plants, 1.0

$F_{V,K}$ = factor that results from the time integral of the indirect intake of soil during consumption of vegetation for the $K^{th}$ chemical from the start of irrigation to the end of the exposure duration, 30 y for the all pathways farmer. The irrigation water concentration is constant. The plants are harvested at the end of the irrigation season. Note that this factor is the average per year.

$ID_K$ = irrigation deposition rate for the $K^{th}$ chemical during the irrigation season, $mg/m^2$ per year (1 y = 365 d)

$J_{SPLASH}$ = average soil deposition rate due to rain splash (see Section A5.2), $2.7 \times 10^{-4}$ $kg/m^2$ per day

$T_W$ = effective exposure time for contaminants deposited on the exposed surfaces of plants, 19.16 days. This is based on a growing period of 60 days and a weathering half time of 14 days.

$Y_V$ = yield, or standing biomass of the plants, 2 kg(wet)/$m^2$ for all plant types from Table A42

The concentration of a chemical in animal products is calculated in a formula similar to that used for radionuclides. The transfer factors for chemicals into animal products are listed in Table A38.

$$C_{A,q,K} = B_{A,q,K}\left(C_{S,K}\, M_{S,q}\, F_{A,q,K} + C_{V,K}\, M_{V,q} + C_{W,K}\, V_{W,q}\right)$$

where,

$B_{A,q,K}$ = animal transfer factor for the $K^{th}$ chemical into animal product type q from Table A38, in day/kg

$C_{A,q,K}$ = concentration of the $K^{th}$ chemical in animal product type q, in mg/kg

$C_{S,K}$ = concentration of the $K^{th}$ chemical in irrigated soil at the end of the year with no decay or leaching, in mg/kg

$C_{V,K}$ = chemical concentration in plants eaten by the animals, in mg/kg wet weight

$C_{W,K}$ = concentration of the $K^{th}$ chemical in the irrigation water, in mg/L

$F_{A,q,K}$ = factor that results from the time integral of the indirect intake of soil during consumption of animal product q for the $K^{th}$ chemical from the start of irrigation to the end of the exposure duration, 30 y for the all pathways farmer. The factor $F_{V,K}$ is used for beef (slaughtered at the end of the irrigation season). The factor $F_{M,K}$ is used for milk, poultry, and eggs (collected and eaten continuously during the year).

$M_{S,q}$ = daily mass of soil ingested by animal type q in Table A35, in kg/d

$M_{V,q}$ = daily mass of animal fodder eaten by animal type q, in kg (wet)/d. These amounts are shown in Table A35.

q = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

$V_{W,q}$ = daily volume of water ingested by animal type q from Table A35, in L/d

Dermal Absorption of Chemicals for the All Pathways Farmer

The average daily dose via dermal absorption is calculated from the estimated contact with soil and water presented in Section A3.4.2. Soil contacts only the exposed skin, while water contacts the entire body surface during showering or swimming activities.

There are no reference doses or slope factors for dermal absorption, so the ingestion values are used in their place. Because the ingestion factors deal with unit amounts entering the mouth, and the dermal absorption intakes estimate the amounts entering body fluids, the dermal intakes are divided by the GI absorption factor (f1). The formula used to calculate the average daily dose of the $K^{th}$ chemical from dermal absorption is shown below. Note that the permeability coefficient is usually represented with the symbol $K_P$. A different symbol ($U_D$) is used here to avoid confusion with the chemical index K.

$$W_{D,K} = \frac{C_{S,K}\, M_D\, F_{D,K}\, F_{M,K} + C_{W,K}\, F_{E,K}\, V_D\, U_{D,K}}{(365\ \mathrm{d/y})\, M_{ADULT}\, (f1)_K}$$

where,

$C_{S,K}$ = concentration of the $K^{th}$ chemical in the surface soil, in mg/kg. This concentration includes the accumulation from prior years.

$C_{W,K}$ = concentration of the $K^{th}$ chemical in the water, in mg/L

$(f1)_K$ = GI absorption factor, the fraction of the material ingested that is absorbed into body fluids (see Table A23)

$F_{D,K}$ = dermal absorption factors from Table A23 for contact with soil

$F_{E,K}$ = enhanced dermal absorption of organic chemicals in aqueous solution described in EPA 2004. For inorganic chemicals $F_{E,K} = 1.00$. See next page for the calculation of $F_{E,K}$.

$F_{M,K}$ = factor that results from the time integral of the soil intake rate for dermal contact for the $K^{th}$ chemical from the start of irrigation to the end of the exposure duration, 30 y for the all pathways farmer. Note that this factor is the average per year.

$M_{ADULT}$ = mass of an adult, 70 kg

$M_D$ = mass of contaminated soil absorbed through the skin during the year, 0.456 kg/y from Table A21. Numbers shown in Table A21 are calculated as the product of the skin contact area, the soil adherence, and the exposure frequency.

$U_{D,K}$ = permeability coefficient for dermal absorption of the $K^{th}$ chemical in water solution in contact with the skin, in cm/h. Values are listed in Table A23.

$V_D$ = volume of contaminated drinking water absorbed through the skin in a year, 1,825 L/y per cm/h from Table A22. Numbers shown in Table A22 are calculated as the product of the whole body skin area, the event duration, the number of events per day, and the exposure frequency.

$W_{D,K}$ = average daily dose of the $K^{th}$ chemical from dermal absorption, in mg/kg per day. These are adjusted by the GI absorption factors $(f1)_K$ so they can be used with the ingestion reference dose and cancer slope factors.

The enhanced dermal absorption factor for organic chemicals in aqueous solution ($F_{E,K}$) is relatively complicated. It depends on skin permeability parameters listed in Tables A23 and A23a. The method used to calculate this factor is shown below. The reason for the enhanced absorption is that the epidermis soaks up the chemical while it is in contact with the water. This is especially true for chemicals that are lipophilic. The skin then releases the chemical into the blood for some period of time after the shower or swim.

$$\text{when } T_{EVENT} \le T_{SS,K} \quad \text{then} \quad F_{E,K} = F_{LOSS,K}\sqrt{\frac{24\ T_{LAG,K}}{\pi\ T_{EVENT}}}$$

$$\text{when } T_{EVENT} > T_{SS,K} \quad \text{then} \quad F_{E,K} = \frac{F_{LOSS,K}}{1+B_K}\left(1 + \frac{6\,p_K\ T_{LAG,K}}{T_{EVENT}}\right)$$

where,

$B_K$ = permeability ratio for the $K^{th}$ chemical. Values are listed in Table A23a.

$F_{E,K}$ = enhanced dermal absorption of organic chemicals in aqueous solution described in EPA 2004. For inorganic chemicals $F_{E,K} = 1.00$.

$F_{LOSS,K}$ = fraction of the $K^{th}$ chemical deposited on the skin that is lost through the normal process of shedding skin cells (desquamation)

$p_K$ = parameter used in the EPA dermal absorption model. Values are listed in Table A23a.

$T_{EVENT}$ = how long the chemical is in contact with the skin, in hours per event. Showers are either 10 minutes or 15 minutes. Swimming periods last 52 minutes on the average. Values are listed in Table A22.

$T_{LAG,K}$ = time needed for the $K^{th}$ chemical to reach a steady transfer rate through the stratum corneum, which is the outer portion of the epidermis, in hours. Values are listed in Table A23a.

$T_{SS,K}$ = time for the $K^{th}$ chemical to reach a steady state transfer rate through the epidermis, in hours. Values are listed in Table A23a.

Hazard Quotient and Increased Cancer Risk for the All Pathways Farmer -- Chemicals

The calculated hazard quotient and cancer risk per unit concentration in the well or the Columbia River for the All Pathways Farmer are shown in Table 15. These factors are calculated from the sums of the inhalation, ingestion, and dermal absorption intakes, as shown in the equation below. The factors must be multiplied by the estimated water concentration in the contaminated water, in mg per L.

$$W_K = W_{B,K} + W_{G,K} + W_{D,K}$$

**Table 15. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the All Pathways Farmer Scenario**

| | | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| CASRN | Chemical Name | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 50-32-8 | Benzo[a]pyrene | na | 2.47E+00 | na | 6.75E+00 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 3.65E+00 | na | 1.64E+01 |
| 56-23-5 | Carbon tetrachloride | 4.38E+01 | 5.24E-03 | 4.93E+01 | 5.45E-03 |
| 56-55-3 | Benz[a]anthracene | na | 1.74E-01 | na | 3.96E-01 |
| 57-12-5 | Cyanide, free | 3.13E+01 | na | 3.13E+01 | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 4.58E+00 | na | 4.58E+00 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.29E+00 | na | 2.29E+00 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 2.04E+02 | 3.40E-02 | 2.70E+02 | 4.51E-02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 2.12E-01 | na | 2.14E-01 | na |
| 60-34-4 | Methylhydrazine | na | 3.43E+00 | na | 3.43E+00 |
| 60-57-1 | Dieldrin | 1.78E+03 | 1.06E+00 | 9.20E+03 | 3.60E+00 |
| 62-75-9 | N-Nitrosodimethylamine | 2.10E+05 | 3.69E+01 | 2.10E+05 | 3.69E+01 |
| 64-18-6 | Formic acid | 4.82E-01 | na | 4.82E-01 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 1.23E+00 | na | 1.23E+00 | na |
| 67-64-1 | Acetone (2-Propanone) | 2.20E-01 | na | 2.21E-01 | na |
| 67-66-3 | Chloroform | 1.88E+02 | 5.55E-03 | 1.88E+02 | 5.56E-03 |
| 67-72-1 | Hexachloroethane | 5.12E+01 | 1.26E-03 | 9.08E+01 | 1.50E-03 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 2.30E+01 | na | 2.30E+01 | na |
| 71-43-2 | Benzene | 2.64E+01 | 2.60E-03 | 2.67E+01 | 2.63E-03 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 1.25E-01 | na | 1.26E-01 | na |
| 72-20-8 | Endrin | 3.23E+03 | na | 4.12E+03 | na |
| 74-83-9 | Bromomethane | 1.36E+02 | na | 1.37E+02 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | 6.16E+00 | 6.46E-04 | 6.16E+00 | 6.48E-04 |
| 75-00-3 | Ethyl Chloride | 1.37E-01 | 4.04E-05 | 1.38E-01 | 4.09E-05 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 1.59E+01 | 2.21E-02 | 1.61E+01 | 2.24E-02 |
| 75-05-8 | Acetonitrile | 9.26E+00 | na | 9.26E+00 | na |
| 75-07-0 | Acetaldehyde | 6.16E+01 | 5.23E-04 | 6.16E+01 | 5.23E-04 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 7.88E-01 | 2.28E-04 | 7.92E-01 | 2.29E-04 |
| 75-15-0 | Carbon disulfide | 1.09E+00 | na | 1.10E+00 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 8.51E-02 | na | 8.53E-02 |

**Table 15. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the All Pathways Farmer Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.42E+00 | na | 1.43E+00 | na |
| 75-35-4 | 1,1-Dichloroethylene | 3.36E+00 | na | 3.38E+00 | na |
| 75-45-6 | Chlorodifluoromethane | 1.11E-02 | na | 1.11E-02 | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 1.11E-02 | na | 1.11E-02 | na |
| 75-69-4 | Trichlorofluoromethane | 9.09E-01 | na | 9.17E-01 | na |
| 75-71-8 | Dichlorodifluoromethane | 2.94E+00 | na | 2.95E+00 | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 1.95E-02 | na | 1.97E-02 | na |
| 76-44-8 | Heptachlor | 3.34E+02 | 6.28E-01 | 2.89E+03 | 3.10E+00 |
| 78-83-1 | Isobutanol | 3.70E-01 | na | 3.71E-01 | na |
| 78-87-5 | 1,2-Dichloropropane | 1.39E+02 | 9.44E-04 | 1.39E+02 | 9.69E-04 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 3.22E-01 | na | 3.23E-01 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 9.32E+00 | 4.78E-03 | 9.50E+00 | 4.80E-03 |
| 79-01-6 | Trichloroethylene | 1.44E+02 | 3.38E-02 | 1.50E+02 | 3.41E-02 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 8.83E+00 | na | 8.83E+00 | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 6.32E-01 | 1.68E-02 | 6.62E-01 | 1.70E-02 |
| 79-46-9 | 2-Nitropropane | 2.77E+01 | 6.38E-01 | 2.77E+01 | 6.38E-01 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 1.73E+01 | 5.79E-03 | 4.95E+01 | 1.65E-02 |
| 83-32-9 | Acenaphthene | 1.37E+00 | na | 1.84E+00 | na |
| 84-66-2 | Diethyl phthalate | 1.15E-01 | na | 1.18E-01 | na |
| 84-74-2 | Dibutyl phthalate | 4.92E-01 | na | 1.25E+00 | na |
| 85-68-7 | Butyl benzyl phthalate | 3.27E-01 | na | 8.98E-01 | na |
| 86-73-7 | Fluorene | 1.93E+00 | na | 3.02E+00 | na |
| 86-74-8 | Carbazole | na | 6.97E-04 | na | 8.71E-04 |
| 87-68-3 | Hexachlorobutadiene | 2.47E+02 | 7.77E-03 | 6.57E+02 | 1.19E-02 |
| 87-86-5 | Pentachlorophenol | 2.50E+00 | 3.86E-03 | 5.60E+00 | 8.64E-03 |
| 88-06-2 | 2,4,6-Trichlorophenol | 6.56E+02 | 3.88E-04 | 7.32E+02 | 4.24E-04 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 7.78E+01 | na | 9.30E+01 | na |
| 91-20-3 | Naphthalene | 1.87E+02 | na | 1.87E+02 | na |
| 92-52-4 | 1,1'-Biphenyl | 1.30E+00 | na | 1.90E+00 | na |
| 95-47-6 | o-Xylene | 5.72E+00 | na | 5.75E+00 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 3.87E+00 | na | 3.89E+00 | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 3.18E+00 | na | 3.31E+00 | na |
| 95-57-8 | 2-Chlorophenol | 2.40E+01 | na | 2.42E+01 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 9.35E+01 | na | 9.38E+01 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 6.58E-01 | na | 7.38E-01 | na |
| 98-86-2 | Acetophenone | 1.12E+00 | na | 1.12E+00 | na |
| 98-95-3 | Nitrobenzene | 4.74E+02 | na | 4.76E+02 | na |
| 100-00-5 | p-Chloronitrobenzene | 2.86E+02 | 2.88E-04 | 2.88E+02 | 2.94E-04 |
| 100-02-7 | 4-Nitrophenol | 2.39E+01 | na | 2.40E+01 | na |

**Table 15. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the All Pathways Farmer Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 3.00E+03 | na | 3.01E+03 | na |
| 100-41-4 | Ethyl benzene | 8.88E-01 | 2.61E-04 | 9.57E-01 | 2.61E-04 |
| 100-42-5 | Styrene | 7.30E-01 | na | 7.54E-01 | na |
| 100-51-6 | Benzyl alcohol | 6.09E-01 | na | 6.10E-01 | na |
| 106-42-3 | p-Xylene | 5.72E+00 | na | 5.75E+00 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 3.79E+01 | na | 3.81E+01 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 1.88E+00 | 1.86E-03 | 2.26E+00 | 1.98E-03 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 6.63E+01 | 1.79E-01 | 6.64E+01 | 1.80E-01 |
| 106-99-0 | 1,3-Butadiene | 2.77E+02 | 7.13E-03 | 2.77E+02 | 7.13E-03 |
| 107-02-8 | 2-Propenal (Acrolein) | 2.80E+04 | na | 2.80E+04 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 5.54E+02 | na | 5.54E+02 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 1.15E+02 | 7.65E-03 | 1.15E+02 | 7.66E-03 |
| 107-13-1 | Acrylonitrile | 3.80E+02 | 3.98E-02 | 3.80E+02 | 3.99E-02 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 8.28E-01 | na | 8.31E-01 | na |
| 108-38-3 | m-Xylene | 5.72E+00 | na | 5.76E+00 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 3.75E+00 | na | 3.77E+00 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 9.34E+01 | na | 9.36E+01 | na |
| 108-87-2 | Methyl cyclohexane | 1.85E-01 | na | 1.85E-01 | na |
| 108-88-3 | Toluene (Methyl benzene) | 5.13E-01 | na | 5.54E-01 | na |
| 108-90-7 | Chlorobenzene | 1.13E+01 | na | 1.15E+01 | na |
| 108-94-1 | Cyclohexanone | 3.59E-02 | na | 3.60E-02 | na |
| 108-95-2 | Phenol (Carbolic acid) | 1.02E+00 | na | 1.02E+00 | na |
| 109-99-9 | Tetrahydrofuran | 2.21E+00 | 7.07E-04 | 2.21E+00 | 7.08E-04 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 3.68E+01 | na | 3.71E+01 | na |
| 110-54-3 | n-Hexane | 1.67E+00 | na | 2.10E+00 | na |
| 110-80-5 | 2-Ethoxyethanol | 1.33E+00 | na | 1.33E+00 | na |
| 110-82-7 | Cyclohexane | 9.26E-02 | na | 9.26E-02 | na |
| 110-86-1 | Pyridine | 2.60E+02 | na | 2.61E+02 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 2.60E-01 | na | 2.61E-01 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 1.23E+01 | na | 1.23E+01 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 2.50E+02 | 3.00E-02 | 2.52E+02 | 3.03E-02 |
| 117-84-0 | Di-n-octylphthalate | 1.54E+02 | na | 1.55E+02 | na |
| 118-74-1 | Hexachlorobenzene | 2.57E+02 | 2.49E-01 | 1.09E+03 | 7.04E-01 |
| 120-12-7 | Anthracene | 2.48E-01 | na | 4.83E-01 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.43E+02 | na | 1.46E+02 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 9.91E+01 | na | 9.98E+01 | na |
| 121-44-8 | Triethylamine | 7.92E+01 | na | 7.92E+01 | na |
| 122-39-4 | Diphenylamine | 2.86E+00 | na | 3.39E+00 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 1.44E-03 | na | 1.44E-03 |

**Table 15. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the All Pathways Farmer Scenario**

| | | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| CASRN | Chemical Name | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 126-73-8 | Tributyl Phosphate | 3.07E-01 | 1.42E-04 | 3.36E-01 | 1.56E-04 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.51E+03 | na | 1.51E+03 | na |
| 127-18-4 | Tetrachloroethylene | 4.12E+00 | 8.81E-03 | 5.19E+00 | 1.13E-02 |
| 129-00-0 | Pyrene | 6.22E+00 | na | 1.15E+01 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 8.02E-02 | na | 8.07E-02 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 3.16E+00 | na | 3.23E+00 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 1.50E+00 | na | 1.55E+00 | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 3.40E-01 | na | 1.51E+00 |
| 205-99-2 | Benzo[b]fluoranthene | na | 1.48E-01 | na | 3.80E-01 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 6.59E+00 | na | 1.29E+01 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 2.40E-02 | na | 6.53E-02 |
| 218-01-9 | Chrysene | na | 1.81E-03 | na | 4.25E-03 |
| 309-00-2 | Aldrin | 1.68E+04 | 4.84E+00 | 1.04E+05 | 2.38E+01 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 1.13E+02 | 3.65E-01 | 1.58E+02 | 4.26E-01 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 3.08E+02 | 4.97E-02 | 4.18E+02 | 6.67E-02 |
| 541-73-1 | 1,3-Dichlorobenzene | 4.19E+01 | na | 5.69E+01 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 2.88E+01 | 2.36E-03 | 2.89E+01 | 2.40E-03 |
| 563-68-8 | Thallium acetate | 5.71E+02 | na | 1.49E+04 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 1.04E+00 | na | 1.04E+00 |
| 1314-62-1 | Vanadium pentoxide | 3.67E+00 | na | 6.91E+00 | na |
| 1330-20-7 | Xylenes (mixtures) | 5.71E+00 | na | 5.74E+00 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 1.08E-01 | na | 6.51E+00 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 7.41E-02 | na | 6.48E+00 |
| 6533-73-9 | Thallium carbonate | 6.42E+02 | na | 1.68E+04 | na |
| 7429-90-5 | Aluminum | 3.91E-02 | na | 1.07E-01 | na |
| 7439-89-6 | Iron | 1.43E-01 | na | 2.41E-01 | na |
| 7439-93-2 | Lithium | 3.73E+00 | na | 3.90E+00 | na |
| 7439-96-5 | Manganese | 1.77E+00 | na | 2.23E+00 | na |
| 7439-97-6 | Mercury metal vapor | 3.91E-02 | na | 3.91E-02 | na |
| 7439-98-7 | Molybdenum | 3.85E+01 | na | 3.90E+01 | na |
| 7440-02-0 | Nickel (soluble salts) | 4.15E+00 | na | 4.96E+00 | na |
| 7440-22-4 | Silver | 7.35E+00 | na | 8.11E+00 | na |
| 7440-24-6 | Strontium, Stable | 3.53E-01 | na | 3.71E-01 | na |
| 7440-28-0 | Thallium metal | 7.78E+02 | na | 2.03E+04 | na |
| 7440-31-5 | Tin | 1.22E-01 | na | 7.72E-01 | na |
| 7440-36-0 | Antimony | 8.15E+01 | na | 1.27E+02 | na |
| 7440-38-2 | Arsenic (inorganic) | 1.14E+02 | 2.21E-02 | 2.39E+02 | 4.61E-02 |
| 7440-39-3 | Barium | 2.64E-01 | na | 2.83E-01 | na |
| 7440-41-7 | Beryllium and compounds | 1.78E+01 | 4.21E-05 | 2.77E+01 | 4.21E-05 |
| 7440-42-8 | Boron and borates only | 1.64E+00 | na | 1.64E+00 | na |

**Table 15. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the All Pathways Farmer Scenario**

| | | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| CASRN | Chemical Name | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 7440-43-9 | Cadmium | 9.56E+01 | 3.10E-05 | 1.34E+02 | 3.10E-05 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 2.07E-01 | na | 2.07E-01 | na |
| 7440-48-4 | Cobalt | 4.73E+00 | 4.79E-05 | 6.80E+00 | 4.79E-05 |
| 7440-50-8 | Copper | 6.23E+00 | na | 6.94E+00 | na |
| 7440-62-2 | Vanadium metal | 5.02E+00 | na | 9.73E+00 | na |
| 7440-66-6 | Zinc and compounds | 6.81E+01 | na | 6.82E+01 | na |
| 7446-18-6 | Thallium sulfate | 6.42E+02 | na | 1.68E+04 | na |
| 7487-94-7 | Mercuric chloride | 1.32E+03 | na | 1.75E+03 | na |
| 7664-41-7 | Ammonia | 3.65E+00 | na | 3.65E+00 | na |
| 7723-14-0 | Phosphorus, white | 1.10E+05 | na | 1.20E+05 | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 1.84E+00 | na | 1.91E+00 | na |
| 7782-49-2 | Selenium and compounds | 1.31E+01 | na | 1.76E+01 | na |
| 7791-12-0 | Thallium chloride | 6.42E+02 | na | 1.68E+04 | na |
| 8001-35-2 | Toxaphene | na | 7.79E-02 | na | 4.21E-01 |
| 10102-45-1 | Thallium (I) nitrate | 5.70E+02 | na | 1.49E+04 | na |
| 11096-82-5 | Aroclor 1260 | na | 4.97E+00 | na | 5.52E+00 |
| 11097-69-1 | Aroclor 1254 | 2.78E+04 | 2.32E-01 | 9.34E+05 | 1.58E+01 |
| 11104-28-2 | Aroclor 1221 | na | 4.14E-02 | na | 1.10E-01 |
| 11141-16-5 | Aroclor 1232 | na | 4.14E-02 | na | 1.10E-01 |
| 12672-29-6 | Aroclor 1248 | na | 1.08E-01 | na | 7.10E+00 |
| 12674-11-2 | Aroclor 1016 | 2.09E+03 | 4.53E-02 | 3.46E+04 | 2.00E+00 |
| 14797-55-8 | Nitrate | 1.35E-02 | na | 1.39E-02 | na |
| 14797-65-0 | Nitrite | 2.16E-01 | na | 2.22E-01 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 2.73E-02 | na | 5.12E-02 | na |
| 16984-48-8 | Fluorine anion | 1.84E+00 | na | 1.91E+00 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 1.08E+01 | 5.19E-05 | 1.95E+01 | 5.19E-05 |
| 22967-92-6 | Methyl mercury | 3.96E+03 | na | 5.26E+03 | na |
| 53469-21-9 | Aroclor 1242 | na | 1.06E-01 | na | 6.51E+00 |
| na | Uranium (soluble salts) | 5.49E+01 | na | 5.92E+01 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 1.56E+00 | 7.41E-06 | 2.82E+00 | 7.41E-06 |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The total risk to the All Pathways Farmer is calculated using intakes from 30 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario factors must be multiplied by the appropriate water concentration. The "Well Water Only" columns assume all the contaminated water comes from a well. The "Columbia River" columns assume all the contaminated water comes from the Columbia River.
- Results using route-to-route extrapolations are shown in Table C4.

## 3.6 POPULATION ALONG THE COLUMBIA RIVER

The unit exposure factors for the estimated 5 million people living along the Columbia River is calculated using consumption rates discussed in Appendix A. The contaminants are located in the Columbia River due to flow from the aquifer into the river. As time goes on, some contaminants accumulate in the soil due to irrigation from the river. The soil leaching rates are presented in Section A6.0. These are different due to different irrigation rates.

The affected population has 50% of its garden produce and animal products contaminated. The other half comes from distant sources that are not contaminated. Average drinking water and food consumption rates apply to the population. The average fish consumption is based on the total harvested from the Columbia River each year. All of the pathways used for the All Pathways Farmer are used for the population. Consumption of game and waterfowl is not included. The dermal exposures are given in Section A3.4. There are minor differences with the All Pathways Farmer in the average intakes from various pathways. Three significant differences are (1) the lower average irrigation rate (63.5 cm/y rather than 82.3 cm/y), (2) much smaller fish consumption rates, and (3) scaling by 5 million. The lower irrigation rate reflects increased precipitation near the ocean. The smaller fish consumption rate is based on estimates of the annual harvest of fish from the Columbia River averaged over the large population.

Scenario dose factors for the Columbia River Population are presented in Table 16 as the collective, or total, dose equivalent in person-rem per pCi/L in the water. These unit dose factors must be multiplied by the water concentration to calculate the actual dose. The radiation dose to this population is the 50 year committed effective dose equivalent from one year of exposure. The dose from drinking water is the main contributor to the total for most radionuclides. The average dose per individual can be calculated by dividing the doses in Table 19 by the population, 5,000,000 people.

**Table 16. Unit Dose Factors for the Columbia River Population (person-rem/y per pCi/L)**

| Nuclide | Total Population | Drinking Water | Ratio | Nuclide | Total Population | Drinking Water | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 2.48E-01 | 1.74E-01 | 1.42 | Eu-155 | 6.85E+00 | 4.16E+00 | 1.65 |
| Be-10 | 1.63E+01 | 1.27E+01 | 1.28 | Gd-152 | 5.77E+02 | 4.38E+02 | 1.32 |
| C-14 | 2.04E+01 | 5.69E+00 | 3.59 | Tb-157 | 4.83E-01 | 3.38E-01 | 1.43 |
| Na-22 | 1.95E+02 | 3.13E+01 | 6.23 | Ho-166m | 1.36E+02 | 2.20E+01 | 6.21 |
| Al-26 | 2.23E+02 | 3.97E+01 | 5.62 | Re-187 | 4.08E-02 | 2.59E-02 | 1.58 |
| Si-32+D | 3.82E+01 | 2.99E+01 | 1.28 | Tl-204 | 2.03E+01 | 9.15E+00 | 2.22 |
| Cl-36 | 1.22E+02 | 8.25E+00 | 14.7 | Pb-205 | 5.75E+00 | 4.45E+00 | 1.29 |
| K-40 | 1.24E+02 | 5.06E+01 | 2.46 | Pb-210+D | 1.93E+04 | 1.46E+04 | 1.32 |
| Ca-41 | 5.52E+00 | 3.47E+00 | 1.59 | Bi-207 | 1.05E+02 | 1.49E+01 | 7.04 |
| Ti-44+D | 3.02E+02 | 6.69E+01 | 4.51 | Po-209 | 9.88E+03 | 6.46E+03 | 1.53 |
| V-49 | 2.16E-01 | 1.67E-01 | 1.29 | Po-210 | 7.53E+03 | 5.18E+03 | 1.45 |
| Mn-53 | 3.78E-01 | 2.94E-01 | 1.28 | Ra-226+D | 5.03E+03 | 3.61E+03 | 1.39 |
| Mn-54 | 2.89E+01 | 7.54E+00 | 3.83 | Ra-228+D | 5.36E+03 | 3.92E+03 | 1.37 |
| Fe-55 | 2.76E+00 | 1.65E+00 | 1.67 | Ac-227+D | 5.00E+04 | 4.02E+04 | 1.24 |
| Fe-60+D | 7.67E+02 | 4.15E+02 | 1.85 | Th-228+D | 2.77E+03 | 2.21E+03 | 1.26 |
| Co-60 | 2.11E+02 | 7.34E+01 | 2.87 | Th-229+D | 1.37E+04 | 1.10E+04 | 1.25 |

**Table 16. Unit Dose Factors for the Columbia River Population (person-rem/y per pCi/L)**

| Nuclide | Total Population | Drinking Water | Ratio | Nuclide | Total Population | Drinking Water | Ratio |
|---|---|---|---|---|---|---|---|
| Ni-59 | 1.42E+00 | 5.72E-01 | 2.49 | Th-230 | 1.86E+03 | 1.49E+03 | 1.25 |
| Ni-63 | 3.92E+00 | 1.57E+00 | 2.49 | Th-232 | 9.34E+03 | 7.44E+03 | 1.26 |
| Se-79 | 5.55E+01 | 2.37E+01 | 2.34 | Pa-231 | 3.59E+04 | 2.88E+04 | 1.25 |
| Rb-87 | 3.46E+01 | 1.34E+01 | 2.58 | U-232 | 4.81E+03 | 3.57E+03 | 1.35 |
| Sr-90+D | 7.15E+02 | 4.18E+02 | 1.71 | U-233 | 1.05E+03 | 7.87E+02 | 1.33 |
| Zr-93 | 5.62E+00 | 4.52E+00 | 1.24 | U-234 | 1.03E+03 | 7.72E+02 | 1.33 |
| Nb-91 | 1.90E+00 | 1.42E+00 | 1.34 | U-235+D | 9.79E+02 | 7.29E+02 | 1.34 |
| Nb-93m | 1.77E+00 | 1.42E+00 | 1.24 | U-236 | 9.77E+02 | 7.32E+02 | 1.33 |
| Nb-94 | 1.23E+02 | 1.95E+01 | 6.32 | U-238+D | 9.76E+02 | 7.31E+02 | 1.34 |
| Mo-93 | 5.60E+00 | 3.67E+00 | 1.52 | Np-237+D | 1.53E+04 | 1.21E+04 | 1.26 |
| Tc-97 | 1.07E+00 | 4.67E-01 | 2.29 | Pu-236 | 3.93E+03 | 3.18E+03 | 1.24 |
| Tc-99 | 9.06E+00 | 3.98E+00 | 2.27 | Pu-238 | 1.08E+04 | 8.72E+03 | 1.24 |
| Ru-106+D | 1.61E+02 | 7.46E+01 | 2.16 | Pu-239 | 1.20E+04 | 9.64E+03 | 1.24 |
| Pd-107 | 8.32E-01 | 4.07E-01 | 2.04 | Pu-240 | 1.20E+04 | 9.64E+03 | 1.24 |
| Ag-108m+D | 1.28E+02 | 2.08E+01 | 6.14 | Pu-241+D | 2.32E+02 | 1.87E+02 | 1.24 |
| Cd-109+D | 4.85E+01 | 3.58E+01 | 1.35 | Pu-242 | 1.14E+04 | 9.15E+03 | 1.24 |
| Cd-113m | 6.01E+02 | 4.39E+02 | 1.37 | Pu-244+D | 1.13E+04 | 9.06E+03 | 1.25 |
| In-115 | 8.52E+02 | 4.30E+02 | 1.98 | Am-241 | 1.23E+04 | 9.92E+03 | 1.24 |
| Sn-121m+D | 1.80E+01 | 6.13E+00 | 2.94 | Am-242m+D | 1.19E+04 | 9.58E+03 | 1.24 |
| Sn-126+D | 2.93E+02 | 5.73E+01 | 5.12 | Am-243+D | 1.23E+04 | 9.88E+03 | 1.24 |
| Sb-125 | 2.33E+01 | 7.65E+00 | 3.04 | Cm-242 | 3.80E+02 | 3.13E+02 | 1.22 |
| Te-125m | 1.37E+01 | 1.00E+01 | 1.37 | Cm-243 | 8.52E+03 | 6.85E+03 | 1.24 |
| I-129 | 2.07E+03 | 7.52E+02 | 2.75 | Cm-244 | 6.83E+03 | 5.49E+03 | 1.24 |
| Cs-134 | 6.11E+02 | 2.00E+02 | 3.06 | Cm-245 | 1.27E+04 | 1.02E+04 | 1.24 |
| Cs-135 | 5.68E+01 | 1.93E+01 | 2.95 | Cm-246 | 1.25E+04 | 1.01E+04 | 1.24 |
| Cs-137+D | 4.32E+02 | 1.36E+02 | 3.17 | Cm-247+D | 1.16E+04 | 9.32E+03 | 1.25 |
| Ba-133 | 2.78E+01 | 9.27E+00 | 3.00 | Cm-248 | 4.62E+04 | 3.71E+04 | 1.24 |
| Ce-144+D | 7.19E+01 | 5.76E+01 | 1.25 | Cm-250+D | 2.64E+05 | 2.12E+05 | 1.24 |
| Pm-147 | 3.80E+00 | 2.85E+00 | 1.33 | Bk-247 | 1.59E+04 | 1.28E+04 | 1.24 |
| Sm-147 | 6.79E+02 | 5.05E+02 | 1.34 | Cf-248 | 1.20E+03 | 9.11E+02 | 1.31 |
| Sm-151 | 1.42E+00 | 1.06E+00 | 1.34 | Cf-249 | 1.73E+04 | 1.29E+04 | 1.34 |
| Eu-150 | 1.07E+02 | 1.73E+01 | 6.15 | Cf-250 | 7.78E+03 | 5.81E+03 | 1.34 |
| Eu-152 | 7.92E+01 | 1.76E+01 | 4.49 | Cf-251 | 1.77E+04 | 1.32E+04 | 1.34 |
| Eu-154 | 8.96E+01 | 2.60E+01 | 3.44 | Cf-252 | 3.93E+03 | 2.95E+03 | 1.33 |

Notes:

- The unit dose factors for the Columbia River Population are the total 50 year committed effective dose equivalent from one year of exposure to 5 million people. The average per person can be obtained by dividing the values on this table by 5,000,000.
- These scenario dose factors must be multiplied by the water concentration.
- The "Total population" column includes the full scenario. The column "Drinking Water" shows just the drinking water dose. The "Ratio" column is the "Total Population" divided by the "Drinking Water" doses.

The increase in cancer risk due to radioactive contaminants entering the Columbia River is calculated using the same equations presented for the radiation dose previously. The two differences are (1) the use of the risk coefficients from Federal Guidance Report Number 13

(Tables A32 and A33) rather than radiation dose factors, and (2) the calculation of the cumulative risk from 70 years of contamination. The lifetime exposure is at the adult consumption rates.

The lifetime increase in the risk of developing some type of cancer from the radionuclides is the sum of 70 years of exposure. Each year there is a small amount of the radioactive material in the soil from previous years. This leads to a total risk that is greater than 70 times the first year's risk for many nuclides. The estimated risks from radioactive materials in the Columbia River are shown in Table 17. The first column of risks shows the 70-year total. The second column shows the risk from the first year multiplied by 70. The third column is the ratio of the 70-year total to the 70-times-first-year risk. If the two numbers are within 10%, they are not shown. Radionuclides with large ratios generally indicate that the isotopes accumulate in the soil and that the soil pathways (soil ingestion and inhalation, plants, and animals) are significant compared to the drinking water pathway. The average lifetime risk per individual can be calculated by dividing the collective risk in Table 17 by the population, 5,000,000 people.

**Table 17. Unit Risk Factors for Radionuclides in the Columbia River Population Scenario (total risk per pCi/L)**

| Nuclide | 70-year Total | 70 Times First Year | Ratio | Nuclide | 70-year Total | 70 Times First Year | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 3.28E-02 | 3.28E-02 | 0.0 | Eu-155 | 9.43E-01 | 6.02E-01 | 1.6 |
| Be-10 | 1.99E+00 | 1.89E+00 | 0.0 | Gd-152 | 8.46E+00 | 7.98E+00 | 0.0 |
| C-14 | 2.43E+00 | 1.28E+00 | 1.9 | Tb-157 | 7.91E-02 | 5.40E-02 | 1.5 |
| Na-22 | 2.85E+01 | 1.33E+01 | 2.1 | Ho-166m | 1.40E+02 | 8.56E+00 | 16.4 |
| Al-26 | 2.52E+02 | 1.58E+01 | 15.9 | Re-187 | 1.67E-02 | 6.24E-03 | 2.7 |
| Si-32+D | 4.26E+00 | 3.28E+00 | 1.3 | Tl-204 | 3.07E+00 | 3.03E+00 | 0.0 |
| Cl-36 | 6.19E+01 | 1.23E+01 | 5.0 | Pb-205 | 1.78E-01 | 1.67E-01 | 0.0 |
| K-40 | 3.92E+01 | 1.37E+01 | 2.9 | Pb-210+D | 3.14E+02 | 2.68E+02 | 1.2 |
| Ca-41 | 2.99E-01 | 1.17E-01 | 2.6 | Bi-207 | 8.58E+01 | 6.79E+00 | 12.6 |
| Ti-44+D | 1.64E+02 | 2.45E+01 | 6.7 | Po-209 | 4.47E+02 | 3.72E+02 | 1.2 |
| V-49 | 3.33E-02 | 3.32E-02 | 0.0 | Po-210 | 2.67E+02 | 2.66E+02 | 0.0 |
| Mn-53 | 8.28E-02 | 4.21E-02 | 2.0 | Ra-226+D | 3.10E+02 | 1.16E+02 | 2.7 |
| Mn-54 | 3.04E+00 | 1.77E+00 | 1.7 | Ra-228+D | 3.45E+02 | 2.99E+02 | 1.2 |
| Fe-55 | 3.15E-01 | 3.12E-01 | 0.0 | Ac-227+D | 1.41E+02 | 1.25E+02 | 1.1 |
| Fe-60+D | 2.57E+02 | 7.02E+01 | 3.7 | Th-228+D | 8.73E+01 | 7.94E+01 | 0.0 |
| Co-60 | 4.83E+01 | 1.15E+01 | 4.2 | Th-229+D | 1.62E+02 | 1.35E+02 | 1.2 |
| Ni-59 | 2.04E-01 | 1.63E-01 | 1.3 | Th-230 | 2.58E+01 | 2.30E+01 | 1.1 |
| Ni-63 | 4.84E-01 | 3.98E-01 | 1.2 | Th-232 | 2.20E+02 | 3.08E+01 | 7.1 |
| Se-79 | 4.13E+00 | 3.88E+00 | 0.0 | Pa-231 | 6.38E+01 | 4.41E+01 | 1.4 |
| Rb-87 | 9.97E+00 | 3.13E+00 | 3.2 | U-232 | 1.48E+02 | 8.31E+01 | 1.8 |
| Sr-90+D | 7.27E+01 | 2.71E+01 | 2.7 | U-233 | 2.10E+01 | 1.99E+01 | 0.0 |
| Zr-93 | 2.97E-01 | 2.80E-01 | 0.0 | U-234 | 2.06E+01 | 1.96E+01 | 0.0 |
| Nb-91 | 3.61E-01 | 2.15E-01 | 1.7 | U-235+D | 2.63E+01 | 2.03E+01 | 1.3 |
| Nb-93m | 2.16E-01 | 2.08E-01 | 0.0 | U-236 | 1.95E+01 | 1.86E+01 | 0.0 |
| Nb-94 | 1.33E+02 | 7.97E+00 | 16.7 | U-238+D | 2.66E+01 | 2.44E+01 | 0.0 |
| Mo-93 | 2.45E+00 | 1.06E+00 | 2.3 | Np-237+D | 3.07E+01 | 1.81E+01 | 1.7 |
| Tc-97 | 1.03E+00 | 1.46E-01 | 7.0 | Pu-236 | 2.14E+01 | 1.88E+01 | 1.1 |

**Table 17. Unit Risk Factors for Radionuclides in the Columbia River Population Scenario (total risk per pCi/L)**

| Nuclide | 70-year Total | 70 Times First Year | Ratio | Nuclide | 70-year Total | 70 Times First Year | Ratio |
|---|---|---|---|---|---|---|---|
| Tc-99 | 1.05E+01 | 1.50E+00 | 7.0 | Pu-238 | 3.38E+01 | 3.29E+01 | 0.0 |
| Ru-106+D | 2.17E+01 | 2.11E+01 | 0.0 | Pu-239 | 3.51E+01 | 3.39E+01 | 0.0 |
| Pd-107 | 1.55E-01 | 1.21E-01 | 1.3 | Pu-240 | 3.51E+01 | 3.39E+01 | 0.0 |
| Ag-108m+D | 1.24E+02 | 8.15E+00 | 15.2 | Pu-241+D | 4.77E-01 | 4.43E-01 | 0.0 |
| Cd-109+D | 1.45E+00 | 1.41E+00 | 0.0 | Pu-242 | 3.32E+01 | 3.21E+01 | 0.0 |
| Cd-113m | 1.01E+01 | 8.06E+00 | 1.3 | Pu-244+D | 6.58E+01 | 3.76E+01 | 1.7 |
| In-115 | 1.51E+01 | 1.46E+01 | 0.0 | Am-241 | 2.75E+01 | 2.61E+01 | 0.0 |
| Sn-121m+D | 2.86E+00 | 2.56E+00 | 1.1 | Am-242m+D | 2.04E+01 | 1.84E+01 | 0.0 |
| Sn-126+D | 1.86E+02 | 2.70E+01 | 6.9 | Am-243+D | 4.00E+01 | 2.78E+01 | 1.4 |
| Sb-125 | 4.69E+00 | 1.92E+00 | 2.4 | Cm-242 | 9.58E+00 | 9.58E+00 | 0.0 |
| Te-125m | 9.64E-01 | 9.64E-01 | 0.0 | Cm-243 | 2.91E+01 | 2.41E+01 | 1.2 |
| I-129 | 1.25E+02 | 1.09E+02 | 1.1 | Cm-244 | 2.13E+01 | 2.10E+01 | 0.0 |
| Cs-134 | 3.80E+01 | 2.87E+01 | 1.3 | Cm-245 | 3.16E+01 | 2.64E+01 | 1.2 |
| Cs-135 | 5.86E+00 | 3.09E+00 | 1.9 | Cm-246 | 2.65E+01 | 2.56E+01 | 0.0 |
| Cs-137+D | 5.97E+01 | 2.15E+01 | 2.8 | Cm-247+D | 5.15E+01 | 2.63E+01 | 2.0 |
| Ba-133 | 1.05E+01 | 2.70E+00 | 3.9 | Cm-248 | 2.48E+02 | 2.39E+02 | 0.0 |
| Ce-144+D | 9.14E+00 | 9.05E+00 | 0.0 | Cm-250+D | 5.80E+02 | 5.38E+02 | 0.0 |
| Pm-147 | 4.81E-01 | 4.79E-01 | 0.0 | Bk-247 | 3.79E+01 | 3.14E+01 | 1.2 |
| Sm-147 | 1.08E+01 | 1.03E+01 | 0.0 | Cf-248 | 1.22E+01 | 1.22E+01 | 0.0 |
| Sm-151 | 1.66E-01 | 1.59E-01 | 0.0 | Cf-249 | 6.16E+01 | 3.60E+01 | 1.7 |
| Eu-150 | 8.17E+01 | 6.07E+00 | 13.4 | Cf-250 | 2.44E+01 | 2.37E+01 | 0.0 |
| Eu-152 | 4.10E+01 | 5.15E+00 | 8.0 | Cf-251 | 4.59E+01 | 3.67E+01 | 1.3 |
| Eu-154 | 3.39E+01 | 6.33E+00 | 5.4 | Cf-252 | 1.91E+01 | 1.89E+01 | 0.0 |

Notes:

- The total risk to the population along the Columbia River is calculated using intakes from 70 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario risk factors must be multiplied by the water concentration.
- The "70-year Total" column gives the Columbia River Population scenario risk factors. The column "70 Times First Year" shows the first year risk multiplied by 70. The "Ratio" column is the "70-year Total" divided by the "70 Times First Year" risks. Blank entries indicate the two risks are within 10 percent of each other.

The hazard quotient and cancer risk from chemicals are calculated using the same consumption parameters discussed in Appendix A for the population. The contaminant concentration in river water is expressed in mg/L. The chemical dose is normalized to the average adult body mass, 70 kg. The hazard quotient is based on the annual average daily dose (averaged over the period of exposure). The increased cancer risk is based on the lifetime average daily dose. To calculate the average daily dose over a lifetime, the dose from 70 consecutive years is calculated and then divided by (70 y)(365 d/y) to obtain the daily average. As part of this calculation, the concentration of the contaminants in soil is increased each year. The effect of leaching from the surface layer is included using the leaching coefficients shown in Table A41. Dermal absorption during showering and swimming is included.

The calculated hazard quotient and cancer risk per unit concentration in the Columbia River for a population of 5 million are shown in Table 18. The factors must be multiplied by the estimated water concentration in the Columbia River, in mg per L.

**Table 18. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the Columbia River Population Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 50-32-8 | Benzo[a]pyrene | na | 3.12E+07 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 4.86E+07 |
| 56-23-5 | Carbon tetrachloride | 2.40E+08 | 6.30E+04 |
| 56-55-3 | Benz[a]anthracene | na | 2.15E+06 |
| 57-12-5 | Cyanide, free | 2.41E+08 | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 8.35E+07 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 1.77E+07 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 1.58E+09 | 6.18E+05 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 1.35E+06 | na |
| 60-34-4 | Methylhydrazine | na | 6.24E+07 |
| 60-57-1 | Dieldrin | 1.02E+10 | 1.33E+07 |
| 62-75-9 | N-Nitrosodimethylamine | 1.64E+12 | 6.71E+08 |
| 64-18-6 | Formic acid | 3.73E+06 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 9.44E+06 | na |
| 67-64-1 | Acetone (2-Propanone) | 1.65E+06 | na |
| 67-66-3 | Chloroform | 9.40E+08 | 6.49E+04 |
| 67-72-1 | Hexachloroethane | 2.77E+08 | 1.50E+04 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.17E+08 | na |
| 71-43-2 | Benzene | 1.38E+08 | 3.17E+04 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 6.35E+05 | na |
| 72-20-8 | Endrin | 1.69E+10 | na |
| 74-83-9 | Bromomethane | 7.10E+08 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | 3.08E+07 | 8.16E+03 |
| 75-00-3 | Ethyl Chloride | 7.57E+05 | 5.56E+02 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 8.81E+07 | 2.96E+05 |
| 75-05-8 | Acetonitrile | 4.63E+07 | na |
| 75-07-0 | Acetaldehyde | 3.08E+08 | 6.10E+03 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 4.61E+06 | 2.97E+03 |
| 75-15-0 | Carbon disulfide | 5.67E+06 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 1.33E+06 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 7.36E+06 | na |
| 75-35-4 | 1,1-Dichloroethylene | 1.72E+07 | na |
| 75-45-6 | Chlorodifluoromethane | 5.54E+04 | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 5.54E+04 | na |
| 75-69-4 | Trichlorofluoromethane | 4.60E+06 | na |
| 75-71-8 | Dichlorodifluoromethane | 1.48E+07 | na |

**Table 18. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the Columbia River Population Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 9.80E+04 | na |
| 76-44-8 | Heptachlor | 1.76E+09 | 7.52E+06 |
| 78-83-1 | Isobutanol | 2.68E+06 | na |
| 78-87-5 | 1,2-Dichloropropane | 6.95E+08 | 1.28E+04 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 2.10E+06 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 5.70E+07 | 5.81E+04 |
| 79-01-6 | Trichloroethylene | 7.82E+08 | 4.02E+05 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 4.53E+07 | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 3.85E+06 | 2.05E+05 |
| 79-46-9 | 2-Nitropropane | 1.39E+08 | 7.44E+06 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 9.92E+07 | 7.74E+04 |
| 83-32-9 | Acenaphthene | 7.69E+06 | na |
| 84-66-2 | Diethyl phthalate | 8.44E+05 | na |
| 84-74-2 | Dibutyl phthalate | 2.97E+06 | na |
| 85-68-7 | Butyl benzyl phthalate | 2.19E+06 | na |
| 86-73-7 | Fluorene | 1.11E+07 | na |
| 86-74-8 | Carbazole | na | 1.45E+04 |
| 87-68-3 | Hexachlorobutadiene | 1.30E+09 | 9.22E+04 |
| 87-86-5 | Pentachlorophenol | 1.43E+07 | 5.14E+04 |
| 88-06-2 | 2,4,6-Trichlorophenol | 4.41E+09 | 5.78E+03 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 6.42E+08 | na |
| 91-20-3 | Naphthalene | 9.37E+08 | na |
| 92-52-4 | 1,1'-Biphenyl | 7.32E+06 | na |
| 95-47-6 | o-Xylene | 2.87E+07 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 3.06E+07 | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 1.61E+07 | na |
| 95-57-8 | 2-Chlorophenol | 1.79E+08 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 4.68E+08 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 4.42E+06 | na |
| 98-86-2 | Acetophenone | 8.15E+06 | na |
| 98-95-3 | Nitrobenzene | 2.82E+09 | na |
| 100-00-5 | p-Chloronitrobenzene | 1.67E+09 | 4.98E+03 |
| 100-02-7 | 4-Nitrophenol | 1.88E+08 | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 2.38E+10 | na |
| 100-41-4 | Ethyl benzene | 4.61E+06 | 3.05E+03 |
| 100-42-5 | Styrene | 3.77E+06 | na |
| 100-51-6 | Benzyl alcohol | 4.57E+06 | na |
| 106-42-3 | p-Xylene | 2.87E+07 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 2.99E+08 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 1.00E+07 | 2.21E+04 |

**Table 18. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the Columbia River Population Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 3.38E+08 | 1.10E+06 |
| 106-99-0 | 1,3-Butadiene | 1.39E+09 | 8.32E+04 |
| 107-02-8 | 2-Propenal (Acrolein) | 1.40E+11 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 2.77E+09 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 5.77E+08 | 9.32E+04 |
| 107-13-1 | Acrylonitrile | 2.12E+09 | 5.86E+05 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 5.17E+06 | na |
| 108-38-3 | m-Xylene | 2.87E+07 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 2.95E+07 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 4.67E+08 | na |
| 108-87-2 | Methyl cyclohexane | 9.24E+05 | na |
| 108-88-3 | Toluene (Methyl benzene) | 2.80E+06 | na |
| 108-90-7 | Chlorobenzene | 5.74E+07 | na |
| 108-94-1 | Cyclohexanone | 2.68E+05 | na |
| 108-95-2 | Phenol (Carbolic acid) | 8.11E+06 | na |
| 109-99-9 | Tetrahydrofuran | 1.17E+07 | 9.38E+03 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 2.26E+08 | na |
| 110-54-3 | n-Hexane | 8.61E+06 | na |
| 110-80-5 | 2-Ethoxyethanol | 1.01E+07 | na |
| 110-82-7 | Cyclohexane | 4.63E+05 | na |
| 110-86-1 | Pyridine | 1.97E+09 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 1.90E+06 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 9.51E+07 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 1.45E+09 | 4.05E+05 |
| 117-84-0 | Di-n-octylphthalate | 1.03E+09 | na |
| 118-74-1 | Hexachlorobenzene | 1.33E+09 | 2.97E+06 |
| 120-12-7 | Anthracene | 1.48E+06 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 7.18E+08 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 7.93E+08 | na |
| 121-44-8 | Triethylamine | 3.96E+08 | na |
| 122-39-4 | Diphenylamine | 2.01E+07 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 2.54E+04 |
| 126-73-8 | Tributyl Phosphate | 2.14E+06 | 2.31E+03 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 8.92E+09 | na |
| 127-18-4 | Tetrachloroethylene | 2.20E+07 | 1.10E+05 |
| 129-00-0 | Pyrene | 3.56E+07 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 5.58E+05 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 1.84E+07 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 8.51E+06 | na |

**Table 18. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the Columbia River Population Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 4.52E+06 |
| 205-99-2 | Benzo[b]fluoranthene | na | 1.89E+06 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 3.62E+07 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 3.04E+05 |
| 218-01-9 | Chrysene | na | 2.26E+04 |
| 309-00-2 | Aldrin | 9.24E+10 | 6.06E+07 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 8.30E+08 | 5.10E+06 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 2.44E+09 | 9.05E+05 |
| 541-73-1 | 1,3-Dichlorobenzene | 2.30E+08 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 1.45E+08 | 3.03E+04 |
| 563-68-8 | Thallium acetate | 4.32E+09 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 1.93E+07 |
| 1314-62-1 | Vanadium pentoxide | 2.72E+07 | na |
| 1330-20-7 | Xylenes (mixtures) | 2.86E+07 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 9.28E+05 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 6.10E+05 |
| 6533-73-9 | Thallium carbonate | 4.86E+09 | na |
| 7429-90-5 | Aluminum | 2.83E+05 | na |
| 7439-89-6 | Iron | 1.10E+06 | na |
| 7439-93-2 | Lithium | 2.86E+07 | na |
| 7439-96-5 | Manganese | 1.66E+07 | na |
| 7439-97-6 | Mercury metal vapor | 1.24E+05 | na |
| 7439-98-7 | Molybdenum | 4.18E+08 | na |
| 7440-02-0 | Nickel (soluble salts) | 3.83E+07 | na |
| 7440-22-4 | Silver | 5.42E+07 | na |
| 7440-24-6 | Strontium, Stable | 4.81E+06 | na |
| 7440-28-0 | Thallium metal | 5.89E+09 | na |
| 7440-31-5 | Tin | 9.41E+05 | na |
| 7440-36-0 | Antimony | 6.85E+08 | na |
| 7440-38-2 | Arsenic (inorganic) | 8.86E+08 | 4.00E+05 |
| 7440-39-3 | Barium | 2.15E+06 | na |
| 7440-41-7 | Beryllium and compounds | 1.26E+08 | 6.50E+02 |
| 7440-42-8 | Boron and borates only | 1.52E+07 | na |
| 7440-43-9 | Cadmium | 1.01E+09 | 4.65E+02 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 1.38E+06 | na |
| 7440-48-4 | Cobalt | 3.83E+07 | 7.13E+02 |
| 7440-50-8 | Copper | 8.22E+07 | na |
| 7440-62-2 | Vanadium metal | 3.63E+07 | na |
| 7440-66-6 | Zinc and compounds | 7.30E+08 | na |
| 7446-18-6 | Thallium sulfate | 4.85E+09 | na |
| 7487-94-7 | Mercuric chloride | 9.71E+09 | na |

**Table 18. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the Columbia River Population Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 7664-41-7 | Ammonia | 1.82E+07 | na |
| 7723-14-0 | Phosphorus, white | 9.49E+11 | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 1.39E+07 | na |
| 7782-49-2 | Selenium and compounds | 6.85E+07 | na |
| 7791-12-0 | Thallium chloride | 4.86E+09 | na |
| 8001-35-2 | Toxaphene | na | 1.06E+06 |
| 10102-45-1 | Thallium (I) nitrate | 4.32E+09 | na |
| 11096-82-5 | Aroclor 1260 | na | 3.26E+07 |
| 11097-69-1 | Aroclor 1254 | 1.46E+11 | 1.79E+06 |
| 11104-28-2 | Aroclor 1221 | na | 4.35E+05 |
| 11141-16-5 | Aroclor 1232 | na | 4.35E+05 |
| 12672-29-6 | Aroclor 1248 | na | 9.34E+05 |
| 12674-11-2 | Aroclor 1016 | 1.11E+10 | 4.54E+05 |
| 14797-55-8 | Nitrate | 6.83E+04 | na |
| 14797-65-0 | Nitrite | 1.09E+06 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 1.83E+05 | na |
| 16984-48-8 | Fluorine anion | 1.39E+07 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 5.75E+07 | 3.79E+02 |
| 22967-92-6 | Methyl mercury | 2.91E+10 | na |
| 53469-21-9 | Aroclor 1242 | na | 9.17E+05 |
| na | Uranium (soluble salts) | 3.46E+08 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 8.38E+06 | 5.41E+01 |

Notes:
- CASRN = Chemical Abstract Service Reference Number
- The total risk to the population along the Columbia River (5 million people) is calculated using intakes from 70 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario risk factors must be multiplied by the water concentration.
- Results using route-to-route extrapolations are shown in Table C8.

## 3.7 HSRAM INDUSTRIAL SCENARIO

The default commercial/industrial exposure scenario presented in the HSRAM is used to represent an occupationally exposed individual. The worker is primarily located indoors. Outdoor activities may include building and grounds maintenance. The principle avenue for the contaminants to get into the worker is through the drinking water. Soil is contaminated by irrigation of grass and other plants. This leads to dermal absorption of chemicals and external exposure from radionuclides. A small amount becomes airborne and is inhaled. The contaminated water comes from a well or is drawn from the Columbia River. The intakes from either source (assuming the same water concentration) are the same because there are no additional pathways associated with the Columbia River. The intakes continue for 20 years, and then the worker retires, or finds a different work location.

The worker consumes water at the rate of 1 L/d for 250 days during the year. The total drinking water intake is 250 L/y. The individual has a 10-minute shower at work and inhales the equivalent of 0.49 mL/y (Table A16). Volatile materials are inhaled in much greater quantities (Tables A16 and A17). Chemicals are absorbed through the skin during the shower as described in Section A3.4.2.

The soil becomes contaminated just as in the All Pathways Farmer scenario. The soil is irrigated with 82.3 cm water during a 6-month growing season. The irrigation is for dust control and landscape foliage. The actual soil concentration depends on the leaching coefficient for the material from the surface layer of soil. The worker ingests 7.3 g/y (Table A8) and inhales 0.25 g/y (Table A10). The worker's skin comes in contact with the soil. For chemicals, the effective dermal intake is 146 g/y (Table A21) times the dermal absorption factor for the chemical. For radionuclides, there is an effective external exposure time of 934 h/y (Table A18).

The lifetime increase in the worker's risk of developing some type of cancer from the radionuclides is the sum of 20 years of exposure. Each year there is a small amount of the radioactive material in the soil from previous years. This leads to a total risk that is greater than 20 times the first year's risk. The estimated risks from radioactive materials are shown in Table 19. The first column of risks shows the 20-year total. The second column shows the risk from the first year multiplied by 20. The third column is the ratio of the 20-year total to the 20-times-first-year risk. If the two numbers are within 10%, the ratio is not shown.

Note that the risk coefficients in Federal Guidance Report Number 13 (Tables A32 and A33) have been used in the industrial scenario although they were not intended for this application. Adults receive the exposures during their working years. There are no exposures during childhood. The risk coefficients were developed for a population containing all ages. They can be applied to an individual only if there is a lifetime of exposure. The scenario risk factors for increased cancer risk in Table 19 may either overestimate or underestimate the worker risk depending on whether the increased risk coefficient for children is offset by the reduced consumption rates during childhood.

**Table 19. Unit Risk Factors for Radionuclides: Industrial Scenario (risk per pCi/L)**

| Nuclide | 20-year Total | 20 Times First Year | Ratio | Nuclide | 20-year Total | 20 Times First Year | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 6.75E-10 | 6.75E-10 | | Eu-155 | 1.41E-08 | 1.02E-08 | 1.4 |
| Be-10 | 3.53E-08 | 3.52E-08 | | Gd-152 | 1.51E-07 | 1.49E-07 | |
| C-14 | 7.76E-09 | 7.75E-09 | | Tb-157 | 1.05E-09 | 9.40E-10 | 1.1 |
| Na-22 | 2.96E-07 | 1.02E-07 | 2.9 | Ho-166m | 6.49E-07 | 8.51E-08 | 7.6 |
| Al-26 | 1.15E-06 | 1.64E-07 | 7.0 | Re-187 | 8.98E-11 | 8.95E-11 | |
| Si-32+D | 6.29E-08 | 6.20E-08 | | Tl-204 | 2.94E-08 | 2.93E-08 | |
| Cl-36 | 1.66E-08 | 1.65E-08 | | Pb-205 | 3.17E-09 | 3.17E-09 | |
| K-40 | 1.79E-07 | 1.28E-07 | 1.4 | Pb-210+D | 4.46E-06 | 4.45E-06 | |
| Ca-41 | 1.77E-09 | 1.77E-09 | | Bi-207 | 5.21E-07 | 6.94E-08 | 7.5 |
| Ti-44+D | 8.90E-07 | 1.95E-07 | 4.6 | Po-209 | 2.36E-06 | 2.35E-06 | |
| V-49 | 6.10E-10 | 6.10E-10 | | Po-210 | 1.89E-06 | 1.89E-06 | |
| Mn-53 | 7.82E-10 | 7.80E-10 | | Ra-226+D | 2.61E-06 | 1.98E-06 | 1.3 |
| Mn-54 | 4.70E-08 | 2.83E-08 | 1.7 | Ra-228+D | 5.67E-06 | 5.24E-06 | |

**Table 19. Unit Risk Factors for Radionuclides: Industrial Scenario (risk per pCi/L)**

| Nuclide | 20-year Total | 20 Times First Year | Ratio | Nuclide | 20-year Total | 20 Times First Year | Ratio |
|---|---|---|---|---|---|---|---|
| Fe-55 | 4.31E-09 | 4.31E-09 | | Ac-227+D | 2.57E-06 | 2.45E-06 | |
| Fe-60+D | 1.40E-06 | 9.04E-07 | 1.6 | Th-228+D | 1.66E-06 | 1.55E-06 | |
| Co-60 | 5.55E-07 | 1.47E-07 | 3.8 | Th-229+D | 2.78E-06 | 2.65E-06 | |
| Ni-59 | 1.37E-09 | 1.37E-09 | | Th-230 | 4.64E-07 | 4.56E-07 | |
| Ni-63 | 3.36E-09 | 3.35E-09 | | Th-232 | 9.26E-07 | 5.08E-07 | 1.8 |
| Se-79 | 3.65E-08 | 3.65E-08 | | Pa-231 | 9.17E-07 | 8.67E-07 | |
| Rb-87 | 2.62E-08 | 2.61E-08 | | U-232 | 1.86E-06 | 1.47E-06 | 1.3 |
| Sr-90+D | 3.72E-07 | 3.70E-07 | | U-233 | 3.62E-07 | 3.59E-07 | |
| Zr-93 | 5.57E-09 | 5.55E-09 | | U-234 | 3.56E-07 | 3.54E-07 | |
| Nb-91 | 4.63E-09 | 4.05E-09 | 1.1 | U-235+D | 3.97E-07 | 3.62E-07 | |
| Nb-93m | 4.03E-09 | 4.02E-09 | | U-236 | 3.37E-07 | 3.35E-07 | |
| Nb-94 | 6.16E-07 | 8.15E-08 | 7.6 | U-238+D | 4.44E-07 | 4.36E-07 | |
| Mo-93 | 1.68E-08 | 1.68E-08 | | Np-237+D | 4.01E-07 | 3.42E-07 | 1.2 |
| Tc-97 | 1.37E-09 | 1.35E-09 | | Pu-236 | 3.87E-07 | 3.74E-07 | |
| Tc-99 | 1.38E-08 | 1.38E-08 | | Pu-238 | 6.63E-07 | 6.56E-07 | |
| Ru-106+D | 2.22E-07 | 2.15E-07 | | Pu-239 | 6.83E-07 | 6.76E-07 | |
| Pd-107 | 1.25E-09 | 1.25E-09 | | Pu-240 | 6.83E-07 | 6.76E-07 | |
| Ag-108m+D | 6.00E-07 | 8.27E-08 | 7.3 | Pu-241+D | 8.94E-09 | 8.81E-09 | |
| Cd-109+D | 2.52E-08 | 2.50E-08 | | Pu-242 | 6.48E-07 | 6.41E-07 | |
| Cd-113m | 1.44E-07 | 1.44E-07 | | Pu-244+D | 8.49E-07 | 7.30E-07 | 1.2 |
| In-115 | 1.69E-07 | 1.69E-07 | | Am-241 | 5.29E-07 | 5.21E-07 | |
| Sn-121m+D | 1.76E-08 | 1.75E-08 | | Am-242m+D | 3.73E-07 | 3.63E-07 | |
| Sn-126+D | 8.41E-07 | 1.88E-07 | 4.5 | Am-243+D | 5.98E-07 | 5.45E-07 | |
| Sb-125 | 6.77E-08 | 3.15E-08 | 2.1 | Cm-242 | 1.93E-07 | 1.93E-07 | |
| Te-125m | 1.67E-08 | 1.67E-08 | | Cm-243 | 5.08E-07 | 4.77E-07 | |
| I-129 | 7.42E-07 | 7.40E-07 | | Cm-244 | 4.23E-07 | 4.19E-07 | |
| Cs-134 | 3.54E-07 | 2.48E-07 | 1.4 | Cm-245 | 5.46E-07 | 5.22E-07 | |
| Cs-135 | 2.37E-08 | 2.37E-08 | | Cm-246 | 5.17E-07 | 5.11E-07 | |
| Cs-137+D | 3.27E-07 | 1.67E-07 | 2.0 | Cm-247+D | 6.15E-07 | 5.09E-07 | 1.2 |
| Ba-133 | 1.10E-07 | 4.23E-08 | 2.6 | Cm-248 | 4.82E-06 | 1.87E-06 | 2.6 |
| Ce-144+D | 1.79E-07 | 1.77E-07 | | Cm-250+D | 1.09E-05 | 1.07E-05 | |
| Pm-147 | 8.46E-09 | 8.45E-09 | | Bk-247 | 6.52E-07 | 6.23E-07 | |
| Sm-147 | 1.89E-07 | 1.87E-07 | | Cf-248 | 2.23E-07 | 2.22E-07 | |
| Sm-151 | 2.78E-09 | 2.78E-09 | | Cf-249 | 7.51E-07 | 6.44E-07 | 1.2 |
| Eu-150 | 4.80E-07 | 5.93E-08 | 8.1 | Cf-250 | 4.36E-07 | 4.32E-07 | |
| Eu-152 | 3.38E-07 | 6.07E-08 | 5.6 | Cf-251 | 6.98E-07 | 6.63E-07 | |
| Eu-154 | 3.41E-07 | 8.46E-08 | 4.0 | Cf-252 | 3.45E-07 | 2.43E-07 | 1.4 |

Notes:

- The radiation risk to this individual is calculated using intakes from 20 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario risk factors must be multiplied by the water concentration.
- The "20-year Total" column gives the industrial scenario risk factors. The column "20 Times First Year" shows the first year risk multiplied by 20. The "Ratio" column is the "20-year Total" divided by the "20 Times First Year" factors. Blank entries indicate the two risk factors are within 10 percent of each other.

The hazard quotient and cancer risk from chemicals are calculated using the same consumption parameters discussed in Appendix A for the HSRAM Industrial scenario. The same intakes occur regardless of whether the water comes from a well or from the Columbia River because there are no additional pathways for water coming from the river. In addition, the dilution that occurs when groundwater reaches the river does not enter into the calculation of unit factors, i.e., factors that are normalized to a unit water concentration.

The contaminant concentration in the water is expressed in mg/L. The chemical dose is normalized to the average adult body mass, 70 kg. The hazard quotient is calculated from the average annual daily dose. The increased cancer risk is calculated from the lifetime average daily dose. To calculate these average daily doses, the dose from 20 consecutive years is calculated and then divided by (20 y)(365 d/y) for the hazard quotient and (70 y)(365 d/y) for the cancer risk. As part of this calculation, the concentration of the contaminants in soil is increased each year. The effect of leaching from the surface layer is included using the leaching coefficients shown in Table A41. Dermal absorption during showering is included.

The calculated hazard quotient and cancer risk per unit concentration in the water for the HSRAM industrial scenario are shown in Table 20. The factors must be multiplied by the estimated water concentration, in mg per L.

**Table 20. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Industrial Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 50-32-8 | Benzo[a]pyrene | na | 1.69E+00 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 2.20E+00 |
| 56-23-5 | Carbon tetrachloride | 2.08E+01 | 2.01E-03 |
| 56-55-3 | Benz[a]anthracene | na | 1.18E-01 |
| 57-12-5 | Cyanide, free | 4.97E-01 | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 9.80E-03 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.04E-02 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 4.84E+01 | 5.39E-03 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 5.06E-02 | na |
| 60-34-4 | Methylhydrazine | na | 9.06E-03 |
| 60-57-1 | Dieldrin | 1.34E+03 | 4.91E-01 |
| 62-75-9 | N-Nitrosodimethylamine | 1.23E+03 | 2.47E-01 |
| 64-18-6 | Formic acid | 4.93E-03 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 1.96E-02 | na |
| 67-64-1 | Acetone (2-Propanone) | 1.09E-02 | na |
| 67-66-3 | Chloroform | 1.16E+02 | 2.30E-03 |
| 67-72-1 | Hexachloroethane | 3.65E+01 | 5.41E-04 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.38E+01 | na |
| 71-43-2 | Benzene | 1.44E+01 | 9.53E-04 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 7.52E-02 | na |
| 72-20-8 | Endrin | 3.55E+03 | na |

**Table 20. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Industrial Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 74-83-9 | Bromomethane | 7.64E+01 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | 3.84E+00 | 2.16E-04 |
| 75-00-3 | Ethyl Chloride | 6.11E-02 | 8.79E-06 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 7.01E+00 | 2.72E-03 |
| 75-05-8 | Acetonitrile | 5.78E+00 | na |
| 75-07-0 | Acetaldehyde | 3.84E+01 | 2.17E-04 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 2.86E-01 | 6.85E-05 |
| 75-15-0 | Carbon disulfide | 6.13E-01 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 1.28E-02 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 7.98E-01 | na |
| 75-35-4 | 1,1-Dichloroethylene | 1.96E+00 | na |
| 75-45-6 | Chlorodifluoromethane | 6.91E-03 | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 6.91E-03 | na |
| 75-69-4 | Trichlorofluoromethane | 5.58E-01 | na |
| 75-71-8 | Dichlorodifluoromethane | 1.81E+00 | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 1.20E-02 | na |
| 76-44-8 | Heptachlor | 2.61E+02 | 2.95E-01 |
| 78-83-1 | Isobutanol | 3.36E-02 | na |
| 78-87-5 | 1,2-Dichloropropane | 8.67E+01 | 2.19E-04 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 8.56E-02 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 2.71E+00 | 1.79E-03 |
| 79-01-6 | Trichloroethylene | 8.41E+01 | 1.39E-02 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 5.25E+00 | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 1.98E-01 | 6.32E-03 |
| 79-46-9 | 2-Nitropropane | 1.73E+01 | 2.65E-01 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 1.06E+01 | 2.36E-03 |
| 83-32-9 | Acenaphthene | 1.04E+00 | na |
| 84-66-2 | Diethyl phthalate | 1.38E-02 | na |
| 84-74-2 | Dibutyl phthalate | 2.57E-01 | na |
| 85-68-7 | Butyl benzyl phthalate | 1.98E-01 | na |
| 86-73-7 | Fluorene | 1.37E+00 | na |
| 86-74-8 | Carbazole | na | 1.47E-04 |
| 87-68-3 | Hexachlorobutadiene | 2.14E+02 | 3.63E-03 |
| 87-86-5 | Pentachlorophenol | 1.81E+00 | 1.86E-03 |
| 88-06-2 | 2,4,6-Trichlorophenol | 2.72E+02 | 1.18E-04 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 2.07E+01 | na |
| 91-20-3 | Naphthalene | 1.16E+02 | na |
| 92-52-4 | 1,1'-Biphenyl | 9.08E-01 | na |
| 95-47-6 | o-Xylene | 3.55E+00 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 2.41E-01 | na |

**Table 20. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Industrial Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 1.95E+00 | na |
| 95-57-8 | 2-Chlorophenol | 2.49E+00 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 5.83E+01 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 2.80E-01 | na |
| 98-86-2 | Acetophenone | 1.05E-01 | na |
| 98-95-3 | Nitrobenzene | 1.91E+02 | na |
| 100-00-5 | p-Chloronitrobenzene | 1.27E+02 | 2.25E-05 |
| 100-02-7 | 4-Nitrophenol | 1.33E+00 | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 1.05E+02 | na |
| 100-41-4 | Ethyl benzene | 5.14E-01 | 1.09E-04 |
| 100-42-5 | Styrene | 4.27E-01 | na |
| 100-51-6 | Benzyl alcohol | 3.42E-02 | na |
| 106-42-3 | p-Xylene | 3.55E+00 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 2.30E+00 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 1.06E+00 | 7.51E-04 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 3.96E+01 | 6.54E-02 |
| 106-99-0 | 1,3-Butadiene | 1.73E+02 | 2.96E-03 |
| 107-02-8 | 2-Propenal (Acrolein) | 1.73E+04 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 3.46E+02 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 7.11E+01 | 2.84E-03 |
| 107-13-1 | Acrylonitrile | 1.83E+02 | 8.25E-03 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 2.44E-01 | na |
| 108-38-3 | m-Xylene | 3.55E+00 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 2.41E-01 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 5.82E+01 | na |
| 108-87-2 | Methyl cyclohexane | 1.15E-01 | na |
| 108-88-3 | Toluene (Methyl benzene) | 2.54E-01 | na |
| 108-90-7 | Chlorobenzene | 6.92E+00 | na |
| 108-94-1 | Cyclohexanone | 2.01E-03 | na |
| 108-95-2 | Phenol (Carbolic acid) | 3.49E-02 | na |
| 109-99-9 | Tetrahydrofuran | 1.20E+00 | 2.14E-04 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 1.05E+01 | na |
| 110-54-3 | n-Hexane | 1.17E+00 | na |
| 110-80-5 | 2-Ethoxyethanol | 5.79E-02 | na |
| 110-82-7 | Cyclohexane | 5.78E-02 | na |
| 110-86-1 | Pyridine | 1.02E+01 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 2.21E-02 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 1.64E-01 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 2.01E+02 | 1.60E-02 |
| 117-84-0 | Di-n-octylphthalate | 4.54E+01 | na |

**Table 20. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Industrial Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 118-74-1 | Hexachlorobenzene | 2.59E+02 | 1.40E-01 |
| 120-12-7 | Anthracene | 1.70E-01 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 8.93E+01 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 5.38E+00 | na |
| 121-44-8 | Triethylamine | 4.94E+01 | na |
| 122-39-4 | Diphenylamine | 1.02E+00 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 3.09E-05 |
| 126-73-8 | Tributyl Phosphate | 1.30E-01 | 4.00E-05 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 5.95E+02 | na |
| 127-18-4 | Tetrachloroethylene | 2.24E+00 | 3.15E-03 |
| 129-00-0 | Pyrene | 5.87E+00 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.11E-02 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 1.08E+00 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 5.62E-01 | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 2.06E-01 |
| 205-99-2 | Benzo[b]fluoranthene | na | 1.01E-01 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 6.59E+00 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 1.64E-02 |
| 218-01-9 | Chrysene | na | 1.24E-03 |
| 309-00-2 | Aldrin | 1.44E+04 | 2.57E+00 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 3.02E+01 | 1.16E-01 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 7.65E+01 | 8.79E-03 |
| 541-73-1 | 1,3-Dichlorobenzene | 2.39E+01 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 1.77E+01 | 7.38E-04 |
| 563-68-8 | Thallium acetate | 1.10E+02 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 2.28E-02 |
| 1314-62-1 | Vanadium pentoxide | 1.35E+00 | na |
| 1330-20-7 | Xylenes (mixtures) | 3.54E+00 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 3.91E-02 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 1.51E-02 |
| 6533-73-9 | Thallium carbonate | 1.24E+02 | na |
| 7429-90-5 | Aluminum | 1.31E-02 | na |
| 7439-89-6 | Iron | 3.32E-02 | na |
| 7439-93-2 | Lithium | 4.96E-01 | na |
| 7439-96-5 | Manganese | 4.90E-01 | na |
| 7439-97-6 | Mercury metal vapor | 1.67E-02 | na |
| 7439-98-7 | Molybdenum | 1.99E+00 | na |
| 7440-02-0 | Nickel (soluble salts) | 4.97E-01 | na |
| 7440-22-4 | Silver | 2.00E+00 | na |
| 7440-24-6 | Strontium, Stable | 1.67E-02 | na |

**Table 20. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Industrial Scenario**

| CASRN | Chemical Name | Hazard Quotient per mg/L | Increased Cancer Risk per mg/L |
|---|---|---|---|
| 7440-28-0 | Thallium metal | 1.51E+02 | na |
| 7440-31-5 | Tin | 1.78E-02 | na |
| 7440-36-0 | Antimony | 2.89E+01 | na |
| 7440-38-2 | Arsenic (inorganic) | 3.39E+01 | 4.38E-03 |
| 7440-39-3 | Barium | 7.57E-02 | na |
| 7440-41-7 | Beryllium and compounds | 6.66E+00 | 8.80E-06 |
| 7440-42-8 | Boron and borates only | 5.01E-02 | na |
| 7440-43-9 | Cadmium | 2.24E+01 | 6.52E-06 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 6.45E-02 | na |
| 7440-48-4 | Cobalt | 1.13E+00 | 1.01E-05 |
| 7440-50-8 | Copper | 2.48E-01 | na |
| 7440-62-2 | Vanadium metal | 1.99E+00 | na |
| 7440-66-6 | Zinc and compounds | 3.32E-02 | na |
| 7446-18-6 | Thallium sulfate | 1.24E+02 | na |
| 7487-94-7 | Mercuric chloride | 3.31E+01 | na |
| 7664-41-7 | Ammonia | 2.27E+00 | na |
| 7723-14-0 | Phosphorus, white | 5.00E+02 | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 1.66E-01 | na |
| 7782-49-2 | Selenium and compounds | 1.98E+00 | na |
| 7791-12-0 | Thallium chloride | 1.24E+02 | na |
| 8001-35-2 | Toxaphene | na | 3.68E-02 |
| 10102-45-1 | Thallium (I) nitrate | 1.10E+02 | na |
| 11096-82-5 | Aroclor 1260 | na | 2.70E-01 |
| 11097-69-1 | Aroclor 1254 | 2.15E+04 | 5.91E-02 |
| 11104-28-2 | Aroclor 1221 | na | 1.53E-02 |
| 11141-16-5 | Aroclor 1232 | na | 1.53E-02 |
| 12672-29-6 | Aroclor 1248 | na | 4.13E-02 |
| 12674-11-2 | Aroclor 1016 | 1.90E+03 | 1.41E-02 |
| 14797-55-8 | Nitrate | 6.18E-03 | na |
| 14797-65-0 | Nitrite | 9.88E-02 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 1.12E-02 | na |
| 16984-48-8 | Fluorine anion | 1.66E-01 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 4.43E+00 | 1.50E-05 |
| 22967-92-6 | Methyl mercury | 9.92E+01 | na |
| 53469-21-9 | Aroclor 1242 | na | 3.91E-02 |
| na | Uranium (soluble salts) | 1.65E+01 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 6.42E-01 | 2.14E-06 |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The total risk to the worker is calculated using intakes from 20 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario factors must be multiplied by the water concentration.
- Results using route-to-route extrapolations are shown in Table C8.

## 3.8 HSRAM RECREATIONAL SCENARIO

The default recreational exposure scenario presented in the HSRAM is used to represent a visitor engaging in various forms of recreational activity. The most likely location is near the Columbia River. The HSRAM presents additional parameters to cover possible future recreational activities some distance from the river.

The hazard quotient for chemicals is calculated using the drinking, breathing and soil ingestion rates for children. HSRAM uses the higher normalized intake rates for the child to maximize the average daily intake. The incremental cancer risk is calculated using adult drinking and breathing rates, and an average soil ingestion rate that includes 6 years at the child's higher rate. Thus, the calculation of the 30-year intakes depends on the location of the contaminant.

The principle avenue for the contaminants to get into the visitors is through drinking water and game fish. However, if a well to groundwater is the source of contaminated water then the fish are not contaminated. Hence, for the recreational scenario there are two cases. The first is for a well to groundwater. This water is used to irrigate a recreational area some distance from the Columbia River. The individual drinks from the well and enjoys the park facilities. Soil is contaminated by irrigation of grass and other plants. This leads to dermal absorption of chemicals and external exposure from radionuclides. A small amount becomes airborne and is inhaled. The intakes continue 7 days each year for 30 years.

The second case is for contamination in the Columbia River. In this case the visitor consumes 9.9 kg game fish (Table A4) every year for 30 years. There is an additional small amount of deer mentioned in the HSRAM. This is calculated to be 0.19 deer per year with a mass of 45 kg, with half eaten by one person. The average game intake is 4.2 kg/y. The deer is contaminated by drinking from the river. The daily water intake is 25% of a milk cow. The transfer factors for beef are used to represent the deer meat concentration. The other pathways are regarded as the same as the inland park simply because there may be a park along the river. Dermal contact during swimming is also part of the second case.

The lifetime increase in the visitor's risk of developing some type of cancer from the radionuclides is the sum of 30 years of exposure. The first 6 years are at the child's soil ingestion rate (1.4 g/y), while the last 24 are at the adult's soil ingestion rate (0.7 g/y). Both of these are shown in Table A8. The other intakes are all at the adult rate. Drinking water consumption is 14 L/y. Soil inhalation is 0.007 g/y (Table A10). External exposure is 45 h/y (Table A18). The estimated risks from radioactive materials in the recreation scenarios are shown in Table 21. The first column of risks shows the inland park case in which the radionuclides are from groundwater. The second column of risks shows the Columbia River case, in which the radionuclides are in the surface water. The third column is the ratio of the Columbia River to the inland park risk. For most radionuclides, the fish contributes the majority of the dose. In a few cases, the external dose from shoreline sediments dominates. If the contaminants are from well water, the water gives the majority of the dose.

**Table 21. Unit Risk Factors for Radionuclides: Recreational Scenarios (risk per pCi/L)**

| Nuclide | Inland Park | Columbia River | Ratio | Nuclide | Inland Park | Columbia River | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 4.26E-11 | 9.34E-11 | 2.19 | Eu-155 | 1.10E-09 | 4.59E-08 | 41.9 |
| Be-10 | 2.69E-09 | 3.08E-07 | 114 | Gd-152 | 1.14E-08 | 3.03E-07 | 26.6 |
| C-14 | 5.89E-10 | 2.97E-05 | 50,461 | Tb-157 | 8.36E-11 | 2.33E-09 | 27.9 |
| Na-22 | 2.28E-08 | 2.16E-07 | 9.5 | Ho-166m | 6.82E-08 | 1.25E-06 | 18.3 |
| Al-26 | 1.21E-07 | 5.78E-06 | 47.9 | Re-187 | 6.82E-12 | 9.24E-10 | 135 |
| Si-32+D | 4.79E-09 | 1.11E-07 | 23.1 | Tl-204 | 2.22E-09 | 2.45E-05 | 11,018 |
| Cl-36 | 1.25E-09 | 6.74E-08 | 53.8 | Pb-205 | 2.41E-10 | 7.39E-08 | 307 |
| K-40 | 1.50E-08 | 1.03E-05 | 686 | Pb-210+D | 3.39E-07 | 1.07E-04 | 315 |
| Ca-41 | 1.34E-10 | 5.35E-09 | 40.0 | Bi-207 | 5.18E-08 | 8.02E-07 | 15.5 |
| Ti-44+D | 8.84E-08 | 1.28E-05 | 145 | Po-209 | 1.79E-07 | 4.20E-05 | 234 |
| V-49 | 4.62E-11 | 1.07E-08 | 231 | Po-210 | 1.43E-07 | 3.36E-05 | 236 |
| Mn-53 | 5.95E-11 | 2.68E-08 | 451 | Ra-226+D | 2.20E-07 | 9.25E-06 | 42.1 |
| Mn-54 | 3.48E-09 | 3.93E-07 | 113 | Ra-228+D | 4.35E-07 | 2.22E-05 | 51.0 |
| Fe-55 | 3.26E-10 | 6.93E-08 | 212 | Ac-227+D | 1.97E-07 | 5.25E-06 | 26.7 |
| Fe-60+D | 1.34E-07 | 1.58E-05 | 118 | Th-228+D | 1.25E-07 | 1.28E-05 | 102.2 |
| Co-60 | 4.55E-08 | 2.41E-06 | 52.8 | Th-229+D | 2.14E-07 | 2.18E-05 | 101.9 |
| Ni-59 | 1.04E-10 | 1.17E-08 | 112 | Th-230 | 3.53E-08 | 3.60E-06 | 101.9 |
| Ni-63 | 2.55E-10 | 2.87E-08 | 112 | Th-232 | 9.73E-08 | 5.59E-06 | 57.5 |
| Se-79 | 2.76E-09 | 4.93E-07 | 178 | Pa-231 | 7.18E-08 | 9.30E-07 | 12.9 |
| Rb-87 | 1.99E-09 | 4.20E-06 | 2,113 | U-232 | 1.52E-07 | 1.75E-06 | 11.5 |
| Sr-90+D | 2.82E-08 | 1.74E-06 | 61.6 | U-233 | 2.74E-08 | 3.22E-07 | 11.7 |
| Zr-93 | 4.23E-10 | 1.29E-07 | 305 | U-234 | 2.70E-08 | 3.17E-07 | 11.7 |
| Nb-91 | 3.71E-10 | 1.06E-07 | 285 | U-235+D | 3.09E-08 | 3.59E-07 | 11.6 |
| Nb-93m | 3.06E-10 | 1.05E-07 | 342 | U-236 | 2.56E-08 | 3.00E-07 | 11.7 |
| Nb-94 | 6.47E-08 | 2.08E-06 | 32.2 | U-238+D | 3.38E-08 | 4.06E-07 | 12.0 |
| Mo-93 | 1.27E-09 | 1.40E-08 | 11.0 | Np-237+D | 3.21E-08 | 6.98E-07 | 21.7 |
| Tc-97 | 1.04E-10 | 2.43E-09 | 23.5 | Pu-236 | 2.97E-08 | 6.68E-07 | 22.5 |
| Tc-99 | 1.04E-09 | 2.49E-08 | 23.9 | Pu-238 | 5.02E-08 | 1.13E-06 | 22.4 |
| Ru-106+D | 1.67E-08 | 2.10E-07 | 12.5 | Pu-239 | 5.18E-08 | 1.16E-06 | 22.5 |
| Pd-107 | 9.54E-11 | 1.25E-09 | 13.1 | Pu-240 | 5.18E-08 | 1.16E-06 | 22.5 |
| Ag-108m+D | 6.24E-08 | 1.03E-06 | 16.5 | Pu-241+D | 6.80E-10 | 1.55E-08 | 22.7 |
| Cd-109+D | 1.91E-09 | 4.00E-07 | 210 | Pu-242 | 4.91E-08 | 1.10E-06 | 22.5 |
| Cd-113m | 1.09E-08 | 2.18E-06 | 200 | Pu-244+D | 6.82E-08 | 1.51E-06 | 22.1 |
| In-115 | 1.29E-08 | 1.29E-03 | 100,042 | Am-241 | 4.01E-08 | 8.99E-07 | 22.4 |
| Sn-121m+D | 1.34E-09 | 4.56E-06 | 3,398 | Am-242m+D | 2.84E-08 | 6.19E-07 | 21.8 |
| Sn-126+D | 8.61E-08 | 3.63E-05 | 422 | Am-243+D | 4.69E-08 | 1.04E-06 | 22.3 |
| Sb-125 | 5.21E-09 | 2.18E-07 | 41.9 | Cm-242 | 1.46E-08 | 3.57E-07 | 24.5 |
| Te-125m | 1.26E-09 | 5.60E-07 | 444 | Cm-243 | 3.91E-08 | 8.61E-07 | 22.0 |
| I-129 | 5.63E-08 | 2.38E-06 | 42.3 | Cm-244 | 3.20E-08 | 7.15E-07 | 22.4 |
| Cs-134 | 2.68E-08 | 3.07E-05 | 1,144 | Cm-245 | 4.20E-08 | 9.40E-07 | 22.4 |
| Cs-135 | 1.80E-09 | 3.50E-06 | 1,941 | Cm-246 | 3.91E-08 | 8.76E-07 | 22.4 |
| Cs-137+D | 2.90E-08 | 2.25E-05 | 775 | Cm-247+D | 5.01E-08 | 1.09E-06 | 21.7 |
| Ba-133 | 9.44E-09 | 9.66E-08 | 10.2 | Cm-248 | 3.65E-07 | 8.22E-06 | 22.5 |

**Table 21. Unit Risk Factors for Radionuclides: Recreational Scenarios (risk per pCi/L)**

| Nuclide | Inland Park | Columbia River | Ratio | Nuclide | Inland Park | Columbia River | Ratio |
|---|---|---|---|---|---|---|---|
| Ce-144+D | 1.35E-08 | 4.78E-07 | 35.4 | Cm-250+D | 8.32E-07 | 1.86E-05 | 22.3 |
| Pm-147 | 6.40E-10 | 2.28E-08 | 35.6 | Bk-247 | 5.02E-08 | 1.31E-06 | 26.0 |
| Sm-147 | 1.43E-08 | 3.76E-07 | 26.3 | Cf-248 | 1.68E-08 | 4.80E-07 | 28.5 |
| Sm-151 | 2.12E-10 | 6.34E-09 | 29.9 | Cf-249 | 6.02E-08 | 1.49E-06 | 24.7 |
| Eu-150 | 4.81E-08 | 8.27E-07 | 17.2 | Cf-250 | 3.29E-08 | 8.74E-07 | 26.5 |
| Eu-152 | 3.11E-08 | 5.16E-07 | 16.6 | Cf-251 | 5.38E-08 | 1.40E-06 | 25.9 |
| Eu-154 | 2.96E-08 | 5.33E-07 | 18.0 | Cf-252 | 2.60E-08 | 7.19E-07 | 27.6 |

Notes:

- The radiation risk to this individual is calculated using intakes from 30 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario risk factors must be multiplied by the water concentration.
- The "Inland Park" column gives the recreational scenario risk factors from groundwater. The column "Columbia River" shows the risk factors for surface water. The "Ratio" column is the "Columbia River" divided by the "Inland Park" risk factors.

The hazard quotient and cancer risk from chemicals are calculated using the same consumption parameters discussed in Appendix A for the HSRAM Recreational scenario. The contaminant concentration in well or river water is expressed in mg/L. The chemical dose is normalized to the average adult body mass, 70 kg. To calculate the average daily dose over a lifetime, the total dose from 30 consecutive years is calculated and then divided by (30 y)(365 d/y) for the hazard quotient and (70 y)(365 d/y) for the cancer risk. As part of this calculation, the concentration of the contaminants in soil is increased each year. The effect of leaching and volatilization from the surface layer is included using the leaching coefficients shown in Table A41. Dermal absorption during showering is included.

The calculated hazard quotient and cancer risk per unit concentration in the well or the Columbia River for the HSRAM Recreational scenario are shown in Table 22. The factors must be multiplied by the estimated water concentration, in mg per L.

**Table 22. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Recreational Scenario**

| | | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| CASRN | Chemical Name | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 50-32-8 | Benzo[a]pyrene | na | 7.21E-02 | na | 1.33E+01 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 9.32E-02 | na | 3.89E+01 |
| 56-23-5 | Carbon tetrachloride | 1.90E+00 | 3.86E-05 | 1.99E+01 | 7.40E-04 |
| 56-55-3 | Benz[a]anthracene | na | 4.86E-03 | na | 6.98E-01 |
| 57-12-5 | Cyanide, free | 6.04E-02 | na | 1.27E-01 | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 7.10E-04 | na | 2.35E-03 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.42E-03 | na | 4.94E-03 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 4.52E+00 | 3.86E-04 | 2.00E+02 | 3.29E-02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 6.04E-03 | na | 1.25E-02 | na |
| 60-34-4 | Methylhydrazine | na | 7.09E-04 | na | 2.35E-03 |

**Table 22. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Recreational Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 60-57-1 | Dieldrin | 5.65E+01 | 1.49E-02 | 2.26E+04 | 7.73E+00 |
| 62-75-9 | N-Nitrosodimethylamine | 1.51E+02 | 1.21E-02 | 3.16E+02 | 4.03E-02 |
| 64-18-6 | Formic acid | 6.03E-04 | na | 1.24E-03 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 2.40E-03 | na | 4.91E-03 | na |
| 67-64-1 | Acetone (2-Propanone) | 1.34E-03 | na | 2.72E-03 | na |
| 67-66-3 | Chloroform | 2.03E-01 | 2.75E-06 | 5.59E-01 | 1.20E-05 |
| 67-72-1 | Hexachloroethane | 1.95E+00 | 7.94E-06 | 1.26E+02 | 7.54E-04 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 2.03E-02 | na | 3.39E-02 | na |
| 71-43-2 | Benzene | 3.19E-01 | 1.44E-05 | 1.25E+00 | 1.03E-04 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 6.74E-04 | na | 4.10E-03 | na |
| 72-20-8 | Endrin | 1.03E+02 | na | 3.40E+03 | na |
| 74-83-9 | Bromomethane | 9.07E-01 | na | 1.43E+00 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | 2.30E-03 | 3.19E-06 | 2.30E-03 | 1.05E-05 |
| 75-00-3 | Ethyl Chloride | 3.08E-03 | 7.10E-07 | 5.94E-03 | 2.13E-06 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 4.10E-01 | 3.69E-04 | 9.27E-01 | 1.37E-03 |
| 75-05-8 | Acetonitrile | 3.45E-03 | na | 3.45E-03 | na |
| 75-07-0 | Acetaldehyde | 2.30E-02 | 8.91E-08 | 2.30E-02 | 8.91E-08 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 2.03E-02 | 1.82E-06 | 3.37E-02 | 4.40E-06 |
| 75-15-0 | Carbon disulfide | 1.29E-02 | na | 4.13E-02 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 2.45E-04 | na | 7.88E-04 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.27E-02 | na | 3.29E-02 | na |
| 75-35-4 | 1,1-Dichloroethylene | 2.59E-02 | na | 9.94E-02 | na |
| 75-45-6 | Chlorodifluoromethane | 4.13E-06 | na | 4.13E-06 | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 4.13E-06 | na | 4.13E-06 | na |
| 75-69-4 | Trichlorofluoromethane | 5.18E-03 | na | 3.41E-02 | na |
| 75-71-8 | Dichlorodifluoromethane | 7.87E-03 | na | 3.15E-02 | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 5.17E-05 | na | 7.84E-04 | na |
| 76-44-8 | Heptachlor | 9.21E+00 | 7.66E-03 | 7.75E+03 | 7.48E+00 |
| 78-83-1 | Isobutanol | 4.03E-03 | na | 8.37E-03 | na |
| 78-87-5 | 1,2-Dichloropropane | 5.18E-02 | 1.72E-05 | 5.18E-02 | 1.01E-04 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 2.05E-03 | na | 4.16E-03 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 3.07E-01 | 1.48E-05 | 9.12E-01 | 7.37E-05 |
| 79-01-6 | Trichloroethylene | 5.20E+00 | 1.60E-04 | 3.22E+01 | 1.55E-03 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 5.57E-03 | na | 8.17E-03 | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 2.10E-02 | 5.43E-05 | 1.17E-01 | 5.48E-04 |
| 79-46-9 | 2-Nitropropane | 1.03E-02 | 1.09E-04 | 1.03E-02 | 1.09E-04 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 6.12E-01 | 1.31E-04 | 9.86E+01 | 3.28E-02 |
| 83-32-9 | Acenaphthene | 4.50E-02 | na | 1.57E+00 | na |
| 84-66-2 | Diethyl phthalate | 1.56E-03 | na | 9.21E-03 | na |

**Table 22. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Recreational Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 84-74-2 | Dibutyl phthalate | 1.67E-02 | na | 2.31E+00 | na |
| 85-68-7 | Butyl benzyl phthalate | 1.03E-02 | na | 1.74E+00 | na |
| 86-73-7 | Fluorene | 6.21E-02 | na | 3.50E+00 | na |
| 86-74-8 | Carbazole | na | 8.63E-06 | na | 5.31E-04 |
| 87-68-3 | Hexachlorobutadiene | 9.08E+00 | 7.01E-05 | 1.28E+03 | 1.28E-02 |
| 87-86-5 | Pentachlorophenol | 8.27E-02 | 9.34E-05 | 9.44E+00 | 1.45E-02 |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.71E+01 | 4.94E-06 | 2.71E+02 | 1.23E-04 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 1.53E+00 | na | 4.76E+01 | na |
| 91-20-3 | Naphthalene | 1.43E-01 | na | 1.58E+00 | na |
| 92-52-4 | 1,1'-Biphenyl | 4.42E-02 | na | 1.98E+00 | na |
| 95-47-6 | o-Xylene | 9.22E-03 | na | 1.15E-01 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 2.56E-02 | na | 9.11E-02 | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 1.75E-02 | na | 4.15E-01 | na |
| 95-57-8 | 2-Chlorophenol | 2.58E-01 | na | 1.11E+00 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 6.76E-02 | na | 1.09E+00 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.73E-02 | na | 2.85E-01 | na |
| 98-86-2 | Acetophenone | 1.23E-02 | na | 1.62E-02 | na |
| 98-95-3 | Nitrobenzene | 2.57E+00 | na | 7.22E+00 | na |
| 100-00-5 | p-Chloronitrobenzene | 1.34E+00 | 1.75E-06 | 7.34E+00 | 1.87E-05 |
| 100-02-7 | 4-Nitrophenol | 1.55E-01 | na | 5.05E-01 | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 1.24E+01 | na | 2.72E+01 | na |
| 100-41-4 | Ethyl benzene | 1.42E-02 | 4.45E-08 | 2.34E-01 | 4.45E-08 |
| 100-42-5 | Styrene | 7.11E-03 | na | 8.56E-02 | na |
| 100-51-6 | Benzyl alcohol | 4.06E-03 | na | 4.99E-03 | na |
| 106-42-3 | p-Xylene | 9.27E-03 | na | 1.21E-01 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 2.53E-01 | na | 8.74E-01 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 4.88E-02 | 8.52E-06 | 1.26E+00 | 3.81E-04 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 1.59E-01 | 5.15E-04 | 4.56E-01 | 2.80E-03 |
| 106-99-0 | 1,3-Butadiene | 1.03E-01 | 1.21E-06 | 1.03E-01 | 1.21E-06 |
| 107-02-8 | 2-Propenal (Acrolein) | 1.27E+01 | na | 1.52E+01 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 2.31E-01 | na | 2.85E-01 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 1.03E-01 | 2.31E-05 | 1.62E-01 | 6.90E-05 |
| 107-13-1 | Acrylonitrile | 1.31E+00 | 1.31E-04 | 2.57E+00 | 4.23E-04 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 1.53E-02 | na | 2.66E-02 | na |
| 108-38-3 | m-Xylene | 9.36E-03 | na | 1.31E-01 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 2.56E-02 | na | 9.19E-02 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 6.52E-02 | na | 7.75E-01 | na |
| 108-87-2 | Methyl cyclohexane | 6.89E-05 | na | 6.89E-05 | na |
| 108-88-3 | Toluene (Methyl benzene) | 1.68E-02 | na | 1.51E-01 | na |
| 108-90-7 | Chlorobenzene | 8.20E-02 | na | 8.04E-01 | na |

**Table 22. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Recreational Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 108-94-1 | Cyclohexanone | 2.42E-04 | na | 5.05E-04 | na |
| 108-95-2 | Phenol (Carbolic acid) | 4.12E-03 | na | 9.03E-03 | na |
| 109-99-9 | Tetrahydrofuran | 6.44E-03 | 1.89E-06 | 1.26E-02 | 6.09E-06 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 1.22E+00 | na | 2.20E+00 | na |
| 110-54-3 | n-Hexane | 3.45E-02 | na | 1.43E+00 | na |
| 110-80-5 | 2-Ethoxyethanol | 3.03E-03 | na | 6.20E-03 | na |
| 110-82-7 | Cyclohexane | 3.45E-05 | na | 3.45E-05 | na |
| 110-86-1 | Pyridine | 1.22E+00 | na | 2.57E+00 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 2.43E-03 | na | 5.07E-03 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 2.01E-02 | na | 4.11E-02 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 5.66E+00 | 6.76E-04 | 5.01E+01 | 6.01E-03 |
| 117-84-0 | Di-n-octylphthalate | 1.29E+00 | na | 1.06E+01 | na |
| 118-74-1 | Hexachlorobenzene | 8.41E+00 | 4.18E-03 | 2.55E+03 | 1.40E+00 |
| 120-12-7 | Anthracene | 7.95E-03 | na | 7.28E-01 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 2.18E-01 | na | 1.02E+01 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 6.24E-01 | na | 2.31E+00 | na |
| 121-44-8 | Triethylamine | 2.95E-02 | na | 2.95E-02 | na |
| 122-39-4 | Diphenylamine | 6.64E-02 | na | 1.75E+00 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 2.59E-06 | na | 8.46E-06 |
| 126-73-8 | Tributyl Phosphate | 8.37E-03 | 2.34E-06 | 1.07E-01 | 4.68E-05 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.24E+01 | na | 2.52E+01 | na |
| 127-18-4 | Tetrachloroethylene | 1.39E-01 | 1.71E-04 | 3.48E+00 | 7.90E-03 |
| 129-00-0 | Pyrene | 1.97E-01 | na | 1.62E+01 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.34E-03 | na | 2.77E-03 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 1.23E-01 | na | 3.52E-01 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 6.20E-02 | na | 2.33E-01 | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 8.77E-03 | na | 3.56E+00 |
| 205-99-2 | Benzo[b]fluoranthene | na | 4.32E-03 | na | 7.19E-01 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 2.09E-01 | na | 1.98E+01 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 7.00E-04 | na | 1.28E-01 |
| 218-01-9 | Chrysene | na | 5.23E-05 | na | 7.63E-03 |
| 309-00-2 | Aldrin | 4.34E+02 | 9.03E-02 | 2.64E+05 | 5.77E+01 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 2.74E+00 | 1.95E-03 | 1.37E+02 | 1.83E-01 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 6.89E+00 | 5.53E-04 | 3.34E+02 | 5.06E-02 |
| 541-73-1 | 1,3-Dichlorobenzene | 1.70E+00 | na | 4.91E+01 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 5.24E-02 | 2.63E-05 | 1.61E-01 | 1.66E-04 |
| 563-68-8 | Thallium acetate | 1.37E+01 | na | 4.31E+04 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 1.80E-03 | na | 5.95E-03 |
| 1314-62-1 | Vanadium pentoxide | 1.43E-01 | na | 9.29E+00 | na |

**Table 22. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Recreational Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 1330-20-7 | Xylenes (mixtures) | 9.06E-03 | na | 1.14E-01 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 1.29E-03 | na | 1.93E+01 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 2.46E-04 | na | 1.93E+01 |
| 6533-73-9 | Thallium carbonate | 1.54E+01 | na | 4.85E+04 | na |
| 7429-90-5 | Aluminum | 1.30E-03 | na | 1.99E-01 | na |
| 7439-89-6 | Iron | 4.10E-03 | na | 2.75E-01 | na |
| 7439-93-2 | Lithium | 6.14E-02 | na | 2.66E-01 | na |
| 7439-96-5 | Manganese | 3.20E-02 | na | 1.24E+00 | na |
| 7439-97-6 | Mercury metal vapor | 6.13E-04 | na | 6.13E-04 | na |
| 7439-98-7 | Molybdenum | 2.46E-01 | na | 1.44E+00 | na |
| 7440-02-0 | Nickel (soluble salts) | 6.14E-02 | na | 2.19E+00 | na |
| 7440-22-4 | Silver | 2.46E-01 | na | 1.37E+00 | na |
| 7440-24-6 | Strontium, Stable | 2.05E-03 | na | 4.71E-02 | na |
| 7440-28-0 | Thallium metal | 1.86E+01 | na | 5.88E+04 | na |
| 7440-31-5 | Tin | 2.08E-03 | na | 1.95E+00 | na |
| 7440-36-0 | Antimony | 3.20E+00 | na | 1.14E+02 | na |
| 7440-38-2 | Arsenic (inorganic) | 4.14E+00 | 3.76E-04 | 3.37E+02 | 6.41E-02 |
| 7440-39-3 | Barium | 6.67E-03 | na | 3.34E-02 | na |
| 7440-41-7 | Beryllium and compounds | 6.61E-01 | 5.47E-07 | 2.35E+01 | 5.47E-07 |
| 7440-42-8 | Boron and borates only | 6.14E-03 | na | 2.15E-02 | na |
| 7440-43-9 | Cadmium | 2.55E+00 | 4.02E-07 | 9.23E+01 | 4.02E-07 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 1.27E-03 | na | 1.27E-03 | na |
| 7440-48-4 | Cobalt | 7.40E-02 | 6.22E-07 | 6.06E+00 | 6.22E-07 |
| 7440-50-8 | Copper | 3.07E-02 | na | 2.05E+00 | na |
| 7440-62-2 | Vanadium metal | 1.93E-01 | na | 1.24E+01 | na |
| 7440-66-6 | Zinc and compounds | 4.10E-03 | na | 3.42E-01 | na |
| 7446-18-6 | Thallium sulfate | 1.54E+01 | na | 4.85E+04 | na |
| 7487-94-7 | Mercuric chloride | 4.09E+00 | na | 1.30E+03 | na |
| 7664-41-7 | Ammonia | 1.36E-03 | na | 1.36E-03 | na |
| 7723-14-0 | Phosphorus, white | 6.15E+01 | na | 2.92E+04 | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 2.05E-02 | na | 1.46E-01 | na |
| 7782-49-2 | Selenium and compounds | 2.45E-01 | na | 1.36E+01 | na |
| 7791-12-0 | Thallium chloride | 1.54E+01 | na | 4.85E+04 | na |
| 8001-35-2 | Toxaphene | na | 1.36E-03 | na | 1.04E+00 |
| 10102-45-1 | Thallium (I) nitrate | 1.36E+01 | na | 4.31E+04 | na |
| 11096-82-5 | Aroclor 1260 | na | 1.10E-02 | na | 1.71E+00 |
| 11097-69-1 | Aroclor 1254 | 6.49E+02 | 2.14E-03 | 2.73E+06 | 4.67E+01 |
| 11104-28-2 | Aroclor 1221 | na | 2.84E-04 | na | 2.06E-01 |
| 11141-16-5 | Aroclor 1232 | na | 2.84E-04 | na | 2.06E-01 |
| 12672-29-6 | Aroclor 1248 | na | 1.38E-03 | na | 2.11E+01 |
| 12674-11-2 | Aroclor 1016 | 6.67E+01 | 1.43E-04 | 9.83E+04 | 5.87E+00 |
| 14797-55-8 | Nitrate | 7.62E-04 | na | 1.74E-03 | na |

**Table 22. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Recreational Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 14797-65-0 | Nitrite | 1.22E-02 | na | 2.78E-02 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 9.61E-04 | na | 5.97E-02 | na |
| 16984-48-8 | Fluorine anion | 2.05E-02 | na | 1.46E-01 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 4.39E-01 | 6.73E-07 | 2.69E+01 | 6.73E-07 |
| 22967-92-6 | Methyl mercury | 1.23E+01 | na | 3.91E+03 | na |
| 53469-21-9 | Aroclor 1242 | na | 1.29E-03 | na | 1.93E+01 |
| na | Uranium (soluble salts) | 2.04E+00 | na | 1.18E+01 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 6.36E-02 | 9.62E-08 | 3.89E+00 | 9.62E-08 |

Notes:
- CASRN = Chemical Abstract Service Reference Number
- The total risk to the HSRAM Recreational Visitor is calculated using intakes from 30 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario factors must be multiplied by the appropriate water concentration. The "Inland Well" column assumes all of the contaminated water comes from the well. The "Columbia River" column assumes that all of the contaminated water comes from the Columbia River.
- Results using route-to-route extrapolations are shown in Table C10.

## 3.9 HSRAM RESIDENTIAL SCENARIO

The default residential exposure scenario presented in the HSRAM is similar to the All Pathways Farmer discussed earlier. The differences include the ingestion of deer and fish (HSRAM) rather than milk, meat, poultry and eggs. Another difference is the resident goes swimming in the HSRAM Residential scenario. The intake rates for water, garden produce, soil, and air differ as well. The annual intakes for food and water are shown in Table A4.

The hazard quotient for chemicals is calculated using the drinking, breathing and soil ingestion rates for children. The incremental cancer risk is calculated using adult drinking and breathing rates, and an average soil ingestion rate that includes 6 years at the child's higher rate.

The principle avenues for the contaminants to get into the resident are drinking water and game fish. However, if a well to groundwater is the source of contaminated water then the fish are not contaminated. Hence, for the residential scenario there are two cases. The first is for a well to groundwater. The second is when the water supply is taken directly from the Columbia River. The second case adds fish, sediment exposure, and dermal contact with water during swimming to the first case. The added pathways use the same annual intakes as the recreational scenario along the Columbia River.

The lifetime increase in the resident's risk of developing some type of cancer from the radionuclides is the sum of 30 years of exposure. The first 6 years are at the child's intake rates for some pathways, while the last 24 years are at the adult's rate. Both of these intake rates are shown in Table A8. The other intakes are all at the adult rate. Drinking water consumption is 730 L/y (Table A4). The individual has a 10-minute shower every day and inhales the

equivalent of 0.72 mL/y (Table A16). Soil inhalation is 0.365 g/y (Table A10). External exposure is 7,008 h/y (Table A18). The estimated risks from radioactive materials in the residential scenarios are shown in Table 23. The first column of risks shows the inland resident, who obtains the radionuclides from groundwater. The second column of risks shows the Columbia River case, in which the radionuclides are in the surface water. The third column is the ratio of the Columbia River to the inland resident risk factors.

**Table 23. Unit Risk Factors for Radionuclides: Residential Scenarios (risk per pCi/L)**

| Nuclide | Inland Resident | Columbia River | Ratio | Nuclide | Inland Resident | Columbia River | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 2.56E-09 | 2.61E-09 | | Eu-155 | 1.01E-07 | 1.51E-07 | 1.5 |
| Be-10 | 1.62E-07 | 5.60E-07 | 3.5 | Gd-152 | 6.75E-07 | 1.26E-06 | 1.9 |
| C-14 | 5.14E-08 | 2.98E-05 | 579 | Tb-157 | 6.23E-09 | 1.06E-08 | 1.7 |
| Na-22 | 3.21E-06 | 3.41E-06 | | Ho-166m | 1.03E-05 | 1.16E-05 | 1.1 |
| Al-26 | 1.82E-05 | 2.41E-05 | 1.3 | Re-187 | 5.66E-10 | 1.69E-09 | 3.0 |
| Si-32+D | 3.13E-07 | 5.31E-07 | 1.7 | Tl-204 | 1.33E-07 | 2.46E-05 | 185 |
| Cl-36 | 1.54E-06 | 1.61E-06 | | Pb-205 | 1.43E-08 | 9.40E-08 | 6.6 |
| K-40 | 1.68E-06 | 1.21E-05 | 7.2 | Pb-210+D | 2.09E-05 | 1.35E-04 | 6.5 |
| Ca-41 | 1.06E-08 | 1.72E-08 | 1.6 | Bi-207 | 7.86E-06 | 8.66E-06 | |
| Ti-44+D | 1.28E-05 | 2.58E-05 | 2.0 | Po-209 | 1.52E-05 | 6.12E-05 | 4.0 |
| V-49 | 2.74E-09 | 1.34E-08 | 4.9 | Po-210 | 1.13E-05 | 4.48E-05 | 4.0 |
| Mn-53 | 4.52E-09 | 3.34E-08 | 7.4 | Ra-226+D | 2.01E-05 | 3.74E-05 | 1.9 |
| Mn-54 | 4.59E-07 | 8.50E-07 | 1.9 | Ra-228+D | 2.97E-05 | 5.50E-05 | 1.9 |
| Fe-55 | 1.93E-08 | 8.94E-08 | 4.6 | Ac-227+D | 1.25E-05 | 2.09E-05 | 1.7 |
| Fe-60+D | 1.42E-05 | 3.17E-05 | 2.2 | Th-228+D | 8.51E-06 | 2.15E-05 | 2.5 |
| Co-60 | 6.53E-06 | 8.93E-06 | 1.4 | Th-229+D | 1.36E-05 | 4.13E-05 | 3.0 |
| Ni-59 | 6.60E-09 | 2.17E-08 | 3.3 | Th-230 | 2.12E-06 | 6.70E-06 | 3.2 |
| Ni-63 | 1.61E-08 | 5.20E-08 | 3.2 | Th-232 | 1.12E-05 | 2.87E-05 | 2.6 |
| Se-79 | 1.65E-07 | 6.66E-07 | 4.0 | Pa-231 | 4.67E-06 | 9.50E-06 | 2.0 |
| Rb-87 | 2.14E-07 | 4.47E-06 | 20.8 | U-232 | 1.29E-05 | 1.69E-05 | 1.3 |
| Sr-90+D | 2.39E-06 | 4.55E-06 | 1.9 | U-233 | 1.64E-06 | 2.25E-06 | 1.4 |
| Zr-93 | 2.51E-08 | 1.69E-07 | 6.7 | U-234 | 1.61E-06 | 2.21E-06 | 1.4 |
| Nb-91 | 2.87E-08 | 1.45E-07 | 5.0 | U-235+D | 2.18E-06 | 2.83E-06 | 1.3 |
| Nb-93m | 1.85E-08 | 1.28E-07 | 6.9 | U-236 | 1.53E-06 | 2.09E-06 | 1.4 |
| Nb-94 | 9.80E-06 | 1.19E-05 | 1.2 | U-238+D | 2.09E-06 | 2.88E-06 | 1.4 |
| Mo-93 | 1.15E-07 | 1.41E-07 | 1.2 | Np-237+D | 2.53E-06 | 3.77E-06 | 1.5 |
| Tc-97 | 3.20E-08 | 3.48E-08 | | Pu-236 | 1.88E-06 | 2.71E-06 | 1.4 |
| Tc-99 | 3.27E-07 | 3.56E-07 | | Pu-238 | 2.96E-06 | 5.17E-06 | 1.7 |
| Ru-106+D | 1.07E-06 | 1.29E-06 | 1.2 | Pu-239 | 3.05E-06 | 5.48E-06 | 1.8 |
| Pd-107 | 5.96E-09 | 1.01E-08 | 1.7 | Pu-240 | 3.05E-06 | 5.48E-06 | 1.8 |
| Ag-108m+D | 9.43E-06 | 1.05E-05 | | Pu-241+D | 4.04E-08 | 8.00E-08 | 2.0 |
| Cd-109+D | 1.16E-07 | 5.17E-07 | 4.5 | Pu-242 | 2.89E-06 | 5.20E-06 | 1.8 |
| Cd-113m | 7.03E-07 | 2.98E-06 | 4.2 | Pu-244+D | 5.29E-06 | 8.23E-06 | 1.6 |
| In-115 | 7.58E-07 | 1.29E-03 | 1,697 | Am-241 | 2.39E-06 | 4.25E-06 | 1.8 |
| Sn-121m+D | 8.16E-08 | 4.68E-06 | 57.4 | Am-242m+D | 1.72E-06 | 3.39E-06 | 2.0 |
| Sn-126+D | 1.24E-05 | 4.90E-05 | 3.9 | Am-243+D | 3.30E-06 | 5.40E-06 | 1.6 |
| Sb-125 | 6.54E-07 | 8.74E-07 | 1.3 | Cm-242 | 8.57E-07 | 1.21E-06 | 1.4 |

**Table 23. Unit Risk Factors for Radionuclides: Residential Scenarios (risk per pCi/L)**

| Nuclide | Inland Resident | Columbia River | Ratio | Nuclide | Inland Resident | Columbia River | Ratio |
|---|---|---|---|---|---|---|---|
| Te-125m | 7.27E-08 | 6.31E-07 | 8.7 | Cm-243 | 2.59E-06 | 4.07E-06 | 1.6 |
| I-129 | 3.39E-06 | 6.51E-06 | 1.9 | Cm-244 | 1.88E-06 | 3.05E-06 | 1.6 |
| Cs-134 | 2.65E-06 | 3.33E-05 | 12.6 | Cm-245 | 2.67E-06 | 4.63E-06 | 1.7 |
| Cs-135 | 1.22E-07 | 3.65E-06 | 30.0 | Cm-246 | 2.31E-06 | 4.15E-06 | 1.8 |
| Cs-137+D | 3.49E-06 | 2.61E-05 | 7.5 | Cm-247+D | 4.09E-06 | 6.14E-06 | 1.5 |
| Ba-133 | 1.22E-06 | 1.34E-06 | | Cm-248 | 2.15E-05 | 3.89E-05 | 1.8 |
| Ce-144+D | 8.18E-07 | 1.30E-06 | 1.6 | Cm-250+D | 5.01E-05 | 8.90E-05 | 1.8 |
| Pm-147 | 3.83E-08 | 6.31E-08 | 1.6 | Bk-247 | 3.22E-06 | 5.65E-06 | 1.8 |
| Sm-147 | 8.46E-07 | 1.56E-06 | 1.8 | Cf-248 | 9.97E-07 | 1.51E-06 | 1.5 |
| Sm-151 | 1.27E-08 | 2.53E-08 | 2.0 | Cf-249 | 4.68E-06 | 7.27E-06 | 1.6 |
| Eu-150 | 7.33E-06 | 8.14E-06 | | Cf-250 | 1.95E-06 | 3.20E-06 | 1.6 |
| Eu-152 | 4.63E-06 | 5.15E-06 | | Cf-251 | 3.51E-06 | 6.09E-06 | 1.7 |
| Eu-154 | 4.23E-06 | 4.78E-06 | 1.1 | Cf-252 | 1.54E-06 | 2.32E-06 | 1.5 |

Notes:

- The radiation risk to this individual is calculated using intakes from 30 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario risk factors must be multiplied by the water concentration.
- The "Inland Resident" column gives the residential scenario risk factors from groundwater. The column "Columbia River" shows the risk factors for surface water. The "Ratio" column is the "Columbia River" divided by the "Inland Resident" risk factors.

The hazard quotient and cancer risk from chemicals are calculated using the same consumption parameters discussed in Appendix A for the HSRAM Residential scenario. The contaminant concentration in well or river water is expressed in mg/L. The chemical dose is normalized to the average adult body mass, 70 kg. To calculate the average daily dose over a lifetime, the total dose from 30 consecutive years is calculated and then divided by (30 y)(365 d/y) for the hazard quotient and (70 y)(365 d/y) for the cancer risk. As part of this calculation, the concentration of the contaminants in soil is increased each year. The effect of leaching from the surface layer is included using the leaching coefficients shown in Table A41. Dermal absorption during showering is included.

The calculated hazard quotient and cancer risk per unit concentration in the well or the Columbia River for the HSRAM Residential scenario are shown in Table 24. The factors must be multiplied by the estimated water concentration, in mg per L.

**Table 24. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Residential Scenario**

| | | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| CASRN | Chemical Name | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 50-32-8 | Benzo[a]pyrene | na | 3.78E+00 | na | 1.70E+01 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 4.87E+00 | na | 4.36E+01 |
| 56-23-5 | Carbon tetrachloride | 1.06E+02 | 4.67E-03 | 1.24E+02 | 5.37E-03 |
| 56-55-3 | Benz[a]anthracene | na | 2.62E-01 | na | 9.55E-01 |
| 57-12-5 | Cyanide, free | 3.14E+01 | na | 3.15E+01 | na |

**Table 24. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Residential Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 4.30E+00 | na | 4.30E+00 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.23E+00 | na | 2.23E+00 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 3.44E+02 | 3.83E-02 | 5.40E+02 | 7.07E-02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 4.13E-01 | na | 4.19E-01 | na |
| 60-34-4 | Methylhydrazine | na | 3.22E+00 | na | 3.22E+00 |
| 60-57-1 | Dieldrin | 3.10E+03 | 1.13E+00 | 2.56E+04 | 8.84E+00 |
| 62-75-9 | N-Nitrosodimethylamine | 2.02E+05 | 3.47E+01 | 2.02E+05 | 3.47E+01 |
| 64-18-6 | Formic acid | 4.73E-01 | na | 4.74E-01 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 1.24E+00 | na | 1.24E+00 | na |
| 67-64-1 | Acetone (2-Propanone) | 2.54E-01 | na | 2.55E-01 | na |
| 67-66-3 | Chloroform | 1.34E+02 | 3.86E-03 | 1.34E+02 | 3.87E-03 |
| 67-72-1 | Hexachloroethane | 1.08E+02 | 1.09E-03 | 2.32E+02 | 1.84E-03 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.64E+01 | na | 1.65E+01 | na |
| 71-43-2 | Benzene | 3.10E+01 | 2.20E-03 | 3.20E+01 | 2.29E-03 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 1.12E-01 | na | 1.15E-01 | na |
| 72-20-8 | Endrin | 5.38E+03 | na | 8.67E+03 | na |
| 74-83-9 | Bromomethane | 1.30E+02 | na | 1.31E+02 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | 4.22E+00 | 5.47E-04 | 4.22E+00 | 5.54E-04 |
| 75-00-3 | Ethyl Chloride | 2.22E-01 | 4.92E-05 | 2.25E-01 | 5.06E-05 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 2.79E+01 | 2.61E-02 | 2.84E+01 | 2.71E-02 |
| 75-05-8 | Acetonitrile | 6.35E+00 | na | 6.35E+00 | na |
| 75-07-0 | Acetaldehyde | 4.22E+01 | 3.58E-04 | 4.22E+01 | 3.58E-04 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 1.41E+00 | 2.14E-04 | 1.42E+00 | 2.17E-04 |
| 75-15-0 | Carbon disulfide | 1.26E+00 | na | 1.29E+00 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 7.75E-02 | na | 7.81E-02 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.48E+00 | na | 1.50E+00 | na |
| 75-35-4 | 1,1-Dichloroethylene | 3.32E+00 | na | 3.40E+00 | na |
| 75-45-6 | Chlorodifluoromethane | 7.59E-03 | na | 7.59E-03 | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 7.59E-03 | na | 7.59E-03 | na |
| 75-69-4 | Trichlorofluoromethane | 8.15E-01 | na | 8.44E-01 | na |
| 75-71-8 | Dichlorodifluoromethane | 2.29E+00 | na | 2.31E+00 | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 1.51E-02 | na | 1.59E-02 | na |
| 76-44-8 | Heptachlor | 4.91E+02 | 6.16E-01 | 8.24E+03 | 8.08E+00 |
| 78-83-1 | Isobutanol | 4.89E-01 | na | 4.94E-01 | na |
| 78-87-5 | 1,2-Dichloropropane | 9.52E+01 | 1.16E-03 | 9.52E+01 | 1.25E-03 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 3.45E-01 | na | 3.47E-01 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 1.95E+01 | 3.73E-03 | 2.01E+01 | 3.79E-03 |
| 79-01-6 | Trichloroethylene | 3.00E+02 | 2.77E-02 | 3.27E+02 | 2.91E-02 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 6.25E+00 | na | 6.25E+00 | na |

**Table 24. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Residential Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 1.32E+00 | 1.32E-02 | 1.42E+00 | 1.37E-02 |
| 79-46-9 | 2-Nitropropane | 1.90E+01 | 4.37E-01 | 1.90E+01 | 4.37E-01 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 3.50E+01 | 7.85E-03 | 1.33E+02 | 4.06E-02 |
| 83-32-9 | Acenaphthene | 2.56E+00 | na | 4.08E+00 | na |
| 84-66-2 | Diethyl phthalate | 1.63E-01 | na | 1.71E-01 | na |
| 84-74-2 | Dibutyl phthalate | 9.86E-01 | na | 3.28E+00 | na |
| 85-68-7 | Butyl benzyl phthalate | 6.06E-01 | na | 2.34E+00 | na |
| 86-73-7 | Fluorene | 3.59E+00 | na | 7.03E+00 | na |
| 86-74-8 | Carbazole | na | 8.11E-04 | na | 1.33E-03 |
| 87-68-3 | Hexachlorobutadiene | 4.87E+02 | 7.37E-03 | 1.76E+03 | 2.01E-02 |
| 87-86-5 | Pentachlorophenol | 4.58E+00 | 5.30E-03 | 1.39E+01 | 1.97E-02 |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.16E+03 | 4.36E-04 | 1.41E+03 | 5.55E-04 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 1.23E+02 | na | 1.69E+02 | na |
| 91-20-3 | Naphthalene | 1.31E+02 | na | 1.33E+02 | na |
| 92-52-4 | 1,1'-Biphenyl | 2.53E+00 | na | 4.47E+00 | na |
| 95-47-6 | o-Xylene | 4.20E+00 | na | 4.31E+00 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 4.52E+00 | na | 4.59E+00 | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 2.83E+00 | na | 3.23E+00 | na |
| 95-57-8 | 2-Chlorophenol | 3.14E+01 | na | 3.23E+01 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 6.53E+01 | na | 6.63E+01 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.16E+00 | na | 1.43E+00 | na |
| 98-86-2 | Acetophenone | 1.48E+00 | na | 1.49E+00 | na |
| 98-95-3 | Nitrobenzene | 4.63E+02 | na | 4.68E+02 | na |
| 100-00-5 | p-Chloronitrobenzene | 2.65E+02 | 2.99E-04 | 2.71E+02 | 3.16E-04 |
| 100-02-7 | 4-Nitrophenol | 2.78E+01 | na | 2.82E+01 | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 3.25E+03 | na | 3.26E+03 | na |
| 100-41-4 | Ethyl benzene | 1.16E+00 | 1.79E-04 | 1.38E+00 | 1.79E-04 |
| 100-42-5 | Styrene | 7.78E-01 | na | 8.56E-01 | na |
| 100-51-6 | Benzyl alcohol | 7.15E-01 | na | 7.16E-01 | na |
| 106-42-3 | p-Xylene | 4.20E+00 | na | 4.31E+00 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 4.44E+01 | na | 4.50E+01 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 3.20E+00 | 1.51E-03 | 4.40E+00 | 1.89E-03 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 5.14E+01 | 1.40E-01 | 5.17E+01 | 1.42E-01 |
| 106-99-0 | 1,3-Butadiene | 1.90E+02 | 4.88E-03 | 1.90E+02 | 4.88E-03 |
| 107-02-8 | 2-Propenal (Acrolein) | 1.93E+04 | na | 1.93E+04 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 3.81E+02 | na | 3.81E+02 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 8.14E+01 | 5.96E-03 | 8.15E+01 | 6.01E-03 |
| 107-13-1 | Acrylonitrile | 3.29E+02 | 3.53E-02 | 3.30E+02 | 3.55E-02 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 1.27E+00 | na | 1.28E+00 | na |

**Table 24. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Residential Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 108-38-3 | m-Xylene | 4.21E+00 | na | 4.33E+00 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 4.41E+00 | na | 4.47E+00 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 6.52E+01 | na | 6.59E+01 | na |
| 108-87-2 | Methyl cyclohexane | 1.27E-01 | na | 1.27E-01 | na |
| 108-88-3 | Toluene (Methyl benzene) | 1.02E+00 | na | 1.16E+00 | na |
| 108-90-7 | Chlorobenzene | 1.08E+01 | na | 1.15E+01 | na |
| 108-94-1 | Cyclohexanone | 4.22E-02 | na | 4.25E-02 | na |
| 108-95-2 | Phenol (Carbolic acid) | 1.10E+00 | na | 1.10E+00 | na |
| 109-99-9 | Tetrahydrofuran | 1.81E+00 | 5.75E-04 | 1.81E+00 | 5.79E-04 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 7.75E+01 | na | 7.85E+01 | na |
| 110-54-3 | n-Hexane | 2.39E+00 | na | 3.79E+00 | na |
| 110-80-5 | 2-Ethoxyethanol | 1.34E+00 | na | 1.35E+00 | na |
| 110-82-7 | Cyclohexane | 6.35E-02 | na | 6.35E-02 | na |
| 110-86-1 | Pyridine | 2.87E+02 | na | 2.88E+02 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 3.29E-01 | na | 3.31E-01 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 1.23E+01 | na | 1.23E+01 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 2.95E+02 | 3.53E-02 | 3.40E+02 | 4.06E-02 |
| 117-84-0 | Di-n-octylphthalate | 6.76E+01 | na | 7.70E+01 | na |
| 118-74-1 | Hexachlorobenzene | 4.44E+02 | 2.94E-01 | 2.99E+03 | 1.69E+00 |
| 120-12-7 | Anthracene | 4.60E-01 | na | 1.18E+00 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.04E+02 | na | 1.14E+02 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 1.15E+02 | na | 1.16E+02 | na |
| 121-44-8 | Triethylamine | 5.43E+01 | na | 5.43E+01 | na |
| 122-39-4 | Diphenylamine | 4.81E+00 | na | 6.49E+00 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 1.39E-03 | na | 1.39E-03 |
| 126-73-8 | Tributyl Phosphate | 5.53E-01 | 1.76E-04 | 6.51E-01 | 2.20E-04 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.64E+03 | na | 1.65E+03 | na |
| 127-18-4 | Tetrachloroethylene | 8.32E+00 | 1.09E-02 | 1.17E+01 | 1.86E-02 |
| 129-00-0 | Pyrene | 1.07E+01 | na | 2.67E+01 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.23E-01 | na | 1.24E-01 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 7.28E+00 | na | 7.51E+00 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 3.58E+00 | na | 3.75E+00 | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 4.58E-01 | na | 4.01E+00 |
| 205-99-2 | Benzo[b]fluoranthene | na | 2.27E-01 | na | 9.42E-01 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 1.11E+01 | na | 3.07E+01 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 3.67E-02 | na | 1.64E-01 |
| 218-01-9 | Chrysene | na | 2.77E-03 | na | 1.03E-02 |
| 309-00-2 | Aldrin | 2.28E+04 | 5.52E+00 | 2.86E+05 | 6.31E+01 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 1.98E+02 | 3.20E-01 | 3.33E+02 | 5.01E-01 |

**Table 24. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Residential Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 5.21E+02 | 5.52E-02 | 8.48E+02 | 1.05E-01 |
| 541-73-1 | 1,3-Dichlorobenzene | 9.49E+01 | na | 1.42E+02 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 2.15E+01 | 2.40E-03 | 2.16E+01 | 2.54E-03 |
| 563-68-8 | Thallium acetate | 7.58E+02 | na | 4.39E+04 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 1.00E+00 | na | 1.00E+00 |
| 1314-62-1 | Vanadium pentoxide | 7.99E+00 | na | 1.71E+01 | na |
| 1330-20-7 | Xylenes (mixtures) | 4.19E+00 | na | 4.29E+00 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 8.73E-02 | na | 1.94E+01 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 3.26E-02 | na | 1.93E+01 |
| 6533-73-9 | Thallium carbonate | 8.52E+02 | na | 4.93E+04 | na |
| 7429-90-5 | Aluminum | 7.17E-02 | na | 2.70E-01 | na |
| 7439-89-6 | Iron | 2.30E-01 | na | 5.01E-01 | na |
| 7439-93-2 | Lithium | 3.45E+00 | na | 3.65E+00 | na |
| 7439-96-5 | Manganese | 2.08E+00 | na | 3.28E+00 | na |
| 7439-97-6 | Mercury metal vapor | 3.16E-02 | na | 3.16E-02 | na |
| 7439-98-7 | Molybdenum | 3.82E+01 | na | 3.94E+01 | na |
| 7440-02-0 | Nickel (soluble salts) | 4.00E+00 | na | 6.12E+00 | na |
| 7440-22-4 | Silver | 1.37E+01 | na | 1.48E+01 | na |
| 7440-24-6 | Strontium, Stable | 3.10E-01 | na | 3.55E-01 | na |
| 7440-28-0 | Thallium metal | 1.03E+03 | na | 5.98E+04 | na |
| 7440-31-5 | Tin | 1.18E-01 | na | 2.06E+00 | na |
| 7440-36-0 | Antimony | 1.86E+02 | na | 2.97E+02 | na |
| 7440-38-2 | Arsenic (inorganic) | 2.33E+02 | 2.30E-02 | 5.66E+02 | 8.67E-02 |
| 7440-39-3 | Barium | 4.02E-01 | na | 4.29E-01 | na |
| 7440-41-7 | Beryllium and compounds | 3.65E+01 | 2.85E-05 | 5.93E+01 | 2.85E-05 |
| 7440-42-8 | Boron and borates only | 1.54E+00 | na | 1.56E+00 | na |
| 7440-43-9 | Cadmium | 1.69E+02 | 2.10E-05 | 2.58E+02 | 2.10E-05 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 6.55E-02 | na | 6.55E-02 | na |
| 7440-48-4 | Cobalt | 4.60E+00 | 3.24E-05 | 1.06E+01 | 3.24E-05 |
| 7440-50-8 | Copper | 5.43E+00 | na | 7.45E+00 | na |
| 7440-62-2 | Vanadium metal | 1.07E+01 | na | 2.28E+01 | na |
| 7440-66-6 | Zinc and compounds | 1.50E+01 | na | 1.53E+01 | na |
| 7446-18-6 | Thallium sulfate | 8.52E+02 | na | 4.93E+04 | na |
| 7487-94-7 | Mercuric chloride | 3.54E+02 | na | 1.65E+03 | na |
| 7664-41-7 | Ammonia | 2.50E+00 | na | 2.50E+00 | na |
| 7723-14-0 | Phosphorus, white | 3.14E+04 | na | 6.06E+04 | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 1.16E+00 | na | 1.29E+00 | na |
| 7782-49-2 | Selenium and compounds | 1.40E+01 | na | 2.74E+01 | na |
| 7791-12-0 | Thallium chloride | 8.52E+02 | na | 4.93E+04 | na |
| 8001-35-2 | Toxaphene | na | 8.67E-02 | na | 1.12E+00 |
| 10102-45-1 | Thallium (I) nitrate | 7.57E+02 | na | 4.39E+04 | na |
| 11096-82-5 | Aroclor 1260 | na | 5.93E-01 | na | 2.30E+00 |

**Table 24. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Residential Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 11097-69-1 | Aroclor 1254 | 3.41E+04 | 1.31E-01 | 2.76E+06 | 4.69E+01 |
| 11104-28-2 | Aroclor 1221 | na | 3.78E-02 | na | 2.43E-01 |
| 11141-16-5 | Aroclor 1232 | na | 3.78E-02 | na | 2.43E-01 |
| 12672-29-6 | Aroclor 1248 | na | 9.18E-02 | na | 2.11E+01 |
| 12674-11-2 | Aroclor 1016 | 3.56E+03 | 3.05E-02 | 1.02E+05 | 5.90E+00 |
| 14797-55-8 | Nitrate | 3.97E-02 | na | 4.07E-02 | na |
| 14797-65-0 | Nitrite | 6.36E-01 | na | 6.51E-01 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 5.23E-02 | na | 1.11E-01 | na |
| 16984-48-8 | Fluorine anion | 1.16E+00 | na | 1.29E+00 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 2.42E+01 | 3.51E-05 | 5.06E+01 | 3.51E-05 |
| 22967-92-6 | Methyl mercury | 1.06E+03 | na | 4.96E+03 | na |
| 53469-21-9 | Aroclor 1242 | na | 8.72E-02 | na | 1.94E+01 |
| na | Uranium (soluble salts) | 1.16E+02 | na | 1.25E+02 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 3.50E+00 | 5.02E-06 | 7.32E+00 | 5.02E-06 |

Notes:
- CASRN = Chemical Abstract Service Reference Number
- The total risk to the HSRAM Residential scenario is calculated using intakes from 30 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario factors must be multiplied by the appropriate water concentration. The "Inland Well" column assumes all of the contaminated water comes from the well. The "Columbia River" column assumes that all of the contaminated water comes from the Columbia River.
- Results using route-to-route extrapolations are shown in Table C12.

## 3.10 HSRAM AGRICULTURAL SCENARIO

The agricultural exposure scenario presented in the HSRAM is similar to the All Pathways Farmer discussed earlier. The difference is that the HSRAM includes deer and swimming, and the intake rates for water, soil, food, and air are different. For food and water, these are shown in Table A4. The HSRAM Residential and Agricultural scenarios are the same except for the addition of beef, milk, and the deer.

The usual two versions of the agricultural scenario are calculated. The first places the farm inland so that the contaminants come from groundwater. The second case adds game animal products, shoreline sediments, and dermal contact during swimming to the first case.

The lifetime increase in the resident's risk of developing some type of cancer from the radionuclides is the sum of 30 years of exposure. The first 6 years are at the child's soil ingestion rate (73 g/y), while the last 24 are at the adult's soil ingestion rate (36.5 g/y). Both of these are shown in Table A8. The other intakes are all at the adult rate. Drinking water consumption is 730 L/y (Table A4). The individual has a 10-minute shower every day and inhales the equivalent of 0.72 mL/y (Table A16). Soil inhalation is 0.365 g/y (Table A10). External exposure is 7,008 h/y (Table A18). The estimated risks from radioactive materials in

the residential scenarios are shown in Table 25. The first column of risks shows the inland resident, who obtains the radionuclides from groundwater. The second column of risks shows the Columbia River case, in which the radionuclides are in the surface water. The third column is the ratio of the Columbia River to the inland resident risk factors.

**Table 25. Unit Risk Factors for Radionuclides: Agricultural Scenarios (risk per pCi/L)**

| Nuclide | Inland Resident | Columbia River | Ratio | Nuclide | Inland Resident | Columbia River | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 3.06E-09 | 3.12E-09 | | Eu-155 | 1.07E-07 | 1.57E-07 | 1.5 |
| Be-10 | 1.66E-07 | 5.65E-07 | 3.4 | Gd-152 | 7.39E-07 | 1.33E-06 | 1.8 |
| C-14 | 2.12E-07 | 2.99E-05 | 141 | Tb-157 | 6.80E-09 | 1.12E-08 | 1.6 |
| Na-22 | 4.24E-06 | 4.44E-06 | | Ho-166m | 1.03E-05 | 1.16E-05 | 1.1 |
| Al-26 | 1.82E-05 | 2.41E-05 | 1.3 | Re-187 | 1.05E-09 | 2.18E-09 | 2.1 |
| Si-32+D | 3.14E-07 | 5.32E-07 | 1.7 | Tl-204 | 3.15E-07 | 2.48E-05 | 78.9 |
| Cl-36 | 6.66E-06 | 6.73E-06 | | Pb-205 | 1.51E-08 | 9.48E-08 | 6.3 |
| K-40 | 3.53E-06 | 1.39E-05 | 3.9 | Pb-210+D | 2.52E-05 | 1.39E-04 | 5.5 |
| Ca-41 | 2.58E-08 | 3.24E-08 | 1.3 | Bi-207 | 7.88E-06 | 8.68E-06 | |
| Ti-44+D | 1.45E-05 | 2.75E-05 | 1.9 | Po-209 | 2.45E-05 | 7.05E-05 | 2.9 |
| V-49 | 2.90E-09 | 1.36E-08 | 4.7 | Po-210 | 1.55E-05 | 4.90E-05 | 3.2 |
| Mn-53 | 4.64E-09 | 3.35E-08 | 7.2 | Ra-226+D | 2.27E-05 | 4.00E-05 | 1.8 |
| Mn-54 | 4.60E-07 | 8.51E-07 | 1.8 | Ra-228+D | 3.59E-05 | 6.12E-05 | 1.7 |
| Fe-55 | 2.85E-08 | 9.87E-08 | 3.5 | Ac-227+D | 1.26E-05 | 2.10E-05 | 1.7 |
| Fe-60+D | 1.64E-05 | 3.39E-05 | 2.1 | Th-228+D | 8.52E-06 | 2.15E-05 | 2.5 |
| Co-60 | 6.65E-06 | 9.05E-06 | 1.4 | Th-229+D | 1.36E-05 | 4.13E-05 | 3.0 |
| Ni-59 | 2.83E-08 | 4.35E-08 | 1.5 | Th-230 | 2.12E-06 | 6.71E-06 | 3.2 |
| Ni-63 | 6.88E-08 | 1.05E-07 | 1.5 | Th-232 | 1.18E-05 | 2.92E-05 | 2.5 |
| Se-79 | 3.50E-07 | 8.51E-07 | 2.4 | Pa-231 | 4.68E-06 | 9.51E-06 | 2.0 |
| Rb-87 | 7.36E-07 | 4.99E-06 | 6.8 | U-232 | 1.34E-05 | 1.74E-05 | 1.3 |
| Sr-90+D | 5.99E-06 | 8.16E-06 | 1.4 | U-233 | 1.77E-06 | 2.39E-06 | 1.3 |
| Zr-93 | 2.51E-08 | 1.69E-07 | 6.7 | U-234 | 1.74E-06 | 2.35E-06 | 1.3 |
| Nb-91 | 2.87E-08 | 1.45E-07 | 5.0 | U-235+D | 2.32E-06 | 2.97E-06 | 1.3 |
| Nb-93m | 1.85E-08 | 1.28E-07 | 6.9 | U-236 | 1.65E-06 | 2.22E-06 | 1.3 |
| Nb-94 | 9.80E-06 | 1.19E-05 | 1.2 | U-238+D | 2.26E-06 | 3.04E-06 | 1.3 |
| Mo-93 | 1.52E-07 | 1.78E-07 | 1.2 | Np-237+D | 2.57E-06 | 3.81E-06 | 1.5 |
| Tc-97 | 4.52E-08 | 4.81E-08 | | Pu-236 | 1.88E-06 | 2.72E-06 | 1.4 |
| Tc-99 | 4.63E-07 | 4.92E-07 | | Pu-238 | 2.96E-06 | 5.17E-06 | 1.7 |
| Ru-106+D | 2.14E-06 | 2.36E-06 | | Pu-239 | 3.05E-06 | 5.48E-06 | 1.8 |
| Pd-107 | 1.98E-08 | 2.39E-08 | 1.2 | Pu-240 | 3.05E-06 | 5.48E-06 | 1.8 |
| Ag-108m+D | 9.44E-06 | 1.05E-05 | | Pu-241+D | 4.04E-08 | 8.00E-08 | 2.0 |
| Cd-109+D | 1.36E-07 | 5.37E-07 | 4.0 | Pu-242 | 2.90E-06 | 5.20E-06 | 1.8 |
| Cd-113m | 8.57E-07 | 3.13E-06 | 3.7 | Pu-244+D | 5.29E-06 | 8.24E-06 | 1.6 |
| In-115 | 9.29E-07 | 1.29E-03 | 1,386 | Am-241 | 2.39E-06 | 4.25E-06 | 1.8 |
| Sn-121m+D | 2.84E-07 | 4.88E-06 | 17.2 | Am-242m+D | 1.72E-06 | 3.39E-06 | 2.0 |

**Table 25. Unit Risk Factors for Radionuclides: Agricultural Scenarios (risk per pCi/L)**

| Nuclide | Inland Resident | Columbia River | Ratio | Nuclide | Inland Resident | Columbia River | Ratio |
|---|---|---|---|---|---|---|---|
| Sn-126+D | 1.40E-05 | 5.06E-05 | 3.6 | Am-243+D | 3.30E-06 | 5.40E-06 | 1.6 |
| Sb-125 | 6.57E-07 | 8.78E-07 | 1.3 | Cm-242 | 8.59E-07 | 1.22E-06 | 1.4 |
| Te-125m | 7.95E-08 | 6.38E-07 | 8.0 | Cm-243 | 2.59E-06 | 4.08E-06 | 1.6 |
| I-129 | 1.67E-05 | 1.98E-05 | 1.2 | Cm-244 | 1.89E-06 | 3.05E-06 | 1.6 |
| Cs-134 | 4.94E-06 | 3.56E-05 | 7.2 | Cm-245 | 2.68E-06 | 4.63E-06 | 1.7 |
| Cs-135 | 5.15E-07 | 4.04E-06 | 7.8 | Cm-246 | 2.32E-06 | 4.16E-06 | 1.8 |
| Cs-137+D | 5.81E-06 | 2.84E-05 | 4.9 | Cm-247+D | 4.10E-06 | 6.15E-06 | 1.5 |
| Ba-133 | 1.24E-06 | 1.35E-06 | | Cm-248 | 2.16E-05 | 3.89E-05 | 1.8 |
| Ce-144+D | 8.22E-07 | 1.30E-06 | 1.6 | Cm-250+D | 5.03E-05 | 8.92E-05 | 1.8 |
| Pm-147 | 4.33E-08 | 6.81E-08 | 1.6 | Bk-247 | 3.22E-06 | 5.65E-06 | 1.8 |
| Sm-147 | 9.57E-07 | 1.67E-06 | 1.7 | Cf-248 | 1.10E-06 | 1.61E-06 | 1.5 |
| Sm-151 | 1.46E-08 | 2.72E-08 | 1.9 | Cf-249 | 5.05E-06 | 7.64E-06 | 1.5 |
| Eu-150 | 7.34E-06 | 8.16E-06 | | Cf-250 | 2.20E-06 | 3.44E-06 | 1.6 |
| Eu-152 | 4.65E-06 | 5.17E-06 | | Cf-251 | 3.89E-06 | 6.48E-06 | 1.7 |
| Eu-154 | 4.26E-06 | 4.81E-06 | 1.1 | Cf-252 | 1.73E-06 | 2.50E-06 | 1.5 |

Notes:

- The radiation risk to this individual is calculated using intakes from 30 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario risk factors must be multiplied by the water concentration.
- The "Inland Resident" column gives the agricultural scenario risk factors from groundwater. The column "Columbia River" shows the risk factors for surface water. The "Ratio" column is the "Columbia River" divided by the "Inland Resident" risk factors.

The hazard quotient and cancer risk from chemicals are calculated using the consumption parameters discussed in Appendix A for the HSRAM Agricultural scenario. The contaminant concentration in well or river water is expressed in mg/L. The chemical dose is normalized to the average adult body mass, 70 kg. To calculate the average daily dose over a lifetime, the total dose from 30 consecutive years is calculated and then divided by (30 y)(365 d/y) for the hazard quotient and (70 y)(365 d/y) for the cancer risk. As part of this calculation, the concentration of the contaminants in soil is increased each year. The effect of leaching from the surface layer is included using the leaching coefficients shown in Table A41. Dermal absorption during showering is included.

The calculated hazard quotient and cancer risk per unit concentration in the well or the Columbia River for the HSRAM Agricultural scenario are shown in Table 26. The factors must be multiplied by the estimated water concentration, in mg per L.

**Table 26. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Agricultural Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 50-32-8 | Benzo[a]pyrene | na | 3.94E+00 | na | 1.71E+01 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 5.52E+00 | na | 4.43E+01 |
| 56-23-5 | Carbon tetrachloride | 1.06E+02 | 4.67E-03 | 1.24E+02 | 5.37E-03 |
| 56-55-3 | Benz[a]anthracene | na | 2.69E-01 | na | 9.62E-01 |
| 57-12-5 | Cyanide, free | 3.14E+01 | na | 3.15E+01 | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 4.30E+00 | na | 4.30E+00 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.23E+00 | na | 2.23E+00 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 3.46E+02 | 3.85E-02 | 5.41E+02 | 7.10E-02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 4.13E-01 | na | 4.19E-01 | na |
| 60-34-4 | Methylhydrazine | na | 3.22E+00 | na | 3.22E+00 |
| 60-57-1 | Dieldrin | 3.28E+03 | 1.19E+00 | 2.58E+04 | 8.90E+00 |
| 62-75-9 | N-Nitrosodimethylamine | 2.02E+05 | 3.47E+01 | 2.02E+05 | 3.47E+01 |
| 64-18-6 | Formic acid | 4.73E-01 | na | 4.74E-01 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 1.24E+00 | na | 1.24E+00 | na |
| 67-64-1 | Acetone (2-Propanone) | 2.54E-01 | na | 2.55E-01 | na |
| 67-66-3 | Chloroform | 1.34E+02 | 3.86E-03 | 1.34E+02 | 3.87E-03 |
| 67-72-1 | Hexachloroethane | 1.08E+02 | 1.09E-03 | 2.32E+02 | 1.84E-03 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.64E+01 | na | 1.65E+01 | na |
| 71-43-2 | Benzene | 3.10E+01 | 2.20E-03 | 3.20E+01 | 2.29E-03 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 1.12E-01 | na | 1.15E-01 | na |
| 72-20-8 | Endrin | 5.40E+03 | na | 8.69E+03 | na |
| 74-83-9 | Bromomethane | 1.30E+02 | na | 1.31E+02 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | 4.22E+00 | 5.47E-04 | 4.22E+00 | 5.54E-04 |
| 75-00-3 | Ethyl Chloride | 2.22E-01 | 4.92E-05 | 2.25E-01 | 5.06E-05 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 2.79E+01 | 2.61E-02 | 2.84E+01 | 2.71E-02 |
| 75-05-8 | Acetonitrile | 6.35E+00 | na | 6.35E+00 | na |
| 75-07-0 | Acetaldehyde | 4.22E+01 | 3.58E-04 | 4.22E+01 | 3.58E-04 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 1.41E+00 | 2.14E-04 | 1.42E+00 | 2.17E-04 |
| 75-15-0 | Carbon disulfide | 1.26E+00 | na | 1.29E+00 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 7.75E-02 | na | 7.81E-02 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.48E+00 | na | 1.50E+00 | na |
| 75-35-4 | 1,1-Dichloroethylene | 3.32E+00 | na | 3.40E+00 | na |
| 75-45-6 | Chlorodifluoromethane | 7.59E-03 | na | 7.59E-03 | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 7.59E-03 | na | 7.59E-03 | na |
| 75-69-4 | Trichlorofluoromethane | 8.15E-01 | na | 8.44E-01 | na |
| 75-71-8 | Dichlorodifluoromethane | 2.29E+00 | na | 2.31E+00 | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 1.51E-02 | na | 1.59E-02 | na |
| 76-44-8 | Heptachlor | 5.58E+02 | 6.81E-01 | 8.30E+03 | 8.15E+00 |

**Table 26. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Agricultural Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 78-83-1 | Isobutanol | 4.89E-01 | na | 4.94E-01 | na |
| 78-87-5 | 1,2-Dichloropropane | 9.52E+01 | 1.16E-03 | 9.52E+01 | 1.25E-03 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 3.45E-01 | na | 3.47E-01 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 1.95E+01 | 3.73E-03 | 2.01E+01 | 3.79E-03 |
| 79-01-6 | Trichloroethylene | 3.00E+02 | 2.77E-02 | 3.27E+02 | 2.91E-02 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 6.25E+00 | na | 6.25E+00 | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 1.33E+00 | 1.32E-02 | 1.42E+00 | 1.37E-02 |
| 79-46-9 | 2-Nitropropane | 1.90E+01 | 4.37E-01 | 1.90E+01 | 4.37E-01 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 3.54E+01 | 7.99E-03 | 1.33E+02 | 4.07E-02 |
| 83-32-9 | Acenaphthene | 2.56E+00 | na | 4.09E+00 | na |
| 84-66-2 | Diethyl phthalate | 1.63E-01 | na | 1.71E-01 | na |
| 84-74-2 | Dibutyl phthalate | 9.98E-01 | na | 3.29E+00 | na |
| 85-68-7 | Butyl benzyl phthalate | 6.19E-01 | na | 2.35E+00 | na |
| 86-73-7 | Fluorene | 3.60E+00 | na | 7.04E+00 | na |
| 86-74-8 | Carbazole | na | 8.16E-04 | na | 1.34E-03 |
| 87-68-3 | Hexachlorobutadiene | 4.89E+02 | 7.40E-03 | 1.76E+03 | 2.01E-02 |
| 87-86-5 | Pentachlorophenol | 4.74E+00 | 5.53E-03 | 1.41E+01 | 1.99E-02 |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.16E+03 | 4.38E-04 | 1.41E+03 | 5.56E-04 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 1.23E+02 | na | 1.69E+02 | na |
| 91-20-3 | Naphthalene | 1.31E+02 | na | 1.33E+02 | na |
| 92-52-4 | 1,1'-Biphenyl | 2.54E+00 | na | 4.47E+00 | na |
| 95-47-6 | o-Xylene | 4.20E+00 | na | 4.31E+00 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 4.52E+00 | na | 4.59E+00 | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 2.83E+00 | na | 3.23E+00 | na |
| 95-57-8 | 2-Chlorophenol | 3.14E+01 | na | 3.23E+01 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 6.53E+01 | na | 6.63E+01 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.17E+00 | na | 1.43E+00 | na |
| 98-86-2 | Acetophenone | 1.48E+00 | na | 1.49E+00 | na |
| 98-95-3 | Nitrobenzene | 4.63E+02 | na | 4.68E+02 | na |
| 100-00-5 | p-Chloronitrobenzene | 2.66E+02 | 2.99E-04 | 2.72E+02 | 3.16E-04 |
| 100-02-7 | 4-Nitrophenol | 2.78E+01 | na | 2.82E+01 | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 3.25E+03 | na | 3.26E+03 | na |
| 100-41-4 | Ethyl benzene | 1.16E+00 | 1.79E-04 | 1.38E+00 | 1.79E-04 |
| 100-42-5 | Styrene | 7.78E-01 | na | 8.56E-01 | na |
| 100-51-6 | Benzyl alcohol | 7.15E-01 | na | 7.16E-01 | na |
| 106-42-3 | p-Xylene | 4.20E+00 | na | 4.31E+00 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 4.44E+01 | na | 4.50E+01 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 3.20E+00 | 1.51E-03 | 4.41E+00 | 1.89E-03 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 5.15E+01 | 1.40E-01 | 5.17E+01 | 1.42E-01 |
| 106-99-0 | 1,3-Butadiene | 1.90E+02 | 4.88E-03 | 1.90E+02 | 4.88E-03 |

**Table 26. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Agricultural Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 107-02-8 | 2-Propenal (Acrolein) | 1.93E+04 | na | 1.93E+04 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 3.81E+02 | na | 3.81E+02 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 8.14E+01 | 5.96E-03 | 8.15E+01 | 6.01E-03 |
| 107-13-1 | Acrylonitrile | 3.29E+02 | 3.53E-02 | 3.30E+02 | 3.55E-02 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 1.27E+00 | na | 1.28E+00 | na |
| 108-38-3 | m-Xylene | 4.21E+00 | na | 4.33E+00 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 4.41E+00 | na | 4.47E+00 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 6.52E+01 | na | 6.59E+01 | na |
| 108-87-2 | Methyl cyclohexane | 1.27E-01 | na | 1.27E-01 | na |
| 108-88-3 | Toluene (Methyl benzene) | 1.02E+00 | na | 1.16E+00 | na |
| 108-90-7 | Chlorobenzene | 1.08E+01 | na | 1.15E+01 | na |
| 108-94-1 | Cyclohexanone | 4.22E-02 | na | 4.25E-02 | na |
| 108-95-2 | Phenol (Carbolic acid) | 1.10E+00 | na | 1.10E+00 | na |
| 109-99-9 | Tetrahydrofuran | 1.81E+00 | 5.75E-04 | 1.81E+00 | 5.79E-04 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 7.75E+01 | na | 7.85E+01 | na |
| 110-54-3 | n-Hexane | 2.40E+00 | na | 3.79E+00 | na |
| 110-80-5 | 2-Ethoxyethanol | 1.34E+00 | na | 1.35E+00 | na |
| 110-82-7 | Cyclohexane | 6.35E-02 | na | 6.35E-02 | na |
| 110-86-1 | Pyridine | 2.87E+02 | na | 2.88E+02 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 3.29E-01 | na | 3.31E-01 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 1.23E+01 | na | 1.23E+01 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 3.64E+02 | 4.34E-02 | 4.08E+02 | 4.88E-02 |
| 117-84-0 | Di-n-octylphthalate | 1.74E+02 | na | 1.84E+02 | na |
| 118-74-1 | Hexachlorobenzene | 4.52E+02 | 2.99E-01 | 3.00E+03 | 1.69E+00 |
| 120-12-7 | Anthracene | 4.64E-01 | na | 1.18E+00 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.04E+02 | na | 1.14E+02 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 1.15E+02 | na | 1.16E+02 | na |
| 121-44-8 | Triethylamine | 5.43E+01 | na | 5.43E+01 | na |
| 122-39-4 | Diphenylamine | 4.81E+00 | na | 6.50E+00 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 1.39E-03 | na | 1.39E-03 |
| 126-73-8 | Tributyl Phosphate | 5.56E-01 | 1.77E-04 | 6.54E-01 | 2.22E-04 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.64E+03 | na | 1.65E+03 | na |
| 127-18-4 | Tetrachloroethylene | 8.32E+00 | 1.09E-02 | 1.17E+01 | 1.86E-02 |
| 129-00-0 | Pyrene | 1.08E+01 | na | 2.68E+01 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.23E-01 | na | 1.24E-01 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 7.28E+00 | na | 7.51E+00 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 3.58E+00 | na | 3.75E+00 | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 5.16E-01 | na | 4.07E+00 |
| 205-99-2 | Benzo[b]fluoranthene | na | 2.35E-01 | na | 9.49E-01 |

**Table 26. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Agricultural Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 1.13E+01 | na | 3.09E+01 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 3.82E-02 | na | 1.66E-01 |
| 218-01-9 | Chrysene | na | 2.85E-03 | na | 1.04E-02 |
| 309-00-2 | Aldrin | 2.62E+04 | 6.27E+00 | 2.90E+05 | 6.39E+01 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 1.99E+02 | 3.22E-01 | 3.34E+02 | 5.02E-01 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 5.23E+02 | 5.55E-02 | 8.50E+02 | 1.06E-01 |
| 541-73-1 | 1,3-Dichlorobenzene | 9.49E+01 | na | 1.42E+02 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 2.15E+01 | 2.40E-03 | 2.16E+01 | 2.54E-03 |
| 563-68-8 | Thallium acetate | 1.05E+03 | na | 4.42E+04 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 1.00E+00 | na | 1.00E+00 |
| 1314-62-1 | Vanadium pentoxide | 8.15E+00 | na | 1.73E+01 | na |
| 1330-20-7 | Xylenes (mixtures) | 4.19E+00 | na | 4.29E+00 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 1.26E-01 | na | 1.94E+01 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 7.17E-02 | na | 1.93E+01 |
| 6533-73-9 | Thallium carbonate | 1.18E+03 | na | 4.97E+04 | na |
| 7429-90-5 | Aluminum | 7.30E-02 | na | 2.71E-01 | na |
| 7439-89-6 | Iron | 2.66E-01 | na | 5.37E-01 | na |
| 7439-93-2 | Lithium | 6.69E+00 | na | 6.90E+00 | na |
| 7439-96-5 | Manganese | 2.09E+00 | na | 3.29E+00 | na |
| 7439-97-6 | Mercury metal vapor | 3.16E-02 | na | 3.16E-02 | na |
| 7439-98-7 | Molybdenum | 4.64E+01 | na | 4.76E+01 | na |
| 7440-02-0 | Nickel (soluble salts) | 7.98E+00 | na | 1.01E+01 | na |
| 7440-22-4 | Silver | 1.40E+01 | na | 1.51E+01 | na |
| 7440-24-6 | Strontium, Stable | 4.58E-01 | na | 5.03E-01 | na |
| 7440-28-0 | Thallium metal | 1.44E+03 | na | 6.02E+04 | na |
| 7440-31-5 | Tin | 1.97E-01 | na | 2.14E+00 | na |
| 7440-36-0 | Antimony | 1.86E+02 | na | 2.97E+02 | na |
| 7440-38-2 | Arsenic (inorganic) | 2.38E+02 | 2.38E-02 | 5.71E+02 | 8.75E-02 |
| 7440-39-3 | Barium | 4.12E-01 | na | 4.38E-01 | na |
| 7440-41-7 | Beryllium and compounds | 3.67E+01 | 2.85E-05 | 5.95E+01 | 2.85E-05 |
| 7440-42-8 | Boron and borates only | 1.88E+00 | na | 1.89E+00 | na |
| 7440-43-9 | Cadmium | 1.77E+02 | 2.10E-05 | 2.67E+02 | 2.10E-05 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 6.55E-02 | na | 6.55E-02 | na |
| 7440-48-4 | Cobalt | 5.06E+00 | 3.24E-05 | 1.10E+01 | 3.24E-05 |
| 7440-50-8 | Copper | 7.39E+00 | na | 9.41E+00 | na |
| 7440-62-2 | Vanadium metal | 1.09E+01 | na | 2.30E+01 | na |
| 7440-66-6 | Zinc and compounds | 7.62E+01 | na | 7.65E+01 | na |
| 7446-18-6 | Thallium sulfate | 1.18E+03 | na | 4.97E+04 | na |
| 7487-94-7 | Mercuric chloride | 1.55E+03 | na | 2.85E+03 | na |
| 7664-41-7 | Ammonia | 2.50E+00 | na | 2.50E+00 | na |
| 7723-14-0 | Phosphorus, white | 1.42E+05 | na | 1.71E+05 | na |

**Table 26. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals in the HSRAM Agricultural Scenario**

| CASRN | Chemical Name | Well Water Only, per mg/L | | Columbia River, per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 7782-41-4 | Fluorine (soluble fluoride) | 2.61E+00 | na | 2.73E+00 | na |
| 7782-49-2 | Selenium and compounds | 1.69E+01 | na | 3.02E+01 | na |
| 7791-12-0 | Thallium chloride | 1.18E+03 | na | 4.97E+04 | na |
| 8001-35-2 | Toxaphene | na | 9.76E-02 | na | 1.13E+00 |
| 10102-45-1 | Thallium (I) nitrate | 1.05E+03 | na | 4.41E+04 | na |
| 11096-82-5 | Aroclor 1260 | na | 5.02E+00 | na | 6.72E+00 |
| 11097-69-1 | Aroclor 1254 | 4.19E+04 | 2.66E-01 | 2.77E+06 | 4.70E+01 |
| 11104-28-2 | Aroclor 1221 | na | 3.85E-02 | na | 2.44E-01 |
| 11141-16-5 | Aroclor 1232 | na | 3.85E-02 | na | 2.44E-01 |
| 12672-29-6 | Aroclor 1248 | na | 1.30E-01 | na | 2.12E+01 |
| 12674-11-2 | Aroclor 1016 | 3.71E+03 | 3.93E-02 | 1.02E+05 | 5.91E+00 |
| 14797-55-8 | Nitrate | 3.97E-02 | na | 4.07E-02 | na |
| 14797-65-0 | Nitrite | 6.36E-01 | na | 6.51E-01 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 5.54E-02 | na | 1.14E-01 | na |
| 16984-48-8 | Fluorine anion | 2.61E+00 | na | 2.73E+00 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 2.49E+01 | 3.51E-05 | 5.13E+01 | 3.51E-05 |
| 22967-92-6 | Methyl mercury | 4.65E+03 | na | 8.55E+03 | na |
| 53469-21-9 | Aroclor 1242 | na | 1.25E-01 | na | 1.94E+01 |
| na | Uranium (soluble salts) | 1.18E+02 | na | 1.27E+02 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 3.61E+00 | 5.02E-06 | 7.43E+00 | 5.02E-06 |

Notes:
- CASRN = Chemical Abstract Service Reference Number
- The total risk to the HSRAM Agricultural scenario is calculated using intakes from 30 consecutive years. The soil concentration is zero at the start of the exposure.
- These scenario factors must be multiplied by the appropriate water concentration. The "Inland Well" column assumes all of the contaminated water comes from the well. The "Columbia River" column assumes that all of the contaminated water comes from the Columbia River.
- Results using route-to-route extrapolations are shown in Table C14.

## 3.11 MODEL TOXICS CONTROL ACT SCENARIOS

The Model Toxics Control Act (MTCA) Cleanup Regulation, Chapter 173-340 WAC describes various exposure scenarios (methods) that may be used to establish compliance. Method A reiterates national standards. Method B considers residential exposure. Method C considers occupational exposure. The only pathway considered for groundwater is drinking water. For surface water the consequences of fish intake are compared with drinking water and the most limiting is chosen.

For the Method B (Residential) exposure to non-carcinogenic chemicals, the child's body mass (16 kg) and water consumption rate (1 L/d) applies. All other cases use the adult body mass (70 kg) and water consumption rate (2 L/d). Fish is consumed at the rate of 54 g/d. For the Method B (Residential) case, 50% of the fish intake is contaminated. For the Method C

(Occupational) case, 20% of the fish intake is contaminated. The reference doses and slope factors are from Table A34. For carcinogenic chemicals the exposure duration is 30 years while the averaging time is 75 years.

The calculated hazard quotient and cancer risk per unit concentration for the groundwater scenarios are shown in Table 27. Also shown in Table 27 is the inhalation correction factor. This factor doubles the intake for those chemicals that are considered volatile. The calculated hazard quotient and cancer risk per unit concentration for surface water are shown in Table 28. The factors on these tables must be multiplied by the estimated water concentration, in mg per L.

Note that there are significant differences between the MTCA-C and the HSRAM Industrial Scenario. First is the difference in water intake rate. MTCA-C uses 2 L/d while HSRAM Industrial uses 1 L/d. Second is annual exposure time. MTCA-C uses 365 d/y while HSRAM Industrial uses 250 d/y. In effect, the HSRAM average drinking water rate is 0.7 L/d. Third is the volatilization factor used in MTCA in place of the inhalation toxicity parameter. HSRAM Industrial includes the effects of Henry's Law in the inhalation calculation, but uses the inhalation toxicity parameter (if it exists). The ratio of hazard quotient for MTCA-C (groundwater) divided by the hazard quotient for HSRAM Industrial could be as large as 5.84, as shown below. This ratio could be zero if the reference dose for ingestion is not given, but an inhalation reference dose is given in Table A34.

$$\text{Hazard Index Ratio}\left[\frac{\text{MTCA - C (ground water)}}{\text{HSRAM Industrial}}\right] = \left(\frac{2\text{ L/d}}{1\text{ L/d}}\right)\left(\frac{365\text{ d/y}}{250\text{ d/y}}\right)(2) = 5.84$$

In addition to the differences noted above for non-cancer effects, the calculation of increased cancer risk uses a lifetime exposure period and an averaging period. These two are different in MTCA-C and the HSRAM Industrial. In MTCA-C the lifetime exposure period is 30 y and the averaging period is 75 y. In the HSRAM Industrial scenario the lifetime exposure period is 20 y and the averaging period is 70 y. The ratio of increased cancer risks could be as large as 8.18, as shown below.

$$\text{Increased Cancer Ratio}\left[\frac{\text{MTCA - C (ground water)}}{\text{HSRAM Industrial}}\right] = \left(\frac{2\text{ L/d}}{1\text{ L/d}}\right)\left(\frac{365\text{ d/y}}{250\text{ d/y}}\right)(2)\left(\frac{30\text{ y}}{20\text{ y}}\right)\left(\frac{70\text{ y}}{75\text{ y}}\right) = 8.18$$

**Table 27. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Groundwater**

| | | Method B (Residential) per mg/L | | | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|---|
| **CASRN** | **Chemical** | **Hazard Quotient** | **Increased Cancer Risk** | **Inhale Factor** | **Hazard Quotient** | **Increased Cancer Risk** |
| 50-32-8 | Benzo[a]pyrene | na | 8.34E-02 | 1 | na | 8.34E-02 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 8.34E-02 | 1 | na | 8.34E-02 |
| 56-23-5 | Carbon tetrachloride | 1.79E+02 | 2.97E-03 | 2 | 8.16E+01 | 2.97E-03 |
| 56-55-3 | Benz[a]anthracene | na | 8.34E-03 | 1 | na | 8.34E-03 |

**Table 27. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Groundwater**

| CASRN | Chemical | Method B (Residential) per mg/L | | Inhale Factor | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | | Hazard Quotient | Increased Cancer Risk |
| 57-12-5 | Cyanide, free | 3.13E+00 | na | 1 | 1.43E+00 | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 6.86E-02 | 2 | na | 6.86E-02 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.50E-01 | na | 2 | 1.14E-01 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 2.08E+02 | 1.49E-02 | 1 | 9.52E+01 | 1.49E-02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 6.25E-01 | na | 2 | 2.86E-01 | na |
| 60-34-4 | Methylhydrazine | na | 6.86E-02 | 2 | na | 6.86E-02 |
| 60-57-1 | Dieldrin | 1.25E+03 | 1.83E-01 | 1 | 5.71E+02 | 1.83E-01 |
| 62-75-9 | N-Nitrosodimethylamine | 1.56E+04 | 1.17E+00 | 2 | 7.14E+03 | 1.17E+00 |
| 64-18-6 | Formic acid | 6.25E-02 | na | 2 | 2.86E-02 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 2.50E-01 | na | 2 | 1.14E-01 | na |
| 67-64-1 | Acetone (2-Propanone) | 1.39E-01 | na | 2 | 6.35E-02 | na |
| 67-66-3 | Chloroform | 1.25E+01 | 1.39E-04 | 2 | 5.71E+00 | 1.39E-04 |
| 67-72-1 | Hexachloroethane | 1.25E+02 | 3.20E-04 | 2 | 5.71E+01 | 3.20E-04 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.25E+00 | na | 2 | 5.71E-01 | na |
| 71-43-2 | Benzene | 3.13E+01 | 1.26E-03 | 2 | 1.43E+01 | 1.26E-03 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 6.25E-02 | na | 2 | 2.86E-02 | na |
| 72-20-8 | Endrin | 2.08E+02 | na | 1 | 9.52E+01 | na |
| 74-83-9 | Bromomethane | 8.93E+01 | na | 2 | 4.08E+01 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | na | 2.97E-04 | 2 | na | 2.97E-04 |
| 75-00-3 | Ethyl Chloride | 3.13E-01 | 6.63E-05 | 2 | 1.43E-01 | 6.63E-05 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 4.17E+01 | 3.43E-02 | 2 | 1.90E+01 | 1.71E-02 |
| 75-05-8 | Acetonitrile | na | na | 2 | na | na |
| 75-07-0 | Acetaldehyde | na | na | 2 | na | na |
| 75-09-2 | Dichloromethane (Methylene chloride) | 2.08E+00 | 1.71E-04 | 2 | 9.52E-01 | 1.71E-04 |
| 75-15-0 | Carbon disulfide | 1.25E+00 | na | 2 | 5.71E-01 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 2.33E-02 | 2 | na | 2.33E-02 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.25E+00 | na | 2 | 5.71E-01 | na |
| 75-35-4 | 1,1-Dichloroethylene | 2.50E+00 | na | 2 | 1.14E+00 | na |
| 75-45-6 | Chlorodifluoromethane | na | na | 2 | na | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | na | na | 2 | na | na |
| 75-69-4 | Trichlorofluoromethane | 4.17E-01 | na | 2 | 1.90E-01 | na |
| 75-71-8 | Dichlorodifluoromethane | 6.25E-01 | na | 2 | 2.86E-01 | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 4.17E-03 | na | 2 | 1.90E-03 | na |
| 76-44-8 | Heptachlor | 1.25E+02 | 5.14E-02 | 1 | 5.71E+01 | 5.14E-02 |
| 78-83-1 | Isobutanol | 4.17E-01 | na | 2 | 1.90E-01 | na |
| 78-87-5 | 1,2-Dichloropropane | na | 1.55E-03 | 2 | na | 1.55E-03 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 2.08E-01 | na | 2 | 9.52E-02 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 3.13E+01 | 1.30E-03 | 2 | 1.43E+01 | 1.30E-03 |

**Table 27. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Groundwater**

| CASRN | Chemical | Method B (Residential) per mg/L | | Inhale Factor | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | | Hazard Quotient | Increased Cancer Risk |
| 79-01-6 | Trichloroethylene | 4.17E+02 | 9.14E-03 | 2 | 1.90E+02 | 9.14E-03 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 2.50E-01 | na | 2 | 1.14E-01 | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 2.08E+00 | 4.57E-03 | 2 | 9.52E-01 | 4.57E-03 |
| 79-46-9 | 2-Nitropropane | na | na | 2 | na | na |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 2.08E+01 | 2.97E-03 | 1 | 9.52E+00 | 2.97E-03 |
| 83-32-9 | Acenaphthene | 1.04E+00 | na | 1 | 4.76E-01 | na |
| 84-66-2 | Diethyl phthalate | 7.81E-02 | na | 1 | 3.57E-02 | na |
| 84-74-2 | Dibutyl phthalate | 6.25E-01 | na | 1 | 2.86E-01 | na |
| 85-68-7 | Butyl benzyl phthalate | 3.13E-01 | na | 1 | 1.43E-01 | na |
| 86-73-7 | Fluorene | 1.56E+00 | na | 1 | 7.14E-01 | na |
| 86-74-8 | Carbazole | na | 2.29E-04 | 1 | na | 2.29E-04 |
| 87-68-3 | Hexachlorobutadiene | 4.17E+02 | 1.78E-03 | 2 | 1.90E+02 | 1.78E-03 |
| 87-86-5 | Pentachlorophenol | 2.08E+00 | 1.37E-03 | 1 | 9.52E-01 | 1.37E-03 |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.25E+03 | 2.51E-04 | 2 | 5.71E+02 | 2.51E-04 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 6.25E+01 | na | 1 | 2.86E+01 | na |
| 91-20-3 | Naphthalene | 6.25E+00 | na | 2 | 2.86E+00 | na |
| 92-52-4 | 1,1'-Biphenyl | 2.50E+00 | na | 2 | 1.14E+00 | na |
| 95-47-6 | o-Xylene | 6.25E-01 | na | 2 | 2.86E-01 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 2.50E+00 | na | 2 | 1.14E+00 | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 1.39E+00 | na | 2 | 6.35E-01 | na |
| 95-57-8 | 2-Chlorophenol | 2.50E+01 | na | 2 | 1.14E+01 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 2.50E+00 | na | 2 | 1.14E+00 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.25E+00 | na | 2 | 5.71E-01 | na |
| 98-86-2 | Acetophenone | 1.25E+00 | na | 2 | 5.71E-01 | na |
| 98-95-3 | Nitrobenzene | 2.50E+02 | na | 2 | 1.14E+02 | na |
| 100-00-5 | p-Chloronitrobenzene | 1.25E+02 | 1.53E-04 | 2 | 5.71E+01 | 1.53E-04 |
| 100-02-7 | 4-Nitrophenol | 7.81E+00 | na | 1 | 3.57E+00 | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 6.25E+02 | na | 1 | 2.86E+02 | na |
| 100-41-4 | Ethyl benzene | 1.25E+00 | na | 2 | 5.71E-01 | na |
| 100-42-5 | Styrene | 6.25E-01 | na | 2 | 2.86E-01 | na |
| 100-51-6 | Benzyl alcohol | 4.17E-01 | na | 2 | 1.90E-01 | na |
| 106-42-3 | p-Xylene | 6.25E-01 | na | 2 | 2.86E-01 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 2.50E+01 | na | 2 | 1.14E+01 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 4.17E+00 | 5.49E-04 | 2 | 1.90E+00 | 5.49E-04 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | na | 4.57E-02 | 2 | na | 4.57E-02 |
| 106-99-0 | 1,3-Butadiene | na | na | 2 | na | na |
| 107-02-8 | 2-Propenal (Acrolein) | 2.50E+02 | na | 2 | 1.14E+02 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 2.50E+00 | na | 2 | 1.14E+00 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 6.25E+00 | 2.08E-03 | 2 | 2.86E+00 | 2.08E-03 |

**Table 27. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Groundwater**

| CASRN | Chemical | Method B (Residential) per mg/L | | Inhale Factor | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | | Hazard Quotient | Increased Cancer Risk |
| 107-13-1 | Acrylonitrile | 1.25E+02 | 1.23E-02 | 2 | 5.71E+01 | 1.23E-02 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 1.56E+00 | na | 2 | 7.14E-01 | na |
| 108-38-3 | m-Xylene | 6.25E-01 | na | 2 | 2.86E-01 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 2.50E+00 | na | 2 | 1.14E+00 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 2.50E+00 | na | 2 | 1.14E+00 | na |
| 108-87-2 | Methyl cyclohexane | na | na | 2 | na | na |
| 108-88-3 | Toluene (Methyl benzene) | 1.56E+00 | na | 2 | 7.14E-01 | na |
| 108-90-7 | Chlorobenzene | 6.25E+00 | na | 2 | 2.86E+00 | na |
| 108-94-1 | Cyclohexanone | 2.50E-02 | na | 2 | 1.14E-02 | na |
| 108-95-2 | Phenol (Carbolic acid) | 4.17E-01 | na | 2 | 1.90E-01 | na |
| 109-99-9 | Tetrahydrofuran | 5.95E-01 | 1.74E-04 | 2 | 2.72E-01 | 1.74E-04 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 1.25E+02 | na | 2 | 5.71E+01 | na |
| 110-54-3 | n-Hexane | 2.08E+00 | na | 2 | 9.52E-01 | na |
| 110-80-5 | 2-Ethoxyethanol | 3.13E-01 | na | 2 | 1.43E-01 | na |
| 110-82-7 | Cyclohexane | na | na | 2 | na | na |
| 110-86-1 | Pyridine | 1.25E+02 | na | 2 | 5.71E+01 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 2.50E-01 | na | 2 | 1.14E-01 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 2.08E+00 | na | 2 | 9.52E-01 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 3.13E+00 | 1.60E-04 | 1 | 1.43E+00 | 1.60E-04 |
| 117-84-0 | Di-n-octylphthalate | 1.56E+00 | na | 1 | 7.14E-01 | na |
| 118-74-1 | Hexachlorobenzene | 7.81E+01 | 1.83E-02 | 1 | 3.57E+01 | 1.83E-02 |
| 120-12-7 | Anthracene | 2.08E-01 | na | 1 | 9.52E-02 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.25E+01 | na | 2 | 5.71E+00 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 3.13E+01 | na | 1 | 1.43E+01 | na |
| 121-44-8 | Triethylamine | na | na | 2 | na | na |
| 122-39-4 | Diphenylamine | 2.50E+00 | na | 1 | 1.14E+00 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 2.51E-04 | 2 | na | 2.51E-04 |
| 126-73-8 | Tributyl Phosphate | 3.13E-01 | 6.17E-05 | 1 | 1.43E-01 | 6.17E-05 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.25E+03 | na | 2 | 5.71E+02 | na |
| 127-18-4 | Tetrachloroethylene | 1.25E+01 | 1.23E-02 | 2 | 5.71E+00 | 1.23E-02 |
| 129-00-0 | Pyrene | 2.08E+00 | na | 1 | 9.52E-01 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.39E-01 | na | 2 | 6.35E-02 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 1.25E+01 | na | 2 | 5.71E+00 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 6.25E+00 | na | 2 | 2.86E+00 | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 8.34E-03 | 1 | na | 8.34E-03 |
| 205-99-2 | Benzo[b]fluoranthene | na | 8.34E-03 | 1 | na | 8.34E-03 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 1.56E+00 | na | 1 | 7.14E-01 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 8.34E-04 | 1 | na | 8.34E-04 |

**Table 27. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Groundwater**

| CASRN | Chemical | Method B (Residential) per mg/L | | Inhale Factor | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | | Hazard Quotient | Increased Cancer Risk |
| 218-01-9 | Chrysene | na | 8.34E-05 | 1 | na | 8.34E-05 |
| 309-00-2 | Aldrin | 4.17E+03 | 3.89E-01 | 2 | 1.90E+03 | 3.89E-01 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 1.25E+02 | 7.20E-02 | 1 | 5.71E+01 | 7.20E-02 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 3.13E+02 | 2.06E-02 | 1 | 1.43E+02 | 2.06E-02 |
| 541-73-1 | 1,3-Dichlorobenzene | 1.39E+02 | na | 2 | 6.35E+01 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 4.17E+00 | 2.29E-03 | 2 | 1.90E+00 | 2.29E-03 |
| 563-68-8 | Thallium acetate | 6.94E+02 | na | 1 | 3.17E+02 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 8.00E-02 | 1 | na | 8.00E-02 |
| 1314-62-1 | Vanadium pentoxide | 6.94E+00 | na | 1 | 3.17E+00 | na |
| 1330-20-7 | Xylenes (mixtures) | 6.25E-01 | na | 2 | 2.86E-01 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 4.57E-03 | 1 | na | 4.57E-03 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 8.00E-04 | 1 | na | 8.00E-04 |
| 6533-73-9 | Thallium carbonate | 7.81E+02 | na | 1 | 3.57E+02 | na |
| 7429-90-5 | Aluminum | 6.25E-02 | na | 1 | 2.86E-02 | na |
| 7439-89-6 | Iron | 2.08E-01 | na | 1 | 9.52E-02 | na |
| 7439-93-2 | Lithium | 3.13E+00 | na | 1 | 1.43E+00 | na |
| 7439-96-5 | Manganese | 1.34E+00 | na | 1 | 6.12E-01 | na |
| 7439-97-6 | Mercury metal vapor | na | na | 1 | na | na |
| 7439-98-7 | Molybdenum | 1.25E+01 | na | 1 | 5.71E+00 | na |
| 7440-02-0 | Nickel (soluble salts) | 3.13E+00 | na | 1 | 1.43E+00 | na |
| 7440-22-4 | Silver | 1.25E+01 | na | 1 | 5.71E+00 | na |
| 7440-24-6 | Strontium, Stable | 1.04E-01 | na | 1 | 4.76E-02 | na |
| 7440-28-0 | Thallium metal | 9.47E+02 | na | 1 | 4.33E+02 | na |
| 7440-31-5 | Tin | 1.04E-01 | na | 1 | 4.76E-02 | na |
| 7440-36-0 | Antimony | 1.56E+02 | na | 1 | 7.14E+01 | na |
| 7440-38-2 | Arsenic (inorganic) | 2.08E+02 | 1.71E-02 | 1 | 9.52E+01 | 1.71E-02 |
| 7440-39-3 | Barium | 3.13E-01 | na | 1 | 1.43E-01 | na |
| 7440-41-7 | Beryllium and compounds | 3.13E+01 | na | 1 | 1.43E+01 | na |
| 7440-42-8 | Boron and borates only | 3.13E-01 | na | 1 | 1.43E-01 | na |
| 7440-43-9 | Cadmium | 1.25E+02 | na | 1 | 5.71E+01 | na |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | na | na | 1 | na | na |
| 7440-48-4 | Cobalt | 3.13E+00 | na | 1 | 1.43E+00 | na |
| 7440-50-8 | Copper | 1.56E+00 | na | 1 | 7.14E-01 | na |
| 7440-62-2 | Vanadium metal | 8.93E+00 | na | 1 | 4.08E+00 | na |
| 7440-66-6 | Zinc and compounds | 2.08E-01 | na | 1 | 9.52E-02 | na |
| 7446-18-6 | Thallium sulfate | 7.81E+02 | na | 1 | 3.57E+02 | na |
| 7487-94-7 | Mercuric chloride | 2.08E+02 | na | 1 | 9.52E+01 | na |
| 7664-41-7 | Ammonia | na | na | 2 | na | na |
| 7723-14-0 | Phosphorus, white | 6.25E+03 | na | 2 | 2.86E+03 | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 2.08E+00 | na | 2 | 9.52E-01 | na |

**Table 27. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Groundwater**

| CASRN | Chemical | Method B (Residential) per mg/L | | Inhale Factor | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | | Hazard Quotient | Increased Cancer Risk |
| 7782-49-2 | Selenium and compounds | 1.25E+01 | na | 1 | 5.71E+00 | na |
| 7791-12-0 | Thallium chloride | 7.81E+02 | na | 1 | 3.57E+02 | na |
| 8001-35-2 | Toxaphene | na | 1.26E-02 | 1 | na | 1.26E-02 |
| 10102-45-1 | Thallium (I) nitrate | 6.94E+02 | na | 1 | 3.17E+02 | na |
| 11096-82-5 | Aroclor 1260 | na | 4.57E-03 | 1 | na | 4.57E-03 |
| 11097-69-1 | Aroclor 1254 | 3.13E+03 | 4.57E-03 | 1 | 1.43E+03 | 4.57E-03 |
| 11104-28-2 | Aroclor 1221 | na | 4.57E-03 | 2 | na | 4.57E-03 |
| 11141-16-5 | Aroclor 1232 | na | 4.57E-03 | 2 | na | 4.57E-03 |
| 12672-29-6 | Aroclor 1248 | na | 4.57E-03 | 1 | na | 4.57E-03 |
| 12674-11-2 | Aroclor 1016 | 8.93E+02 | 8.00E-04 | 1 | 4.08E+02 | 8.00E-04 |
| 14797-55-8 | Nitrate | 3.91E-02 | na | 1 | 1.79E-02 | na |
| 14797-65-0 | Nitrite | 6.25E-01 | na | 1 | 2.86E-01 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 4.17E-02 | na | 1 | 1.90E-02 | na |
| 16984-48-8 | Fluorine anion | 1.04E+00 | na | 1 | 4.76E-01 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 2.08E+01 | na | 1 | 9.52E+00 | na |
| 22967-92-6 | Methyl mercury | 6.25E+02 | na | 1 | 2.86E+02 | na |
| 53469-21-9 | Aroclor 1242 | na | 4.57E-03 | 1 | na | 4.57E-03 |
| na | Uranium (soluble salts) | 1.04E+02 | na | 1 | 4.76E+01 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 3.01E+00 | na | 1 | 1.38E+00 | na |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The Method B Hazard Quotient uses child consumption rates and body mass. All others use the adult numbers. The reference doses and slope factors for ingestion are shown in Table A34.
- The "Inhale Factor" is included in the Hazard Quotient and Cancer Risk factors. In effect, the hazard quotient and risk factors are doubled for volatile chemicals (Inhale Factor = 2).
- Missing values are indicated with "na", which means "not available". Results using route-to-route extrapolations are shown in Table C16.

**Table 28. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Surface Water**

| CASRN | Chemical Name | Method B (Residential) per mg/L | | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 50-32-8 | Benzo[a]pyrene | na | 1.18E+01 | na | 4.72E+00 |
| 53-70-3 | Dibenz[a,h]anthracene | na | 3.54E+01 | na | 1.42E+01 |
| 56-23-5 | Carbon tetrachloride | 1.79E+02 | 2.97E-03 | 8.16E+01 | 2.97E-03 |
| 56-55-3 | Benz[a]anthracene | na | 6.12E-01 | na | 2.45E-01 |
| 57-12-5 | Cyanide, free | 3.13E+00 | na | 1.43E+00 | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | 6.86E-02 | na | 6.86E-02 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.50E-01 | na | 1.14E-01 | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 2.08E+02 | 2.93E-02 | 9.52E+01 | 1.49E-02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 6.25E-01 | na | 2.86E-01 | na |
| 60-34-4 | Methylhydrazine | na | 6.86E-02 | na | 6.86E-02 |
| 60-57-1 | Dieldrin | 2.21E+04 | 7.09E+00 | 8.86E+03 | 2.83E+00 |
| 62-75-9 | N-Nitrosodimethylamine | 1.56E+04 | 1.17E+00 | 7.14E+03 | 1.17E+00 |
| 64-18-6 | Formic acid | 6.25E-02 | na | 2.86E-02 | na |
| 67-56-1 | Methanol (Methyl alcohol) | 2.50E-01 | na | 1.14E-01 | na |
| 67-64-1 | Acetone (2-Propanone) | 1.39E-01 | na | 6.35E-02 | na |
| 67-66-3 | Chloroform | 1.25E+01 | 1.39E-04 | 5.71E+00 | 1.39E-04 |
| 67-72-1 | Hexachloroethane | 2.37E+02 | 1.33E-03 | 9.49E+01 | 5.31E-04 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.25E+00 | na | 5.71E-01 | na |
| 71-43-2 | Benzene | 3.13E+01 | 1.26E-03 | 1.43E+01 | 1.26E-03 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 6.25E-02 | na | 2.86E-02 | na |
| 72-20-8 | Endrin | 2.59E+03 | na | 1.04E+03 | na |
| 74-83-9 | Bromomethane | 8.93E+01 | na | 4.08E+01 | na |
| 74-87-3 | Methyl chloride (Chloromethane) | na | 2.97E-04 | na | 2.97E-04 |
| 75-00-3 | Ethyl Chloride | 3.13E-01 | 6.63E-05 | 1.43E-01 | 6.63E-05 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 4.17E+01 | 3.43E-02 | 1.90E+01 | 1.71E-02 |
| 75-05-8 | Acetonitrile | na | na | na | na |
| 75-07-0 | Acetaldehyde | na | na | na | na |
| 75-09-2 | Dichloromethane (Methylene chloride) | 2.08E+00 | 1.71E-04 | 9.52E-01 | 1.71E-04 |
| 75-15-0 | Carbon disulfide | 1.25E+00 | na | 5.71E-01 | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | 2.33E-02 | na | 2.33E-02 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.25E+00 | na | 5.71E-01 | na |
| 75-35-4 | 1,1-Dichloroethylene | 2.50E+00 | na | 1.14E+00 | na |
| 75-45-6 | Chlorodifluoromethane | na | na | na | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | na | na | na | na |
| 75-69-4 | Trichlorofluoromethane | 4.17E-01 | na | 1.90E-01 | na |
| 75-71-8 | Dichlorodifluoromethane | 6.25E-01 | na | 2.86E-01 | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 4.17E-03 | na | 1.90E-03 | na |
| 76-44-8 | Heptachlor | 7.66E+03 | 6.90E+00 | 3.06E+03 | 2.76E+00 |

**Table 28. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Surface Water**

| CASRN | Chemical Name | Method B (Residential) per mg/L | | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 78-83-1 | Isobutanol | 4.17E-01 | na | 1.90E-01 | na |
| 78-87-5 | 1,2-Dichloropropane | na | 1.55E-03 | na | 1.55E-03 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 2.08E-01 | na | 9.52E-02 | na |
| 79-00-5 | 1,1,2-Trichloroethane | 3.13E+01 | 1.30E-03 | 1.43E+01 | 1.30E-03 |
| 79-01-6 | Trichloroethylene | 4.17E+02 | 9.14E-03 | 1.90E+02 | 9.14E-03 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 2.50E-01 | na | 1.14E-01 | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 2.08E+00 | 4.57E-03 | 9.52E-01 | 4.57E-03 |
| 79-46-9 | 2-Nitropropane | na | na | na | na |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 9.59E+01 | 2.99E-02 | 3.84E+01 | 1.20E-02 |
| 83-32-9 | Acenaphthene | 1.34E+00 | na | 5.35E-01 | na |
| 84-66-2 | Diethyl phthalate | 7.81E-02 | na | 3.57E-02 | na |
| 84-74-2 | Dibutyl phthalate | 2.25E+00 | na | 8.98E-01 | na |
| 85-68-7 | Butyl benzyl phthalate | 1.69E+00 | na | 6.75E-01 | na |
| 86-73-7 | Fluorene | 3.18E+00 | na | 1.27E+00 | na |
| 86-74-8 | Carbazole | na | 4.51E-04 | na | 2.29E-04 |
| 87-68-3 | Hexachlorobutadiene | 2.46E+03 | 2.30E-02 | 9.84E+02 | 9.21E-03 |
| 87-86-5 | Pentachlorophenol | 8.94E+00 | 1.29E-02 | 3.58E+00 | 5.15E-03 |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.25E+03 | 2.51E-04 | 5.71E+02 | 2.51E-04 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 6.25E+01 | na | 2.86E+01 | na |
| 91-20-3 | Naphthalene | 6.25E+00 | na | 2.86E+00 | na |
| 92-52-4 | 1,1'-Biphenyl | 3.57E+00 | na | 1.43E+00 | na |
| 95-47-6 | o-Xylene | 6.25E-01 | na | 2.86E-01 | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 2.50E+00 | na | 1.14E+00 | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 1.39E+00 | na | 6.35E-01 | na |
| 95-57-8 | 2-Chlorophenol | 2.50E+01 | na | 1.14E+01 | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 2.50E+00 | na | 1.14E+00 | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.25E+00 | na | 5.71E-01 | na |
| 98-86-2 | Acetophenone | 1.25E+00 | na | 5.71E-01 | na |
| 98-95-3 | Nitrobenzene | 2.50E+02 | na | 1.14E+02 | na |
| 100-00-5 | p-Chloronitrobenzene | 1.25E+02 | 1.53E-04 | 5.71E+01 | 1.53E-04 |
| 100-02-7 | 4-Nitrophenol | 7.81E+00 | na | 3.57E+00 | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 6.25E+02 | na | 2.86E+02 | na |
| 100-41-4 | Ethyl benzene | 1.25E+00 | na | 5.71E-01 | na |
| 100-42-5 | Styrene | 6.25E-01 | na | 2.86E-01 | na |
| 100-51-6 | Benzyl alcohol | 4.17E-01 | na | 1.90E-01 | na |
| 106-42-3 | p-Xylene | 6.25E-01 | na | 2.86E-01 | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 2.50E+01 | na | 1.14E+01 | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 4.17E+00 | 6.58E-04 | 1.90E+00 | 5.49E-04 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | na | 4.57E-02 | na | 4.57E-02 |

**Table 28. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Surface Water**

| CASRN | Chemical Name | Method B (Residential) per mg/L | | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 106-99-0 | 1,3-Butadiene | na | na | na | na |
| 107-02-8 | 2-Propenal (Acrolein) | 2.50E+02 | na | 1.14E+02 | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 2.50E+00 | na | 1.14E+00 | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 6.25E+00 | 2.08E-03 | 2.86E+00 | 2.08E-03 |
| 107-13-1 | Acrylonitrile | 1.25E+02 | 1.23E-02 | 5.71E+01 | 1.23E-02 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 1.56E+00 | na | 7.14E-01 | na |
| 108-38-3 | m-Xylene | 6.25E-01 | na | 2.86E-01 | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 2.50E+00 | na | 1.14E+00 | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 2.50E+00 | na | 1.14E+00 | na |
| 108-87-2 | Methyl cyclohexane | na | na | na | na |
| 108-88-3 | Toluene (Methyl benzene) | 1.56E+00 | na | 7.14E-01 | na |
| 108-90-7 | Chlorobenzene | 6.25E+00 | na | 2.86E+00 | na |
| 108-94-1 | Cyclohexanone | 2.50E-02 | na | 1.14E-02 | na |
| 108-95-2 | Phenol (Carbolic acid) | 4.17E-01 | na | 1.90E-01 | na |
| 109-99-9 | Tetrahydrofuran | 5.95E-01 | 1.74E-04 | 2.72E-01 | 1.74E-04 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 1.25E+02 | na | 5.71E+01 | na |
| 110-54-3 | n-Hexane | 2.58E+00 | na | 1.03E+00 | na |
| 110-80-5 | 2-Ethoxyethanol | 3.13E-01 | na | 1.43E-01 | na |
| 110-82-7 | Cyclohexane | na | na | na | na |
| 110-86-1 | Pyridine | 1.25E+02 | na | 5.71E+01 | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 2.50E-01 | na | 1.14E-01 | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 2.08E+00 | na | 9.52E-01 | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 5.93E+00 | 6.64E-04 | 2.37E+00 | 2.66E-04 |
| 117-84-0 | Di-n-octylphthalate | 1.56E+00 | na | 7.14E-01 | na |
| 118-74-1 | Hexachlorobenzene | 2.48E+03 | 1.27E+00 | 9.94E+02 | 5.09E-01 |
| 120-12-7 | Anthracene | 6.85E-01 | na | 2.74E-01 | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.92E+01 | na | 7.67E+00 | na |
| 121-14-2 | 2,4-Dinitrotoluene | 3.13E+01 | na | 1.43E+01 | na |
| 121-44-8 | Triethylamine | na | na | na | na |
| 122-39-4 | Diphenylamine | 2.50E+00 | na | 1.14E+00 | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | 2.51E-04 | na | 2.51E-04 |
| 126-73-8 | Tributyl Phosphate | 3.13E-01 | 6.17E-05 | 1.43E-01 | 6.17E-05 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.25E+03 | na | 5.71E+02 | na |
| 127-18-4 | Tetrachloroethylene | 1.25E+01 | 1.38E-02 | 5.71E+00 | 1.23E-02 |
| 129-00-0 | Pyrene | 1.47E+01 | na | 5.87E+00 | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.39E-01 | na | 6.35E-02 | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 1.25E+01 | na | 5.71E+00 | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 6.25E+00 | na | 2.86E+00 | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | 3.24E+00 | na | 1.30E+00 |

**Table 28. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Surface Water**

| CASRN | Chemical Name | Method B (Residential) per mg/L | | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 205-99-2 | Benzo[b]fluoranthene | na | 6.34E-01 | na | 2.54E-01 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 1.81E+01 | na | 7.24E+00 | na |
| 207-08-9 | Benzo[k]fluoranthene | na | 1.14E-01 | na | 4.55E-02 |
| 218-01-9 | Chrysene | na | 6.69E-03 | na | 2.68E-03 |
| 309-00-2 | Aldrin | 5.19E+05 | 1.06E+02 | 2.08E+05 | 4.24E+01 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 1.30E+02 | 1.64E-01 | 5.71E+01 | 7.20E-02 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 3.13E+02 | 4.51E-02 | 1.43E+02 | 2.06E-02 |
| 541-73-1 | 1,3-Dichlorobenzene | 1.39E+02 | na | 6.35E+01 | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 4.17E+00 | 2.29E-03 | 1.90E+00 | 2.29E-03 |
| 563-68-8 | Thallium acetate | 4.29E+04 | na | 1.71E+04 | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | 8.00E-02 | na | 8.00E-02 |
| 1314-62-1 | Vanadium pentoxide | 8.57E+00 | na | 3.43E+00 | na |
| 1330-20-7 | Xylenes (mixtures) | 6.25E-01 | na | 2.86E-01 | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | 1.79E+01 | na | 7.16E+00 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | 1.79E+01 | na | 7.16E+00 |
| 6533-73-9 | Thallium carbonate | 4.82E+04 | na | 1.93E+04 | na |
| 7429-90-5 | Aluminum | 1.93E-01 | na | 7.71E-02 | na |
| 7439-89-6 | Iron | 2.57E-01 | na | 1.03E-01 | na |
| 7439-93-2 | Lithium | 3.13E+00 | na | 1.43E+00 | na |
| 7439-96-5 | Manganese | 1.34E+00 | na | 6.12E-01 | na |
| 7439-97-6 | Mercury metal vapor | na | na | na | na |
| 7439-98-7 | Molybdenum | 1.25E+01 | na | 5.71E+00 | na |
| 7440-02-0 | Nickel (soluble salts) | 3.13E+00 | na | 1.43E+00 | na |
| 7440-22-4 | Silver | 1.25E+01 | na | 5.71E+00 | na |
| 7440-24-6 | Strontium, Stable | 1.04E-01 | na | 4.76E-02 | na |
| 7440-28-0 | Thallium metal | 5.84E+04 | na | 2.34E+04 | na |
| 7440-31-5 | Tin | 1.93E+00 | na | 7.71E-01 | na |
| 7440-36-0 | Antimony | 1.56E+02 | na | 7.14E+01 | na |
| 7440-38-2 | Arsenic (inorganic) | 3.14E+02 | 5.65E-02 | 1.25E+02 | 2.26E-02 |
| 7440-39-3 | Barium | 3.13E-01 | na | 1.43E-01 | na |
| 7440-41-7 | Beryllium and compounds | 3.13E+01 | na | 1.43E+01 | na |
| 7440-42-8 | Boron and borates only | 3.13E-01 | na | 1.43E-01 | na |
| 7440-43-9 | Cadmium | 1.54E+02 | na | 6.17E+01 | na |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | na | na | na | na |
| 7440-48-4 | Cobalt | 5.79E+00 | na | 2.31E+00 | na |
| 7440-50-8 | Copper | 1.93E+00 | na | 7.71E-01 | na |
| 7440-62-2 | Vanadium metal | 1.10E+01 | na | 4.41E+00 | na |
| 7440-66-6 | Zinc and compounds | 3.24E-01 | na | 1.30E-01 | na |
| 7446-18-6 | Thallium sulfate | 4.82E+04 | na | 1.93E+04 | na |
| 7487-94-7 | Mercuric chloride | 1.29E+03 | na | 5.14E+02 | na |

**Table 28. Unit Factors for Hazard Quotient and Cancer Risk for Chemicals Under the MTCA for Surface Water**

| CASRN | Chemical Name | Method B (Residential) per mg/L | | Method C (Industrial) per mg/L | |
|---|---|---|---|---|---|
| | | Hazard Quotient | Increased Cancer Risk | Hazard Quotient | Increased Cancer Risk |
| 7664-41-7 | Ammonia | na | na | na | na |
| 7723-14-0 | Phosphorus, white | 5.79E+04 | na | 2.31E+04 | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 2.08E+00 | na | 9.52E-01 | na |
| 7782-49-2 | Selenium and compounds | 1.31E+01 | na | 5.71E+00 | na |
| 7791-12-0 | Thallium chloride | 4.82E+04 | na | 1.93E+04 | na |
| 8001-35-2 | Toxaphene | na | 9.56E-01 | na | 3.82E-01 |
| 10102-45-1 | Thallium (I) nitrate | 4.29E+04 | na | 1.71E+04 | na |
| 11096-82-5 | Aroclor 1260 | na | 1.51E+00 | na | 6.05E-01 |
| 11097-69-1 | Aroclor 1254 | 2.71E+06 | 4.34E+01 | 1.09E+06 | 1.74E+01 |
| 11104-28-2 | Aroclor 1221 | na | 3.79E-01 | na | 1.52E-01 |
| 11141-16-5 | Aroclor 1232 | na | 3.79E-01 | na | 1.52E-01 |
| 12672-29-6 | Aroclor 1248 | na | 1.96E+01 | na | 7.82E+00 |
| 12674-11-2 | Aroclor 1016 | 9.74E+04 | 5.45E+00 | 3.90E+04 | 2.18E+00 |
| 14797-55-8 | Nitrate | 3.91E-02 | na | 1.79E-02 | na |
| 14797-65-0 | Nitrite | 6.25E-01 | na | 2.86E-01 | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 5.14E-02 | na | 2.06E-02 | na |
| 16984-48-8 | Fluorine anion | 1.04E+00 | na | 4.76E-01 | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 2.57E+01 | na | 1.03E+01 | na |
| 22967-92-6 | Methyl mercury | 3.86E+03 | na | 1.54E+03 | na |
| 53469-21-9 | Aroclor 1242 | na | 1.79E+01 | na | 7.16E+00 |
| na | Uranium (soluble salts) | 1.04E+02 | na | 4.76E+01 | na |
| na | Total Chromium (1:6 ratio CrVI:Cr III) | 3.72E+00 | na | 1.49E+00 | na |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The fish bioaccumulation factor is from Table A38. The reference doses and slope factors for ingestion are shown in Table A34. This table shows the larger of the drinking water and fish results.
- The Inhale Factor shown in Table 30 is included in the Hazard Quotient and Cancer Risk factors. In effect, the hazard quotient and risk factors are doubled for volatile chemicals (Inhale Factor = 2).
- Missing values are indicated with "na", which means "not available". Results using route-to-route extrapolations are shown in Table C17.

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# APPENDIX A

# DATA USED IN THE CALCULATIONS

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# APPENDIX A. DATA USED IN THE CALCULATIONS

This appendix summarizes the parameters and models used to calculate potential intakes of hazardous materials and convert them to radiation dose or hazard index or incremental cancer risk for the various exposure scenarios. What follows is a description of each parameter, typical values, and the justification for the values chosen. Where these parameters differ from prior performance assessments for Hanford disposal sites, the differences are explained. The mathematical models are described to illustrate how the parameters are used in calculations.

Each of the parameters discussed in this section has a range of possible values. The most likely value for conditions on the Hanford Site is chosen to represent this range. Because each parameter could be represented by a range of values, different analysts could choose different values and obtain different results for the scenario risk factors. Thus, there is some uncertainty to the scenario risk factors. The intent is to select representative values for the parameters rather than worst-case, or maximum values.

Some parameters have a greater effect on the scenario risk factor than others. In other words if the parameter is changed by a small amount, the scenario risk factor may or may not change by a similar amount. When small changes to a parameter lead to similar changes in the scenario risk factor, the scenario risk factor is said to be sensitive to this parameter. Because more than one pathway normally contributes to the final result, parameters for the minor pathways, such as deer meat consumption, have little effect while parameters for the major pathways, such as drinking water or fish, have greater effect. The term "sensitivity" describes the general importance of the parameter to the scenario risk factor.

For the most part this Revision 5 adds chemicals and updates toxicity parameters from those released in Revision 4. The reference for the radioactive decay data was changed from ENDF/VI-B to the NuDat listing available from the USDOE National Nuclear Data Center. Two models were revised to use more current methods. The model describing the fraction of waterborne radioactive contamination that adheres to plant foliage due to overhead irrigation was revised from the simple factor of 25% to a fraction that depends on crop yield. The fraction for chemicals (50%) remains the same in this version. The other change is to use the newer dermal absorption model from EPA. For many chemicals the dermal absorption dose increases.

The discussion of data and models is divided into several topical areas, namely, nuclear and chemical properties, human activities, animal, plant, and soil characteristics. An additional consideration is the potential effects on special groups of individuals who may be exposed in unique ways not normally considered. Information relevant to estimating the dose received by these special groups is included in each section.

## A1.0 NUCLEAR PARAMETERS

The first parameters of interest are basic nuclear properties of the radionuclides that may be found in waste buried on the Hanford Site. The two main selection criteria for these nuclides are the radioactive half-life and the projected inventory in typical N-Reactor fuel. Radionuclides with half-lives greater than approximately one year are considered. If the nuclide is listed as a

constituent in the waste stored in underground tanks or the burial grounds, it was included in the list. For this revision to HNF-SD-WM-TI-707, 4 radionuclides found in laboratory analyses of Hanford waste were added to Table A1. The added radionuclides are Mn-53, Tc-97, Ce-144, and Tb-157.

Table A1 shows the decay half-life and the decay chain branching ratios. A branching ratio is the fraction of decays of a parent nuclide that produce a given progeny nuclide. These parameters are needed to determine the amount of a nuclide, and any radioactive progeny, that is present as a function of time. The numbers are from the Nuclear Wallet Cards of 2005 as displayed on the National Nuclear Data Center web site, www.nndc.bnl.gov using the NuDat software. The conversion from days to years was carried out using the value 365.25636 days per year.

Also shown on Table A1 are the short-lived progeny that are assumed to be in secular equilibrium with the parent. These short half-life progeny are also called "implicit daughters" because their radioactive emissions are not considered separately, but combined with the parent nuclide. When referring to the activity of these groups of nuclides, only the activity of the first member of the decay chain is shown. It is understood that there is additional activity in the progeny nuclides. For example, 1 Ci of Sr-90+D means 1 Ci Sr-90 and 1 Ci Y-90.

**Table A1. Radionuclides to be Considered and Their Half Lives.**

| Nuclide | Half life (y) | Short-lived progeny in equilibrium with parent |
|---|---|---|
| H-3 | 12.320 | |
| Be-10 | 1.5100E+06 | |
| C-14 | 5,699.9 | |
| Na-22 | 2.6027 | |
| Al-26 | 716,988 | |
| Si-32+D | 132.00 | P-32 |
| Cl-36 | 300,995 | |
| K-40 | 1.2480E+09 | |
| Ca-41 | 101,998 | |
| Ti-44+D | 59.999 | Sc-44 |
| V-49 | 0.90074 (329 d) | |
| Mn-53 | 3.7399E+06 | |
| Mn-54 | 0.85452 (312.12 d) | |
| Fe-55 | 2.7370 | |
| Fe-60+D | 1.5000E+06 | Co-60m (0.9976) |
| Co-60 | 5.2710 | |
| Ni-59 | 75,999 | |
| Ni-63 | 100.10 | |
| Se-79 | 294,995 | |
| Rb-87 | 4.9699E+10 | |
| Sr-90+D | 28.899 | Y-90 |
| Zr-93 | 1.5300E+06 | |
| Nb-91 | 679.99 | |
| Nb-93m | 16.130 | |
| Nb-94 | 20,300 | |
| Mo-93 | 3,999.9 | |
| Tc-97 | 4.2099E+06 | |
| Tc-99 | 211,096 | |
| Ru-106+D | 1.02282 (373.59 d) | Rh-106 |
| Pd-107 | 6.4999E+06 | |

**Table A1. Radionuclides to be Considered and Their Half Lives.**

| Nuclide | Half life (y) | Short-lived progeny in equilibrium with parent |
|---|---|---|
| Ag-108m+D | 437.99 | Ag-108 (0.087) |
| Cd-109+D | 1.26322 (461.40 d) | Ag-109m |
| Cd-113m | 14.100 | |
| In-115 | 4.4099E+14 | |
| Sn-121m+D | 43.899 | Sn-121 (0.776) |
| Sn-126+D | 229,996 | Sb-126m, Sb-126 (0.14) |
| Sb-125 | 2.7586 | |
| Te-125m | 0.15715 (57.40 d) | |
| I-129 | 1.5700E+07 | |
| Cs-134 | 2.0652 | |
| Cs-135 | 2.3000E+06 | |
| Cs-137+D | 30.029 | Ba-137m (0.944) |
| Ba-133 | 10.516 | |
| Ce-144+D | 0.78003 (284.91 d) | Pr-144m (0.014), Pr-144 (0.986) |
| Pm-147 | 2.6234 | |
| Sm-147 | 1.060E+11 | |
| Sm-151 | 89.998 | |
| Eu-150 | 36.899 | |
| Eu-152 | 13.506 | |
| Eu-154 | 8.5899 | |
| Eu-155 | 4.7529 | |
| Gd-152 | 1.0800E+14 | |
| Tb-157 | 70.999 | |
| Ho-166m | 1,200 | |
| Re-187 | 4.1199E+10 | |
| Tl-204 | 3.7799 | |
| Pb-205 | 1.7300E+07 | |
| Pb-210+D | 22.200 | Bi-210 |
| Bi-207 | 32.899 | |
| Po-209 | 102.00 | |
| Po-210 | 0.37885 (138.38 d) | |
| Ra-226+D | 1,600.0 | Rn-222, Po-218, Pb-214, Bi-214, Po-214(0.9998) |
| Ra-228+D | 5.7499 | Ac-228 |
| Ac-227+D | 21.772 | Th-227(0.9862), Fr-223(0.0138), Ra-223, Rn-219, Po-215, Pb-211, Bi-211, Tl-207(.9972), Po-211(.0028) |
| Th-228+D | 1.9116 | Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212(0.6406), Tl-208(0.3594) |
| Th-229+D | 7,339.9 | Ra-225, Ac-225, Fr-221, At-217, Bi213, Po-213(0.9791), Tl-209(0.0209) |
| Th-230 | 75,379 | |
| Th-232 | 1.4050E+10 | |
| Pa-231 | 32,759 | |
| U-232 | 68.899 | |
| U-233 | 159,197 | |
| U-234 | 245,496 | |
| U-235+D | 7.0399E+08 | Th-231 |
| U-236 | 2.3420E+07 | |
| U-238+D | 4.4679E+09 | Th-234, Pa-234m, Pa-234 (0.0016) |
| Np-237+D | 2.1440E+06 | Pa-233 |
| Pu-236 | 2.8580 | |
| Pu-238 | 87.698 | |
| Pu-239 | 24,110 | |
| Pu-240 | 6,561 | |

**Table A1. Radionuclides to be Considered and Their Half Lives.**

| Nuclide | Half life (y) | Short-lived progeny in equilibrium with parent |
|---|---|---|
| Pu-241+D | 14.290 | U-237 (2.5E-05) |
| Pu-242 | 374,993 | |
| Pu-244+D | 7.9999E+07 | U-240 (0.9988), Np-240m, Np-240 (0.0012) |
| Am-241 | 432.19 | |
| Am-242m+D | 141.00 | Am-242(0.9955), Np-238(0.0045) |
| Am-243+D | 7,369.9 | Np-239 |
| Cm-242 | 0.44571 (162.80 d) | |
| Cm-243 | 29.099 | |
| Cm-244 | 18.100 | |
| Cm-245 | 8,499.9 | |
| Cm-246 | 4,759.9 | |
| Cm-247+D | 1.5600E+07 | Pu-243 |
| Cm-248 | 347,994 | |
| Cm-250+D | 8,299.9 | Pu-246(0.18), Am-246m, Bk-250(0.08) |
| Bk-247 | 1,380.0 | |
| Cf-248 | 0.91306 (333.5 d) | |
| Cf-249 | 350.99 | |
| Cf-250 | 13.080 | |
| Cf-251 | 897.98 | |
| Cf-252 | 2.6450 | |

Notes:

- Parentheses in the second column show half-lives that are normally given in days.
- Parentheses in the third column show branching ratios that differ from 1.00. Short-lived progeny are radionuclides that are normally found in secular equilibrium with the parent nuclide. They typically have half-lives less than 30 days.
- Half-lives and branching ratios are from NuDat Version 2.1 (www.nndc.bnl.gov).

Table A2 shows the radioactive decay chains included in the exposure scenario calculations. Radioactive decay normally reduces the dose that a receptor could receive. However, in the cases shown on Table A2, the in-growth of the progeny nuclides with time may increase the dose from the parent nuclide. One example of this is Th-232, which has a very long half-life so that there is essentially no change in its activity during the year of exposure. Since the initial activity of the progeny nuclides (Ra-228 and Th-228) is assumed to be zero any increase will have maximum effect on the Th-232 doses. In addition, since the progeny accumulate according to their much shorter half-lives, they are able to increase the dose from Th-232 significantly.

**Table A2. Decay Chains Actually Computed.**

| | | |
|---|---|---|
| Fe-60 | $\xrightarrow[0.9976]{}$ | Co-60 |
| Zr-93 | $\longrightarrow$ | Nb-93m |
| Mo-93 | $\longrightarrow$ | Nb-93m |
| Sb-125 | $\xrightarrow[0.230]{}$ | Te-125m |
| Pm-147 | $\longrightarrow$ | Sm-147 |
| Eu-152 | $\xrightarrow[0.279]{}$ | Gd-152 |
| Pb-210 | $\longrightarrow$ | Po-210 |

**Table A2. Decay Chains Actually Computed.**

| | | | | | | |
|---|---|---|---|---|---|---|
| Po-209 | $\xrightarrow[0.9952]{}$ | Pb-205 | | | | |
| Ra-226 | $\longrightarrow$ | Pb-210 | $\longrightarrow$ | Po-210 | | |
| Ra-228 | $\longrightarrow$ | Th-228 | | | | |
| Th-230 | $\longrightarrow$ | Ra-226 | $\longrightarrow$ | Pb-210 | $\longrightarrow$ | Po-210 |
| Th-232 | $\longrightarrow$ | Ra-228 | $\longrightarrow$ | Th-228 | | |
| Pa-231 | $\longrightarrow$ | Ac-227 | | | | |
| U-232 | $\longrightarrow$ | Th-228 | | | | |
| U-233 | $\longrightarrow$ | Th-229 | | | | |
| U-234 | $\longrightarrow$ | Th-230 | $\longrightarrow$ | Ra-226 | $\longrightarrow$ | Pb-210 |
| U-235 | $\longrightarrow$ | Pa-231 | $\longrightarrow$ | Ac-227 | | |
| Pu-236 | $\longrightarrow$ | U-232 | $\longrightarrow$ | Th-228 | | |
| Pu-238 | $\longrightarrow$ | U-234 | | | | |
| Pu-241 | $\longrightarrow$ | Am-241 | $\longrightarrow$ | Np-237 | | |
| Pu-244 | $\longrightarrow$ | Pu-240 | | | | |
| Am-241 | $\longrightarrow$ | Np-237 | | | | |
| Am-242m | $\longrightarrow$ | Cm-242 | $\longrightarrow$ | Pu-238 | $\longrightarrow$ | U-234 |
| | $\downarrow$ 0.827 | | | | | |
| | $\xrightarrow[0.173]{}$ | Pu-242 | | | | |
| Am-243 | $\longrightarrow$ | Pu-239 | | | | |
| Cm-242 | $\longrightarrow$ | Pu-238 | $\longrightarrow$ | U-234 | | |
| Cm-243 | $\longrightarrow$ | Pu-239 | | | | |
| | $\downarrow$ | | | | | |
| | $\xrightarrow[0.0029]{}$ | Am-243 | | | | |
| Cm-244 | $\longrightarrow$ | Pu-240 | | | | |
| Cm-245 | $\longrightarrow$ | Pu-241 | $\longrightarrow$ | Am-241 | $\longrightarrow$ | Np-237 |
| Cm-247 | $\longrightarrow$ | Am-243 | | | | |
| Cm-250 | $\longrightarrow$ | Cf-250 | | | | |
| | $\downarrow$ 0.08 | $\downarrow$ | | | | |
| | $\xrightarrow[0.18]{}$ | Cm-246 | | | | |
| Bk-247 | $\longrightarrow$ | Am-243 | | | | |
| Cf-248 | $\longrightarrow$ | Cm-244 | $\longrightarrow$ | Pu-240 | | |
| Cf-249 | $\longrightarrow$ | Cm-245 | $\longrightarrow$ | Pu-241 | $\longrightarrow$ | Am-241 |
| Cf-250 | $\longrightarrow$ | Cm-246 | | | | |
| Cf-251 | $\longrightarrow$ | Cm-247 | | | | |
| Cf-252 | $\longrightarrow$ | Cm-248 | | | | |

Notes:

- Decay times are assumed to be less than 1000 years so that the in-growth of progeny with long half-lives can be ignored.
- There is a slight increase in the Pu-238 and U-234 for the Am-242m decay chain that is not shown. This is a result of the low-probability alpha decay of Am-242m. The complete chain is, Am-242m(0.0045) → Np-238 → Pu-238 → U-234.

The decay chains used in these calculations are limited to four radioactive members by the assumption that the decay times involved in the generation of unit dose factors will be less than 1000 years. At longer decay times, the ingrowth of progeny farther down the chain may be important. The longest decay times used in this report is 70 years.

## A2.0 CHEMICALS OF INTEREST

The list of hazardous chemicals used in the generation of unit hazard quotients and unit risk factors comes from PNNL-12040, *Regulatory Data Quality Objectives Supporting Tank Waste Remediation System Privatization Project*, 1998. Table 4.4 lists 125 organic compounds and Table 4.7 lists 51 inorganic compounds that are recommended for characterizing Hanford underground tank waste. In addition, Appendix B lists 1,227 compounds from the TWINS database. Of these, there are 410 compounds listed with at least 10 vapor hits or at least one solid/liquid hit.

The lists found in PNNL-12040 were compared with the list of chemicals for which there is toxicological data according to the Risk Assessment Information System (RAIS). The Oak Ridge National Laboratory (ORNL) maintains this toxicological data listing for human health risk assessments. The data may be obtained from the World Wide Web using the location http://risk.lsd.ornl.gov. The values that were current as of March, 2004 were used for unit risk factors in the present document. The list of chemicals that are found in either the 410-chemical list (Table B.1 of PNNL-12040) or the 176-chemical list (Tables 4.4 and 4.7 of PNNL-12040) was compared with the 695-chemical RAIS database. There were 126 chemicals from PNNL-12040.

Additional sampling and analysis for the 241-C-106 Post-Retrieval Risk Assessment resulted in the addition of 35 more chemicals, bringing the new total to 161. The 161 common chemicals are shown in Table A3 along with the Chemical Abstract Service Reference Number (CASRN).

Additional sampling and analysis for the 200-CS-1 chemical sewer Remedial Investigation and Feasibility Study resulted in the addition of 16 more chemicals, bringing the new total to 177. The 177 common chemicals are shown in Table A3 along with the Chemical Abstract Service Reference Number (CASRN). The chemicals new to this revision of HNF-SD-WM-TI-707 are listed below.

| CASRN | Chemical | CASRN | Chemical |
|---|---|---|---|
| 56-55-3 | Benz[a]anthracene | 205-99-2 | Benzo[b]fluoranthene |
| 86-73-7 | Fluorene | 207-08-9 | Benzo[k]fluoranthene |
| 86-74-8 | Carbazole | 218-01-9 | Chrysene |
| 100-00-5 | p-Chloronitrobenzene | 563-68-8 | Thallium Acetate |
| 100-02-7 | 4-Nitrophenol | 7446-18-6 | Thallium Sulfate |
| 120-12-7 | Anthracene | 7791-12-0 | Thallium Chloride |
| 156-60-5 | trans-1,2-Dichloroethylene | 10102-45-1 | Thallium (I) Nitrate |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | 22967-92-6 | Methyl Mercury |

It is unlikely that any hazardous chemical has been omitted from the detailed study documented in PNNL-12040. In addition, it is assumed that the toxic materials of concern have been studied sufficiently that appropriate measures of their toxicity are available. It may be that serious toxins have not been studied in such detail at this point in time. The list in Table A3 represents the most complete information relevant to tank waste available at the present time. The molecular weights, water solubilities, unitless Henry's Law constants (organics), and logarithms of the octanol-water constants are from the EPA software EPI Suite™ Version 3.20. EPI Suite is a collection of simple programs that can be run all at once using the EPIwin program. Molecular weights are from the DERMwin program. Water solubilities are from the WSKOWwin program. Finally, the Henry's law constants are from the HENRYwin program.

The unitless Henry's law constants for inorganic chemicals are based on observed ratios of airborne and liquid waste concentrations for radionuclides in boiling waste tanks. The number $1x10^{-10}$ is used rather than the default number (1.00) offered by EPI Suite Version 3.20. The application of these parameters is discussed in later sections.

**Table A3. List of Chemicals.**

| CASRN | Chemical | Molecular Weight (g/mole) | Solubility in Water (mg/L) | Unitless Henry's Law Constant | Log($K_{OW}$) |
|---|---|---|---|---|---|
| 50-32-8 | Benzo[a]pyrene | 252.32 | 1.62E-03 | 1.87E-05 | 6.13 |
| 53-70-3 | Dibenz[a,h]anthracene | 278.36 | 2.49E-03 | 5.03E-06 | 6.75 |
| 56-23-5 | Carbon tetrachloride | 153.82 | 7.93E+02 | 1.13E+00 | 2.83 |
| 56-55-3 | Benz[a]anthracene | 228.30 | 9.40E-03 | 4.90E-04 | 5.76 |
| 57-12-5 | Cyanide, free | 27.03 | 1.00E+06 | 5.44E-03 | -0.25 |
| 57-14-7 | 1,1-Dimethylhydrazine | 60.10 | 1.00E+06 | 2.84E-06 | -1.19 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 76.10 | 1.00E+06 | 5.35E-09 | -0.92 |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 290.83 | 7.30E+00 | 2.10E-04 | 3.72 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 74.12 | 6.04E+04 | 5.03E-02 | 0.89 |
| 60-34-4 | Methylhydrazine | 46.07 | 1.00E+06 | 1.29E-06 | -1.05 |
| 60-57-1 | Dieldrin | 380.91 | 1.95E-01 | 4.09E-04 | 5.4 |
| 62-75-9 | N-Nitrosodimethylamine | 74.08 | 1.00E+06 | 7.44E-05 | -0.57 |
| 64-18-6 | Formic acid | 46.03 | 1.00E+06 | 6.83E-06 | -0.54 |
| 67-56-1 | Methanol (Methyl alcohol) | 32.04 | 1.00E+06 | 1.86E-04 | -0.77 |
| 67-64-1 | Acetone (2-Propanone) | 58.08 | 1.00E+06 | 1.62E-03 | -0.24 |
| 67-66-3 | Chloroform | 119.38 | 7.95E+03 | 1.50E-01 | 1.97 |
| 67-72-1 | Hexachloroethane | 236.74 | 5.00E+01 | 1.59E-01 | 4.14 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 74.12 | 6.32E+04 | 3.60E-04 | 0.88 |
| 71-43-2 | Benzene | 78.11 | 1.79E+03 | 2.27E-01 | 2.13 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 133.41 | 1.29E+03 | 7.03E-01 | 2.49 |
| 72-20-8 | Endrin | 380.91 | 2.50E-01 | 2.60E-04 | 5.2 |
| 74-83-9 | Bromomethane | 94.94 | 1.52E+04 | 2.55E-01 | 1.19 |
| 74-87-3 | Methyl chloride (Chloromethane) | 50.49 | 5.32E+03 | 3.61E-01 | 0.91 |
| 75-00-3 | Ethyl Chloride | 64.52 | 6.71E+03 | 4.54E-01 | 1.43 |

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**Table A3. List of Chemicals.**

| CASRN | Chemical | Molecular Weight (g/mole) | Solubility in Water (mg/L) | Unitless Henry's Law Constant | Log($K_{OW}$) |
|---|---|---|---|---|---|
| 75-01-4 | Vinyl chloride (Chloroethene) | 62.50 | 8.80E+03 | 1.14E+00 | 1.62 |
| 75-05-8 | Acetonitrile | 41.05 | 1.00E+06 | 1.41E-03 | -0.34 |
| 75-07-0 | Acetaldehyde | 44.05 | 1.00E+06 | 2.73E-03 | -0.34 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 84.93 | 1.30E+04 | 1.33E-01 | 1.25 |
| 75-15-0 | Carbon disulfide | 76.13 | 1.18E+03 | 5.89E-01 | 1.94 |
| 75-21-8 | Ethylene Oxide (Oxirane) | 44.05 | 1.00E+06 | 6.05E-03 | -0.3 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 98.96 | 5.04E+03 | 2.30E-01 | 1.79 |
| 75-35-4 | 1,1-Dichloroethylene | 96.94 | 2.42E+03 | 1.07E+00 | 2.13 |
| 75-45-6 | Chlorodifluoromethane | 86.47 | 2.77E+03 | 1.66E+00 | 1.08 |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 100.50 | 1.40E+03 | 2.40E+00 | 2.05 |
| 75-69-4 | Trichlorofluoromethane | 137.37 | 1.10E+03 | 3.96E+00 | 2.53 |
| 75-71-8 | Dichlorodifluoromethane | 120.91 | 2.80E+02 | 1.40E+01 | 2.16 |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 187.38 | 1.70E+02 | 2.15E+01 | 3.16 |
| 76-44-8 | Heptachlor | 373.32 | 1.80E-01 | 1.20E-02 | 6.1 |
| 78-83-1 | Isobutanol | 74.12 | 8.50E+04 | 4.00E-04 | 0.76 |
| 78-87-5 | 1,2-Dichloropropane | 112.99 | 2.80E+03 | 1.15E-01 | 1.98 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 72.11 | 2.23E+05 | 2.33E-03 | 0.29 |
| 79-00-5 | 1,1,2-Trichloroethane | 133.41 | 4.59E+03 | 3.37E-02 | 1.89 |
| 79-01-6 | Trichloroethylene | 131.39 | 1.28E+03 | 4.03E-01 | 2.42 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 72.06 | 1.00E+06 | 1.51E-05 | 0.35 |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 167.85 | 2.83E+03 | 1.50E-02 | 2.39 |
| 79-46-9 | 2-Nitropropane | 89.09 | 1.70E+04 | 4.86E-03 | 0.93 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 295.34 | 4.40E-01 | 1.81E-03 | 4.64 |
| 83-32-9 | Acenaphthene | 154.21 | 3.90E+00 | 7.44E-03 | 3.92 |
| 84-66-2 | Diethyl phthalate | 222.24 | 1.08E+03 | 2.49E-05 | 2.42 |
| 84-74-2 | Dibutyl phthalate | 278.35 | 1.12E+01 | 7.40E-05 | 4.5 |
| 85-68-7 | Butyl benzyl phthalate | 312.37 | 2.69E+00 | 5.15E-05 | 4.73 |
| 86-73-7 | Fluorene | 166.22 | 1.89E+00 | 3.93E-03 | 4.18 |
| 86-74-8 | Carbazole | 167.21 | 1.80E+00 | 2.09E-05 | 3.72 |
| 87-68-3 | Hexachlorobutadiene | 260.76 | 3.20E+00 | 4.21E-01 | 4.78 |
| 87-86-5 | Pentachlorophenol | 266.34 | 1.40E+01 | 1.00E-06 | 5.12 |
| 88-06-2 | 2,4,6-Trichlorophenol | 197.45 | 8.00E+02 | 1.06E-04 | 3.69 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 240.22 | 5.20E+01 | 1.86E-05 | 3.56 |
| 91-20-3 | Naphthalene | 128.18 | 3.10E+01 | 1.80E-02 | 3.3 |
| 92-52-4 | 1,1'-Biphenyl | 154.21 | 6.94E+00 | 1.26E-02 | 3.98 |
| 95-47-6 | o-Xylene | 106.17 | 1.78E+02 | 2.12E-01 | 3.12 |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 108.14 | 2.59E+04 | 4.90E-05 | 1.95 |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 147.00 | 1.56E+02 | 7.85E-02 | 3.43 |
| 95-57-8 | 2-Chlorophenol | 128.56 | 1.13E+04 | 4.58E-04 | 2.15 |
| 95-63-6 | 1,2,4-Trimethylbenzene | 120.20 | 5.70E+01 | 2.52E-01 | 3.63 |
| 95-95-4 | 2,4,5-Trichlorophenol | 197.45 | 1.20E+03 | 6.62E-05 | 3.72 |

**Table A3. List of Chemicals.**

| CASRN | Chemical | Molecular Weight (g/mole) | Solubility in Water (mg/L) | Unitless Henry's Law Constant | Log($K_{OW}$) |
|---|---|---|---|---|---|
| 98-86-2 | Acetophenone | 120.15 | 6.13E+03 | 4.25E-04 | 1.58 |
| 98-95-3 | Nitrobenzene | 123.11 | 2.09E+03 | 9.81E-04 | 1.85 |
| 100-00-5 | p-Chloronitrobenzene | 157.56 | 2.25E+02 | 2.00E-04 | 2.39 |
| 100-02-7 | 4-Nitrophenol | 139.11 | 1.16E+04 | 1.70E-08 | 1.91 |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 168.11 | 6.90E+01 | 1.51E-05 | 1.46 |
| 100-41-4 | Ethyl benzene | 106.17 | 1.69E+02 | 3.22E-01 | 3.15 |
| 100-42-5 | Styrene | 104.15 | 3.10E+02 | 1.12E-01 | 2.95 |
| 100-51-6 | Benzyl alcohol | 108.14 | 4.29E+04 | 1.38E-05 | 1.1 |
| 106-42-3 | p-Xylene | 106.17 | 1.62E+02 | 2.82E-01 | 3.15 |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 108.14 | 2.15E+04 | 4.09E-05 | 1.94 |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 147.00 | 8.13E+01 | 9.85E-02 | 3.44 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 187.86 | 3.91E+03 | 2.73E-02 | 1.96 |
| 106-99-0 | 1,3-Butadiene | 54.09 | 7.35E+02 | 3.01E+00 | 1.99 |
| 107-02-8 | 2-Propenal (Acrolein) | 56.06 | 2.12E+05 | 4.99E-03 | -0.01 |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 76.53 | 3.37E+03 | 4.50E-01 | 1.93 |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 98.96 | 8.60E+03 | 4.82E-02 | 1.48 |
| 107-13-1 | Acrylonitrile | 53.06 | 7.45E+04 | 5.64E-03 | 0.25 |
| 108-10-1 | Metbyl isobutyl ketone (4-Methyl-2-pentanone) | 100.16 | 1.90E+04 | 5.64E-03 | 1.31 |
| 108-38-3 | m-Xylene | 106.17 | 1.61E+02 | 2.93E-01 | 3.2 |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 108.14 | 2.27E+04 | 3.50E-05 | 1.96 |
| 108-67-8 | 1,3,5-Trimethylbenzene | 120.20 | 4.82E+01 | 3.58E-01 | 3.42 |
| 108-87-2 | Methyl cyclohexane | 98.19 | 1.40E+01 | 1.76E+01 | 3.61 |
| 108-88-3 | Toluene (Methyl benzene) | 92.14 | 5.26E+02 | 2.71E-01 | 2.73 |
| 108-90-7 | Chlorobenzene | 112.56 | 4.98E+02 | 1.27E-01 | 2.84 |
| 108-94-1 | Cyclohexanone | 98.15 | 2.50E+04 | 3.68E-04 | 0.81 |
| 108-95-2 | Phenol (Carbolic acid) | 94.11 | 8.28E+04 | 1.36E-05 | 1.46 |
| 109-99-9 | Tetrahydrofuran | 72.11 | 1.00E+06 | 2.88E-03 | 0.46 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 68.08 | 1.00E+04 | 2.21E-01 | 1.34 |
| 110-54-3 | n-Hexane | 86.18 | 9.50E+00 | 7.36E+01 | 3.9 |
| 110-80-5 | 2-Ethoxyethanol | 90.12 | 1.00E+06 | 1.92E-05 | -0.32 |
| 110-82-7 | Cyclohexane | 84.16 | 5.50E+01 | 6.13E+00 | 3.44 |
| 110-86-1 | Pyridine | 79.10 | 1.00E+06 | 4.50E-04 | 0.65 |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 118.18 | 1.00E+06 | 6.54E-05 | 0.83 |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 134.18 | 1.00E+06 | 9.11E-10 | -0.54 |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 390.57 | 2.70E-01 | 1.10E-05 | 7.6 |
| 117-84-0 | Di-n-octylphthalate | 390.57 | 2.00E-02 | 1.05E-04 | 8.1 |
| 118-74-1 | Hexachlorobenzene | 284.78 | 6.20E-03 | 6.95E-02 | 5.73 |
| 120-12-7 | Anthracene | 178.24 | 4.34E-02 | 2.27E-03 | 4.45 |
| 120-82-1 | 1,2,4-Tricblorobenzene | 181.45 | 4.90E+01 | 5.80E-02 | 4.02 |
| 121-14-2 | 2,4-Dinitrotoluene | 182.14 | 2.70E+02 | 2.21E-06 | 1.98 |
| 121-44-8 | Triethylamine | 101.19 | 7.37E+04 | 6.09E-03 | 1.45 |

**Table A3. List of Chemicals.**

| CASRN | Chemical | Molecular Weight (g/mole) | Solubility in Water (mg/L) | Unitless Henry's Law Constant | Log($K_{OW}$) |
|---|---|---|---|---|---|
| 122-39-4 | Diphenylamine | 169.23 | 5.30E+01 | 1.39E-04 | 3.5 |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | 88.11 | 1.00E+06 | 1.96E-04 | -0.27 |
| 126-73-8 | Tributyl Phosphate | 266.32 | 2.80E+02 | 6.13E-06 | 4 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 67.09 | 2.54E+04 | 1.01E-02 | 0.68 |
| 127-18-4 | Tetrachloroethylene | 165.83 | 2.06E+02 | 7.23E-01 | 3.4 |
| 129-00-0 | Pyrene | 202.26 | 1.35E-01 | 4.86E-04 | 4.88 |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 88.11 | 8.00E+04 | 5.48E-03 | 0.73 |
| 156-59-2 | cis-1,2-Dichloroethylene | 96.94 | 6.41E+03 | 1.67E-01 | 1.86 |
| 156-60-5 | trans-1,2-Dichloroethylene | 96.94 | 4.52E+03 | 3.83E-01 | 2.09 |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | 276.34 | 1.90E-04 | 1.42E-05 | 6.7 |
| 205-99-2 | Benzo[b]fluoranthene | 252.32 | 1.50E-03 | 2.69E-05 | 5.78 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 202.26 | 2.60E-01 | 3.62E-04 | 5.16 |
| 207-08-9 | Benzo[k]fluoranthene | 252.32 | 8.00E-04 | 2.39E-05 | 6.11 |
| 218-01-9 | Chrysene | 228.30 | 2.00E-03 | 2.14E-04 | 5.81 |
| 309-00-2 | Aldrin | 364.92 | 1.70E-02 | 1.80E-03 | 6.5 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 290.83 | 2.00E+00 | 4.99E-04 | 3.8 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 290.83 | 2.40E-01 | 1.80E-05 | 3.78 |
| 541-73-1 | 1,3-Dichlorobenzene | 147.00 | 1.25E+02 | 1.07E-01 | 3.53 |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 110.97 | 2.80E+03 | 1.45E-01 | 2.03 |
| 563-68-8 | Thallium Acetate | 263.43 | 1.00E+04 | 1.00E-10 | -0.17 |
| 621-64-7 | N-Nitrosodi-N-propylamine | 130.19 | 1.30E+04 | 2.20E-04 | 1.36 |
| 1314-62-1 | Vanadium pentoxide | 181.88 | 1.57E+02 | 1.00E-10 | 2.97 |
| 1330-20-7 | Xylenes (mixtures) | 106.17 | 1.06E+02 | 2.71E-01 | 3.12 |
| 1336-36-3 | Polychlorinated Biphenyls | 291.99 | 7.00E-01 | 1.40E-02 | 6.29 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | 291.99 | 7.00E-01 | 1.40E-02 | 6.29 |
| 6533-73-9 | Thallium carbonate | 468.78 | 5.20E+04 | 1.00E-10 | -0.86 |
| 7429-90-5 | Aluminum | 30.01 | 5.93E+04 | 1.00E-10 | 0.33 |
| 7439-89-6 | Iron | 55.85 | 6.22E+05 | 1.00E-10 | -0.77 |
| 7439-93-2 | Lithium | 6.94 | 1.76E+05 | 1.00E-10 | -0.77 |
| 7439-96-5 | Manganese | 54.94 | 8.70E+04 | 1.00E-10 | 0.23 |
| 7439-97-6 | Mercury metal vapor | 200.59 | 6.00E-02 | 1.00E-10 | 0.62 |
| 7439-98-7 | Molybdenum | 95.94 | 7.64E+04 | 1.00E-10 | 0.23 |
| 7440-02-0 | Nickel (soluble salts) | 58.69 | 4.21E+05 | 1.00E-10 | -0.57 |
| 7440-22-4 | Silver | 107.87 | 7.03E+04 | 1.00E-10 | 0.23 |
| 7440-24-6 | Strontium, Stable | 87.62 | 8.02E+04 | 1.00E-10 | 0.23 |
| 7440-28-0 | Thallium metal | 204.38 | 2.64E+04 | 1.00E-10 | 0.23 |
| 7440-31-5 | Tin | 120.73 | 7.89E+03 | 1.00E-10 | 1.29 |
| 7440-36-0 | Antimony | 124.78 | 2.29E+04 | 1.00E-10 | 0.73 |
| 7440-38-2 | Arsenic (inorganic) | 77.95 | 3.46E+04 | 3.16E-09 | 0.68 |
| 7440-39-3 | Barium | 137.33 | 5.46E+04 | 1.00E-10 | 0.23 |
| 7440-41-7 | Beryllium and compounds | 9.01 | 1.49E+05 | 1.00E-10 | -0.57 |
| 7440-42-8 | Boron and borates only | 13.84 | 4.36E+04 | 1.00E-10 | 0.23 |

**Table A3. List of Chemicals.**

| CASRN | Chemical | Molecular Weight (g/mole) | Solubility in Water (mg/L) | Unitless Henry's Law Constant | Log($K_{OW}$) |
|---|---|---|---|---|---|
| 7440-43-9 | Cadmium | 112.41 | 1.23E+05 | 1.00E-10 | -0.07 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 140.12 | 5.32E+04 | 1.00E-10 | 0.23 |
| 7440-48-4 | Cobalt | 58.93 | 8.73E+04 | 1.00E-10 | 0.23 |
| 7440-50-8 | Copper | 63.55 | 4.20E+05 | 1.00E-10 | -0.57 |
| 7440-62-2 | Vanadium metal | 50.94 | 8.63E+04 | 1.00E-10 | 0.23 |
| 7440-66-6 | Zinc and compounds | 67.41 | 3.43E+05 | 1.00E-10 | -0.47 |
| 7446-18-6 | Thallium Sulfate | 504.82 | 2.98E+01 | 1.00E-10 | 1.58 |
| 7487-94-7 | Mercuric chloride | 271.50 | 6.90E+04 | 1.00E-10 | -0.22 |
| 7664-41-7 | Ammonia | 17.03 | 4.82E+05 | 1.41E-04 | -1.38 |
| 7723-14-0 | Phosphorus, white | 34.00 | 2.04E+05 | 9.97E-11 | -0.27 |
| 7782-41-4 | Fluorine (soluble fluoride) | 38.00 | 1.69E+00 | 1.00E-10 | 0.22 |
| 7782-49-2 | Selenium and compounds | 80.98 | 8.13E+04 | 3.98E-11 | 0.24 |
| 7791-12-0 | Thallium Chloride | 239.84 | 2.90E+03 | 1.00E-10 | 0.54 |
| 8001-35-2 | Toxaphene | 413.82 | 5.50E-01 | 2.45E-04 | 5.78 |
| 10102-45-1 | Thallium (I) Nitrate | 266.39 | 9.55E+04 | 1.00E-10 | 0.21 |
| 11096-82-5 | Aroclor 1260 | 395.33 | 2.83E-04 | 1.37E-02 | 8.27 |
| 11097-69-1 | Aroclor 1254 | 326.44 | 3.40E-03 | 1.16E-02 | 6.79 |
| 11104-28-2 | Aroclor 1221 | 188.66 | 4.83E+00 | 9.32E-03 | 4.53 |
| 11141-16-5 | Aroclor 1232 | 188.66 | 4.83E+00 | 9.32E-03 | 4.53 |
| 12672-29-6 | Aroclor 1248 | 291.99 | 5.26E-02 | 1.80E-02 | 6.34 |
| 12674-11-2 | Aroclor 1016 | 257.55 | 2.70E-01 | 8.17E-03 | 5.62 |
| 14797-55-8 | Nitrate | 62.00 | 9.07E+04 | 1.00E-10 | 0.21 |
| 14797-65-0 | Nitrite | 47.01 | 1.19E+05 | 8.38E-06 | 0.06 |
| 16065-83-1 | Chromium (III) (insoluble salts) | 52.00 | na | 1.00E-10 | na |
| 16984-48-8 | Fluorine anion | 19.00 | 1.69E+00 | 1.00E-10 | 0.22 |
| 18540-29-9 | Chromium (VI) (soluble salts) | 52.00 | na | 1.00E-10 | na |
| 22967-92-6 | Methyl Mercury | 215.63 | 3.10E+04 | 2.95E-01 | 0.08 |
| 53469-21-9 | Aroclor 1242 | 291.99 | 2.77E-01 | 1.40E-02 | 6.29 |
| na | Uranium (soluble salts) | 238.00 | na | 1.00E-10 | na |

Notes:
- CASRN = Chemical Abstract Service Reference Number
- Molecular Weights, Water Solubilities, and most Unitless Henry's Law constants are from the EPI Suite software version 3.20. The Henry's Law constants for inorganic chemicals are based on observed partition fractions for radionuclides in high level tank waste.
- Missing values are indicated with "na", which means "not available".

Version 3.20 of the EPI Suite software reports some of the numbers it calculates incorrectly. This shows up in the calculation of the Log Kow values as well as numbers that are calculated from them. It occurs when more than one chemical is found with a similar structure. The software reports the last chemical on the list rather than the chemical that was requested. This error was observed for Dibenz[a,h]anthracene (53-70-3), gamma-Benzene hexachloride (gamma-Lindane) (58-89-9), Dieldrin (60-57-1), p-Chloronitrobenzene (100-00-5), cis-1,2-Dichloroethylene (156-59-2), alpha-Benzene hexachloride (alpha-Lindane) (319-84-6), and beta-Benzene hexachloride (beta-Lindane) (319-85-7).

With the exception of the State of Washington's MTCA, the chemicals are not separated into volatile and non-volatile in the calculations presented in the main text. Instead, the appropriate chemical property is used to determine the relative volatility. One such property is the Henry's Law Constant, which is the ratio of the saturated vapor concentration to the aqueous concentration. The unitless Henry's Law Constant (H') may be converted into the units atm per mole/L using the factor RT=24.465 L-atm/mole, where R is the idea gas law constant (0.082057 L-atm/mole-K) and T is the temperature (298.15 K). This is shown in the equation below.

$$K_{HENRY} = H' R T$$

The polychlorinated biphenyls (PCBs) are separated into two categories based on the types of chemicals that may be present. The lowest risk PCBs are for mixtures containing less than 0.5% of chemicals with more than 4 chlorine atoms.

Many of the organic chemicals on the list in Table A3 decompose in the environment by the action of sunlight, reactions with other chemicals (oxygen especially), heat, and biological action. The decomposition half-lives are not included in the calculations. In effect, it is assumed that the chemicals do not decompose. For inorganic chemicals this is largely true. However, many organic chemicals have measured half-lives that are less than one year. Examples from Table 1 in Jury (1990) are toluene (50 days) and xylene (110 days).

## A3.0 HUMAN PARAMETERS

In the various exposure scenarios the data for humans falls into two categories. The first data category is needed to estimate the contaminant intakes. This includes the dietary consumption rates, the breathing rate, duration of external exposures, extent and duration of dermal contact, and the like. The second data category is toxicity of the various hazardous materials. For radionuclides, the measures of toxicity are the internal and external dose factors, and the cancer induction risk coefficients. For chemicals, the measures of toxicity are the hazard index and the cancer induction slope factors. Each of these parameters is discussed in this section.

### A3.1 DIETARY CONSUMPTION RATES

In this section the ingestion rates for all types of produce for all exposure scenarios are presented and compared. In addition, consumption rates for water and trace amounts of soil are given. Finally, garden size is discussed because the assumed garden size controls soil concentration in the garden of the post-intrusion resident.

#### A3.1.1 Food and Water

A summary of the food and water consumption rates is given in Table A4. Specific food items are listed in the notes to the table. All values are in units of kilograms. The items ingested are separated into three general categories, namely, plants, animal products, and miscellaneous items. Each of these categories has a short list of items that represents related foods. The columns show distinct consumers represented in the various exposure scenarios.

Edible plants are grouped in to four types. "Leafy" refers to vegetables whose leafy parts are normally eaten, such as lettuce, cabbage and spinach. "Other" is termed "protected" produce because the edible portion is underground or has some type of non-edible covering. Protected produce includes both fruit and vegetables. Examples are melons, avocados, potatoes, onions, peanuts, tree nuts, artichokes, carrots, garlic, onions, radishes, green peas, chili peppers, and sweet corn. "Fruit" is termed "exposed" produce because airborne contaminants may deposit on the edible portion, but the surface area is small compared to leafy vegetables. Exposed produce includes both fruits and vegetables. Examples of exposed produce are apples, apricots, asparagus, bell peppers, broccoli, Brussels sprouts, cauliflower, celery, cherries, cranberries, cucumbers, eggplant, grapes, peaches, pears, plums, snap beans, squash, strawberries, and tomatoes. "Grains" refers to cereals consumed by humans, such as corn (for meal), oats, soybeans, and wheat. Rice is excluded due to the cooler climate.

For a given element, the protected and exposed categories have very similar model parameters (discussed in Section A5.0), e.g., dry-to-wet ratio, crop yield, translocation factor, and root uptake factor. Thus, the issue of whether to include below ground vegetables in the protected or exposed category when dealing with soil contamination is not important. The resulting intakes of radionuclides or toxic chemicals are similar. In effect, there are only three distinct groups of garden produce, namely, leafy vegetables, grains, and everything else.

Edible animal products refer to "Beef", "Milk", "Poultry", and "Eggs". The animal products may be contaminated if the animals ingest contaminated feed and drink. The various animals raised for foods are separated into the two broad categories "Beef" and "Poultry". If the animal resembles a cow (e.g., sheep, goats or pigs), it is "Beef". If the animal resembles a bird (e.g., ducks and turkeys), it is "Poultry". The names simply refer to the most likely animal. "Milk" refers to fresh milk as well as yogurt, ice cream, and condensed milk. In addition, no distinction is made between goat's milk and cow's milk. "Eggs" refers to chicken eggs exclusively.

The miscellaneous category includes "Fish", "Game", and "Water". "Fish" refers to fresh-water fish and shellfish. "Game" refers to wild animals harvested for food, such as deer and waterfowl. "Water" refers to drinking water and beverages made from local water sources.

The column labeled "EPA" comes from an EPA analysis of the 1977-78 USDA Nationwide Food Consumption Survey (Yang and Nelson 1986). The consumption parameters for the "West" region were used in prior Hanford Site disposal facility performance assessments. These consumption rates are averages for all age groups. Game animals were not included in the reference. The non-dairy beverage consumption rates measured by the EPA (Yang and Nelson 1986) for the western region are 1.48 liters per day (540 L/y). The grouted waste performance assessment used 1.84 liters per day (672 L/y) (Roseberry and Burmaster 1992). The traditional assumption widely used in other performance assessments is 2 liters per day (730 L/y), which is 35 percent higher than the EPA average and 9 percent higher than the grouted waste PA.

The column labeled "USDA" comes from indirect estimates of average per capita food consumption based on food production in the United States (Putnam and Allshouse, 1999). Losses from exports, industrial uses, and end-of-year stocks were taken into account. The other and fruit consumption rates do not include bananas, pineapples, or citrus fruits, because they are not grown in southeastern Washington. Similarly, the grain consumption rate excludes rice.

Game meat was not included in the study. The authors concede "fish consumption is likely understated". However, the EPA Exposure Factors Handbook (EPA/600/P 95/002Fa) recommends a total fish consumption rate for the general population that is just 11% larger (7.34 kg/y). Beef includes all red meats. The total milk equivalent consumed per person is given as 579.8 lb/y (263 kg/y). Deducting cheeses and other milk products unlikely to be produced at home leaves 116 kg/y. The owner of the cow is assumed to consume 58 L of milk during the year, which is 22% of the total milk equivalent and 50% of the home milk consumption. These fractions are derived from the EPA Exposure Factors Handbook, which shows 20% to 25% for all dairy products in Table 13-71 under "Questionnaire Response". Note that when converting volumes of milk to mass units, a density of 1.03 kg/L is used. Egg consumption is given as 238.7 per person in 1997. To estimate annual consumption rate shown in Table A4, this was rounded to 240, and an average egg weight of 2 ounces (57 g) was assumed.

Comparing the food and water consumption rates from EPA with those from USDA, only fish consumption shows a small decrease. All other food items have larger intake rates. The values for exposed produce (fruit) and poultry show the largest increase. The USDA column will be used to calculate unit dose factors for the post-intrusion resident, the all pathways farmer, and the Columbia River population scenarios. This differs from previous Hanford performance assessments and leads to a small increase in the doses from the food pathway.

The column labeled "HSRAM" gives the food and water consumption rates for adults in the residential and agricultural scenarios found in DOE/RL-91-45 Revision 3, (HSRAM). The consumption parameters listed in that document for the residential and agricultural scenarios are presented in Table A4. The HSRAM gives just two types of garden produce, namely, fruit and vegetables, for the residential and agricultural scenarios. The vegetable consumption rate was separated into leafy and other by keeping the same relative amounts found in the USDA column.

The game consumption rate has been modified from the HSRAM, which lists 1 g/d animal fat. In Paustenbach (1989) the average successful hunter consumes 60 g/d (22 kg/y), which is about half of the total edible portion of one deer. The animal fat is 1.4%, hence, the animal fat consumption rate is 0.84 g/d, which is rounded to 1 g/d in HSRAM. A modifying factor of 0.19 is used to include the hunter success rate, i.e., the fraction of people who hunt that actually obtain a deer. In Table A4 the mass of deer meat is listed rather than animal fat. The hunter success rate factor is included in the value shown (4.2 kg/y).

The fish consumption rate is the HSRAM value of (27 g/d)(365 d/y)=9,900 g/y, which is considerably larger than the values recommended in the Exposure Factors Handbook (EPA/600-P-95/002Fa Section 10), which lists 6.6 g/d fresh water fish, and 20.1 g/d total as the recommended population averages.

The EPA and USDA numbers must be adjusted for the fraction of food grown locally. The HSRAM values already include these adjustments. These fractions are based on the EPA Exposure Factors Handbook (EPA/600/P-95/002Fa). For garden produce 25 percent of the vegetable diet comes from the garden. The other 75 percent is obtained from uncontaminated sources. For animal products, 50 percent of the animal products (including fish) are locally produced and thus contaminated. Note that the updated Exposure Factors Handbook (EPA/600-P-95/002Fa) gives somewhat different values. The 25 percent and 50 percent fractions continue

to represent the Exposure Factors Handbook values (see Table 13-71 under Questionnaire Response). The adjusted annual intakes are shown in Table A5.

**Table A4. Food and Water Consumptions Rates (kg/y).**

| | EPA | USDA | HSRAM |
|---|---|---|---|
| **Plants:** | | | |
| Leafy: | 16.4 | 17.8 | 5.0 |
| Other: | 55.6 | 86.5 | 24.2 |
| Fruit: | 38.4 | 85.8 | 15.3 |
| Grain: | 74.0 | 81.9 | 0 |
| **Animal Products:** | | | |
| Beef: | 42.0 | 50.3 | 27.4 |
| Milk: | 104 | 116 | 110 |
| Poultry: | 10.6 | 29.4 | 0 |
| Eggs: | 10.6 | 13.6 | 0 |
| **Miscellaneous Items:** | | | |
| Fish: | 6.75 | 6.58 | 9.9 |
| Game: | 0 | 0 | 4.2 |
| Water: | 540 | 545 | 730 |

Notes:

- The column labeled "EPA" comes from an EPA analysis of the 1977-78 USDA Nationwide Food Consumption Survey (Yang and Nelson 1986). These values are shown for comparison with prior performance assessments.
- The column labeled "USDA" comes from indirect estimates of average per capita food consumption based on food production in the United States (Putnam and Allshouse, 1999). Losses such as from exports, industrial uses, and end-of-year stocks are taken into account. These values are used in the Post-Intrusion Resident and All Pathways Farmer exposure scenarios.
- The column labeled "HSRAM" gives the food and water consumption rates for adults in the recreational, residential, and agricultural scenarios. The water ingestion rate for children is half the value shown. The food consumption rates include adjustment for locally grown fractions.
- "Leafy" = cabbage, lettuce, and spinach
- "Other" = protected produce, namely, avocados, melons, artichokes, beets, carrots, chili peppers, sweet corn, garlic, green peas, lima beans, onions, potatoes, radishes, and tree nuts.
- "Fruit" = exposed produce, namely, apples, apricots, cherries, cranberries, grapes, peaches & nectarines, pears, plums & prunes, strawberries, asparagus, bell peppers, broccoli, Brussels sprouts, cauliflower, celery, cucumbers, eggplant, snap beans, and tomatoes.
- "Grain" = wheat, rye, corn, oat, and barley (everything except rice).
- "Beef" = all red meats
- "Milk" = beverage milks, yogurt, fluid cream products, frozen dairy products, condensed & evaporated milk (to convert USDA milk volumes to units of mass, a density of 1.03 kg/L was used)
- "Poultry" = chicken and turkey
- "Eggs" = for the USDA value, the number of eggs consumed (240 per year) is converted to mass units assuming the average mass of an egg is 2 ounces (57 g)
- "Fish" = includes shellfish
- "Game" = venison
- "Water" = includes water added to prepare coffee, tea, soft drinks, beer and distilled sprits, in addition, tap water consumption is assumed to be 25 gallons (95 L) per year.

**Table A5. Food and Water Consumption Rates for the Exposure Scenarios.**

| Food Consumed (kg/y) | All Pathways Farmer | Columbia River Population | HSRAM Recreational | HSRAM Residential | HSRAM Agricultural |
|---|---|---|---|---|---|
| Leafy | 4.45 | 8.9 | 0 | 5 | 5 |
| Other | 21.625 | 43.25 | 0 | 24.2 | 24.2 |
| Fruit | 21.45 | 42.9 | 0 | 15.3 | 15.3 |
| Grain | 0 | 0 | 0 | 0 | 0 |
| Beef | 25.15 | 25.15 | 0 | 0 | 27.4 |
| Milk | 58 | 58 | 0 | 0 | 110 |
| Poultry | 14.7 | 14.7 | 0 | 0 | 0 |
| Eggs | 6.8 | 6.8 | 0 | 0 | 0 |
| Fish | 3.29 | 0.003 | 9.9 | 9.9 | 9.9 |
| Game | 0 | 0 | 4.2 | 0 | 4.2 |
| Water | 545 | 545 | 14 | 730 | 730 |

Notes:

- The post-intrusion scenarios use the same dietary intakes as shown for the All Pathways Farmer. The Suburban Garden case uses only the vegetable amounts, while the Urban Pasture case uses only the milk amount.
- The HSRAM Industrial worker only consumes 1 L/d of drinking water while at work. The total annual intake is 250 L/y.
- The State of Washington MTCA scenarios use 2 L/d or 730 L/y for water. The fish consumption rate for Method B is 27 g/d (9.9 kg/y), and the fish consumption rate for Method C is 10.8 g/d (3.94 kg/y).

Wild game is not included in Table A5 for the All Pathways Farmer because this is an average individual. Hence, the game intake would be small and contribute very little to the total dose or risk or hazard index. If the average value for the HSRAM Recreational Scenario were used for the All Pathways Farmer, the meat intake would increase by about 17%. Since the wild game is not as contaminated as the cow, the resulting dose from a contaminated deer can be neglected. The consumption of wild game by the population is not included for the same reason. It is a minor addition to the total dose or risk or hazard index.

For exposure of the population along the Columbia River, parameters are scaled up by the assumed total population of 5 million. Two exceptions are water intake and fish consumption. The average drinking rate of 545 L/y per person (Putnam and Allshouse 1999) will be used. About half of this number is water, while the rest is various other beverages, most of which are derived from drinking water supplies. The contaminated fraction of the average diet is assumed to be 50%, due to widespread irrigation. The other 50% is obtained from non-irrigated sources or imported from other regions.

The quantity of contaminated fish consumed by the population along the Columbia River is limited by what the river is able to produce. The total mass of fish harvested from the Columbia River annually and consumed locally is approximately 15 metric tons (PNNL-9823). The average amount of fish consumed by 5 million people is thus 3 grams per year per person.

### A3.1.2 Garden Area Determination

From the annual consumption of garden produce it is possible to estimate the minimum garden area needed to supply an individual. This area is required for intruder calculations in which the exhumed waste is spread over a garden.

The quantity of food derived from the garden is proportional to the garden size. To estimate food production per unit garden area, two approaches were considered. The first is commercial food production in Washington State (WA Department of Agriculture 1994). Values for production per acre and per square meter are shown on Table A6. "cwt" means 100 pounds. Bushels of grain were assumed to have a density 70 percent that of water (700 kg/m$^3$). Thus a bushel of grain is assumed to weigh about 54 lb. The categories used for human consumption are from Table A4. The average person consumes the amount shown, in kg/y. Based on the average food production rate, the necessary garden area is 233 m$^2$. This total area is mostly needed for production of grains. This area also requires an efficient gardening operation to succeed.

The second approach to estimating garden size uses garden production estimates published by the Washington State University (WSU) Cooperative Extension (1980). Values are listed in Table A7. The referenced document provides estimates of pounds of produce per 10-foot row in a garden. In addition, it gives recommended row spacing. The spacing was treated as the row width to compute production per unit area. The USDA average annual consumption rates from Table A4 were used to determine garden area needs. The WSU production estimates are higher than the commercial production averages hence the needed garden area is smaller (207 m$^2$). These were assumed to be optimum values under excellent growing conditions.

The post-intrusion resident's garden is assumed to supply vegetables and fruit only. Grains are excluded. Thus, a 100 m$^2$ garden supplies 100% of the garden produce needs of a single adult over a year's time, or 25% of the garden produce needs of a family of four. Note that this area is half that used in the 2001 ILAW PA (DOE/ORP-2000-24) due to the elimination of grains. However, it represents a marked decrease from other Hanford performance assessments, which use a garden area of 2,500 m$^2$.

**Table A6. Commercial Food Production as a Basis for Garden Size.**

| Type of Produce | Yield per acre | Yield kg/m$^2$ | Garden Area, m$^2$ |
|---|---|---|---|
| ***Leafy Vegetables*** | ***17.8 kg/y*** | ***2.35*** | ***7.6 m$^2$*** |
| Cabbage | | | |
| Chard | | | |
| Lettuce | 210 cwt | 2.35 | |
| Spinach | | | |
| ***Exposed Produce*** | ***85.8 kg/y*** | ***1.65*** | ***51.8 m$^2$*** |
| Apple | 17 tons | 3.81 | |
| Apricots | 6.23 tons | 1.40 | |
| Asparagus | 35 cwt | 0.39 | |
| Broccoli | | | |
| Brussels Sprouts | | | |
| Bushberries | 7,000 lb | 0.78 | |

**Table A6. Commercial Food Production as a Basis for Garden Size.**

| Type of Produce | Yield per acre | Yield kg/m$^2$ | Garden Area, m$^2$ |
|---|---|---|---|
| Cauliflower | | | |
| Cherry | 6.93 tons | 1.55 | |
| Cucumber | | | |
| Eggplant | | | |
| Grape | 10.83 tons | 2.43 | |
| Hops | 1,884 lb | 0.21 | |
| Peach | 10 tons | 2.24 | |
| Pear | 15 tons | 3.36 | |
| Plums & Prunes | 8.4 tons | 1.88 | |
| Rhubarb | | | |
| Snap Bean | 90 cwt | 1.01 | |
| Strawberry | 7,000 lb | 0.78 | |
| Tomato | | | |
| ***Protected Produce*** | ***86.5 kg/y*** | ***2.48*** | ***34.9 m$^2$*** |
| Bean (dry) | 19 cwt | 0.21 | |
| Beet | | | |
| Carrot | 580 cwt | 6.50 | |
| Kohlrabi | | | |
| Lentils | 1340 lb | 0.15 | |
| Muskmelon | | | |
| Onion | 360 cwt | 4.04 | |
| Parsnip | | | |
| Peas | 38 cwt | 0.43 | |
| Potato | 590 cwt | 6.61 | |
| Radishes | | | |
| Squash | | | |
| Sweet Corn | 150 cwt | 1.68 | |
| Tree Nuts | 0.87 tons | 0.20 | |
| Turnip | | | |
| Watermelon | | | |
| ***Grains*** | ***81.9 kg/y*** | ***0.59*** | ***138.3 m$^2$*** |
| Barley | 67 bu | 0.41 | |
| Corn (for meal) | 190 bu | 1.16 | |
| Oats | 68 bu | 0.41 | |
| Rye | | | |
| Wheat | 63.6 bu | 0.39 | |
| | | **Total Garden Area:** | **232.6 m$^2$** |

Notes:

- Food production data is from *Washington Agricultural Statistics 1993-1994*.
- Average consumption rates (italics) are from Putnam and Allshouse, 1999.
- A bushel of grain is assumed to have a density 70% of water, so that a bushel weighs 54 lb.

The chosen garden area is consistent with recent performance assessments at other DOE sites. The Class L-II disposal facility at the Oak Ridge Reservation has an intruder garden area of 200 $m^2$ (ORNL-TM/13401). This garden area was judged adequate "to provide half the entire yearly intake of vegetables" (page G-50). A performance assessment for the Nevada Test Site (SAND2001-2977) uses an intruder garden area of 70 $m^2$ based on food consumption.

**Table A7. Homeowner Food Production as a Basis for Garden Area.**

| Type of Produce | Yield lb/10 ft | Row Spacing inches | Yield $kg/m^2$ | Garden Area, $m^2$ |
|---|---|---|---|---|
| ***Leafy Vegetables*** | ***17.8 kg/y*** | | ***4.48*** | ***4.0 $m^2$*** |
| Cabbage | 10 | 24 | 2.44 | |
| Chard | 30 | 18 | 9.76 | |
| Lettuce | 10 | 18 | 3.25 | |
| Spinach | 5 | 12 | 2.44 | |
| ***Exposed Produce*** | ***85.8 kg/y*** | | ***2.09*** | ***41.0 $m^2$*** |
| Apple | | 12 | | |
| Apricots | | 12 | | |
| Asparagus | 5 | 24 | 1.22 | |
| Broccoli | 10 | 24 | 2.44 | |
| Brussels Sprouts | 10 | 24 | 2.44 | |
| Bushberries | | 12 | | |
| Cauliflower | 8 | 24 | 1.95 | |
| Cherry | | 12 | | |
| Cucumber | 12 | 24 | 2.93 | |
| Eggplant | 8 | 36 | 1.30 | |
| Grape | | 12 | | |
| Hops | 0.1 | 1 | 0.59 | |
| Peach | | 12 | | |
| Pear | | 12 | | |
| Plums & Prunes | | 12 | | |
| Rhubarb | 15 | 36 | 2.44 | |
| Snap Bean | 6 | 18 | 1.95 | |
| Strawberry | | 12 | | |
| Tomato | 30 | 48 | 3.66 | |
| ***Protected Produce*** | ***86.5 kg/y*** | | ***3.85*** | ***22.5 $m^2$*** |
| Bean (dry) | | 12 | | |
| Beet | 10 | 12 | 4.88 | |
| Carrot | 12 | 12 | 5.86 | |
| Kohlrabi | 7 | 18 | 2.28 | |
| Lentils | | 12 | | |
| Muskmelon | 30 | 72 | 2.44 | |
| Onion | 10 | 12 | 4.88 | |
| Parsnip | 10 | 18 | 3.25 | |
| Peas | 10 | 18 | 3.25 | |
| Potato | 20 | 24 | 4.88 | |
| Radishes | 4 | 6 | 3.91 | |
| Squash | 25 | 48 | 3.05 | |
| Sweet Corn | 10 | 24 | 2.44 | |
| Tree Nuts | | 12 | | |

**Table A7. Homeowner Food Production as a Basis for Garden Area.**

| Type of Produce | Yield lb/10 ft | Row Spacing inches | Yield $kg/m^2$ | Garden Area, $m^2$ |
|---|---|---|---|---|
| Turnip | 20 | 18 | 6.51 | |
| Watermelon | 40 | 96 | 2.44 | |
| ***Grains*** | ***81.9 kg/y*** | | ***0.59*** | ***139.8 $m^2$*** |
| Barley | 0.1 | 1 | 0.59 | |
| Corn (for meal) | 0.1 | 1 | 0.59 | |
| Oats | 0.1 | 1 | 0.59 | |
| Rye | 0.1 | 1 | 0.59 | |
| Wheat | 0.1 | 1 | 0.59 | |
| | | | **Total Garden Area:** | **207.3 $m^2$** |

Notes:

- Food production data from *Home Gardens*, WSU Cooperative Extension Report EB-422.
- Average consumption rates (italics) are from Putnam and Allshouse, 1999.

### A3.1.3 Soil Ingestion

Inadvertent soil ingestion refers to trace amounts associated with soil dust that adheres to hands and is transferred to food or cigarettes. Another route is airborne soil that deposits on the lips and is subsequently ingested. Deliberate soil ingestion is not considered in the calculations, although it may occur in children. A survey of measurements of soil ingestion is presented in NUREG/CR-5512, Section 6.3.2. Soil ingestion is also discussed in detail in the Exposure Factors Handbook, Chapter 4 (EPA/600-P-95/002Fa). Values used in the unit dose and unit risk factors are shown in Table A8. These are not bounding values, but the typical values that would represent a large number of cases.

**Table A8. Inadvertent Soil Ingestion.**

| Exposure Scenario | Daily Soil Intake Rate (mg/day) | Exposure Frequency (days/year) | Annual Soil Ingestion (g/year) |
|---|---|---|---|
| **Irrigated Land Ingestion Amounts** | | | |
| Well-Driller | 100 | 5 | 0.5 |
| Post-Intrusion Scenarios | 100 | 180 | 18 |
| All Pathways Farmer | 100 | 365 | 36.5 |
| Columbia River Population | 100 | 365 | 36.5 |
| HSRAM Industrial | 50 | 146 | 7.3 |
| Recreational -- Child/Adult | 200 / 100 | 7 | 1.4 / 0.7 |
| Residential -- Child/Adult | 200 / 100 | 365 | 73 / 36.5 |
| Agricultural -- Child/Adult | 200 / 100 | 365 | 73 / 36.5 |
| **Shoreline Sediment Ingestion Amounts** | | | |
| All Pathways Farmer | 100 | 7 | 0.7 |
| Columbia River Population | 100 | 5 | 0.5 |
| Recreational -- Child/Adult | 200 / 100 | 7 | 1.4 / 0.7 |
| Residential -- Child/Adult | 200 / 100 | 7 | 1.4 / 0.7 |
| Agricultural -- Child/Adult | 200 / 100 | 7 | 1.4 / 0.7 |

Notes:
- Inadvertent soil ingestion refers to trace amounts ingested after transfer from hands to food or cigarettes.
- HSRAM values are from DOE/RL-91-45 Revision 3.
- Two values are given for the last three HSRAM scenarios. The first is the rate for children, and the second is the rate for adults.

The average adult is assumed to ingest 100 mg/d in trace amounts. In three of the HSRAM exposure scenarios two daily rates are used. The child's soil intake rate is twice the adult's and applies during the first 6 years. The adult rate is used during the next 24 years. For radionuclides, the 30-year total is used to calculate the increased cancer risk from soil ingestion. For non-carcinogenic chemicals, the child's annual intake rate is used for soil ingestion. For carcinogenic chemicals, the 30-year total averaged over 70 years is used for soil ingestion.

In all prior Hanford Performance Assessments, the Post-Intrusion Resident and All Pathways Farmers ingest 36.5 g/y. In the present calculations, the Post-Intrusion cases ingest

about half as much, 18 g/y. The reduction is based on the limited time of exposure to the contaminated area (garden, pasture, or field).

## A3.2 INHALATION RATES FOR PEOPLE

To determine the internal dose or risk from the inhalation of vapors and suspended particulate matter, one must compute the total activity inhaled. Values for the average air concentration, the time exposed at that concentration, and the average breathing rate during the exposure period are presented in this section. The inhalation intakes are separated into those from contaminated soil and those from contaminated water.

### A3.2.1 Airborne Soil

A mass loading approach is used to estimate airborne concentrations of radionuclides for scenarios involving resuspension of contaminated soil. For the intrusion scenarios, a basic assumption regarding the waste materials in the soil is that the particle size distribution of the waste (either as exhumed waste or as contaminated irrigation water) is similar to that of the soil. If waste particles were finer than soil particles, then soil that becomes airborne would have a higher concentration of waste than the average for the garden. If waste particles were coarser than soil particles, then the airborne soil would be deficient in waste. For the irrigation scenarios, the dissolved and suspended particulate will most likely attach to the finer soil particles because that is where the greatest surface area is found.

The average mass loading in air depends on what is happening to the contaminated soil. Active gardening produces the largest average mass loading, at 0.5 $mg/m^3$. Routine activities outdoors are assumed to take place at an average air concentration of 0.1 $mg/m^3$. Indoor activities are assumed to take place at lower air concentrations due to the presence of other airborne particulate sources. The basis for these air concentrations is presented very effectively in NUREG/CR-5512, Section 6.3.1. It should be noted that the fine particulate suspended in air may have a greater contaminant concentration than the soil from which it is obtained. Hence, the mass loadings that have been chosen are somewhat high. (Typical annual average airborne mass loadings observed outdoors at the Hanford Site are about 0.02 $mg/m^3$. This is based on the discussion in Section 4.1.7 of PNNL-6415 Revision 15)

**<u>Acute Inhalation during Well Drilling</u>**

In the well-drilling scenario, the individual is assumed to be exposed for 40 hours, spread over 5 days. This is the time needed to drill the well. During this time the individual breathes at the outdoor activity rate (1.21 $m^3/h$) defined in Publication 66 (1994) of the International Commission on Radiological Protection (ICRP), titled *Human Respiratory Tract Model for Radiological Protection*. The actual inhalation scenario is highly variable. The worker can be exposed to a high concentration when the waste material comes out of the hole. However, this material is soon buried by clean material coming from farther down the hole. In addition, the material is likely wetted as part of the drilling operation and to minimize fugitive dust emissions. Another modeling approach is to average the contamination over the assumed spreading area and compute the total inhaled over the 40 hour work period. The approach taken in this analysis is to average the exhumed waste over the entire mass of borehole cuttings.

In the Grouted Waste performance assessment (WHC-SD-WM-EE-004) the well-drilling worker inhales resuspended dust at a concentration of 0.1 mg/m$^3$ for one hour. The breathing rate (1.20 m$^3$/h) is from ICRP Publication 23, *Report of the Task Group on Reference Man* (1975). However, the air concentration was not based on the waste concentration, but rather on the average soil concentration after spreading. In effect, the 0.64 m$^3$ of waste exhumed in the Grouted Waste PA was diluted to a total volume of 15 m$^3$=(100 m$^2$)(0.15 m). These assumptions lead to the inhalation of 0.12 mg soil containing 0.0051 mg of waste, as shown in the calculations below. Note that the soil density in the well is assumed to be the same as the soil density of the cuttings to simplify the comparison with the prior performance assessments.

$$\text{Soil Inhaled (Grout PA)} = (1\ \text{h})(1.2\ \text{m}^3/\text{h})(0.1\ \text{mg/m}^3) = 0.12\ \text{mg soil inhaled}$$

$$\text{Waste Inhaled (Grout PA)} = (0.12\ \text{mg soil})\left(\frac{0.64\ \text{m}^3\ \text{grout}}{15\ \text{m}^3\ \text{soil}}\right)$$
$$= 0.0051\ \text{mg grout inhaled}$$

In the 2001 ILAW PA (DOE/ORP-2000-24 Revision 0) the driller inhales suspended soil for a period of 40 hours. The airborne soil is diluted to the average concentration of the borehole cuttings (80 m well depth assumed) in addition to the dilution that results when the exhumed material is spread over an area of 100 m$^2$ to a depth of 0.15 m. Finally, the 2001 ILAW PA assumes that 1% of the exhumed waste is available for inhalation. The inhalation intakes are shown below.

$$\text{Soil Inhaled (ILAW PA)} = (40\ \text{h})(1.2\ \text{m}^3/\text{h})(0.1\ \text{mg/m}^3) = 4.8\ \text{mg soil inhaled}$$

$$\text{Waste Inhaled (ILAW PA)} = (4.8\ \text{mg soil})\left(\frac{0.272\ \text{m}^3\ \text{waste}}{5.84\ \text{m}^3\ \text{borehole}}\right)\left(\frac{0.272\ \text{m}^3\ \text{waste}}{15\ \text{m}^3\ \text{soil}}\right)(0.01)$$
$$= 0.000041\ \text{mg waste inhaled}$$

In the present report, the dilution of the borehole cuttings to a volume of 15 m$^3$ is eliminated. Instead, the exhumed waste volume is averaged over the volume of borehole cuttings. The density of the waste and soil are assumed to be the same. As an example for comparison with the other method, let the well depth be 100 m and the waste depth be 8 m. Also, assume that 10% of the exhumed waste is available for inhalation. Then the resulting inhalation intake is shown below. In this approach, the inhalation intake by the well driller is considerably larger than in previous works.

$$\text{Soil Inhaled (Tank Waste PA)} = (40\ \text{h})(1.21\ \text{m}^3/\text{h})(0.1\ \text{mg/m}^3) = 4.84\ \text{mg soil inhaled}$$

$$\text{Waste Inhaled (Tank Waste PA)} = (4.84\ \text{mg soil})\left(\frac{8\ \text{m waste}}{100\ \text{m well}}\right)(0.1)$$
$$= 0.039\ \text{mg waste inhaled}$$

**Chronic Inhalation Scenarios**

For estimating inhalation of contaminated soil in the suburban garden scenario, the individual spends the entire year living in the contaminated area. The Grouted Waste performance assessment (WHC-SD-WM-EE-004) used an average inhalation rate of 8,520 $m^3$ per year and an average air concentration of 0.1 $mg/m^3$. The annual amount of soil inhaled was 852 mg. The 200 West Area Burial Ground performance assessment (WHC-EP-0645) used more detailed inhalation assumptions based on PNNL-6312. The inhalation dose was based on an annual inhalation of 445 milligrams.

The inhaled amounts used in this report are updated from the 2001 ILAW PA (DOE/ORP-2000-24 Revision 0). These amounts are a refinement of the model used for the 200 West Area Burial Ground (WHC-EP-0645). They are also very similar to the method discussed in NUREG/CR-5512. The post-intrusion residents spend a portion of the day in various average air concentrations. These are shown in Table A9 for all three of the post-intrusion residents as well as the all pathways farmer (irrigation scenario). The breathing rates shown on Table A9 are from ICRP Publication 66 Table B.16B. In Table A9 the 3,102 hour period asleep is 8.5 hours per day (ICRP 66), 365 days per year. The exposed individual is outdoors for a certain number of hours each day for 180 days in every case.

The suburban resident with a garden spends 2 h/d (360 h/y) in or near his garden. Of this, about 10 hours per year are spent in relatively dusty conditions. Due to the small size of the garden (100 $m^2$), it is assumed that the average air concentration during the non-outdoor periods is 10% of the air quality standard, (0.10)(0.050 $mg/m^3$)=0.005 $mg/m^3$. This is the concentration of contaminated soil in the air breathed by the resident. There are other (i.e., uncontaminated) sources for airborne particulate. The total mass of contaminated soil inhaled by the suburban gardener is 87 mg/y, as shown in Table A9.

The rural resident with a cow spends 4 h/d (720 h/y) in or near his pasture and hay field. Of this, about 10 hours per year are spent in relatively dusty conditions. Due to the size of the pasture and hay field (5,000 $m^2$), it is assumed that the average air concentration during the non-outdoor periods is 20% of the air quality standard. The larger value is based on the larger area of the pasture and hay field. The total mass of contaminated soil inhaled by the rural cow owner is 169 mg/y, as shown in Table A9.

The commercial farmer spends 8 h/d (1,440 h/y) in or near his fields. Of this, about 10 hours per year are spent in relatively dusty conditions. Due to the size of the field (160 acre, or 647,500 $m^2$), it is assumed that the average air concentration during the non-outdoor periods is 20% of the air quality standard. The larger value is based on the larger area of the pasture and hay field. The total mass of contaminated soil inhaled by the rural cow owner is 169 mg/y, as shown in Table A9.

The all pathways farmer spends a portion of his time in various average air concentrations. These are shown in Table A9. For 180 days the individual is outdoors. The all pathways farmer spends 10 h/d (1800 h/y) exposed to higher levels of dust outdoors. Of this, about 100 hours are spent in relatively dusty conditions. In Table A9 the 3,102 hour period asleep is 8.5 hours per day (ICRP 66), 365 days per year. During the non-outdoor periods the average air concentration is conservatively chosen to be at the air quality standard as shown in Table A9. The total mass of contaminated soil inhaled by the all pathways farmer is 539 mg.

**Table A9. Calculation of Annual Soil Inhalation Amounts.**

| Activity | Air Concentration ($mg/m^3$) | Exposure Time (hours/year) | Breathing Rate ($m^3$/hour) | Contaminated Soil Inhaled (mg/year) |
|---|---|---|---|---|
| **Post-Intrusion Resident -- Suburban Garden (Annual Average is 0.0107 $mg/m^3$)** | | | | |
| Asleep | 0.005 | 3,102 | 0.45 | 7.0 |
| Indoors | 0.005 | 5,298 | 1.18 | 31.3 |
| Outdoor | 0.1 | 350 | 1.21 | 42.4 |
| Gardening | 0.5 | 10 | 1.21 | 6.1 |
| Away | | 0 | | 0.0 |
| | Total Time: | 8,760 | ***Soil Inhaled:*** | ***87*** |
| **Post-Intrusion Resident -- Rural Pasture (Annual Average is 0.0209 $mg/m^3$)** | | | | |
| Asleep | 0.01 | 3,102 | 0.45 | 14.0 |
| Indoors | 0.01 | 4,938 | 1.18 | 58.3 |
| Outdoor | 0.1 | 700 | 1.21 | 84.7 |
| Gardening | 0.5 | 20 | 1.21 | 12.1 |
| Away | | 0 | | 0.0 |
| | Total Time: | 8,760 | ***Soil Inhaled:*** | ***169*** |
| **Post-Intrusion Resident -- Commercial Farm (Annual Average is 0.0397 $mg/m^3$)** | | | | |
| Asleep | 0.02 | 3,102 | 0.45 | 27.9 |
| Indoors | 0.02 | 4,218 | 1.18 | 99.5 |
| Outdoor | 0.1 | 1,400 | 1.21 | 169.4 |
| Gardening | 0.5 | 40 | 1.21 | 24.2 |
| Away | | 0 | | 0.0 |
| | Total Time: | 8,760 | ***Soil Inhaled:*** | ***321*** |
| **All Pathways Farmer (Annual Average is 0.0666 $mg/m^3$)** | | | | |
| Asleep | 0.05 | 3,102 | 0.45 | 69.8 |
| Indoors | 0.05 | 3,858 | 1.18 | 227.6 |
| Outdoor | 0.1 | 1,750 | 1.21 | 211.8 |
| Gardening | 0.5 | 50 | 1.21 | 30.3 |
| Away | | 0 | | 0.0 |
| | Total Time: | 8,760 | ***Soil Inhaled:*** | ***539*** |

Notes:

- Air concentrations of contaminated soil as well as the time weighting are based on the discussion in NUREG/CR-5512, Section 6.3.1. The All Pathways Farmer is exposed to the more ubiquitous soil contamination resulting from a contaminated water supply. Hence, the air concentration is at the ambient air quality guideline. The Post-intrusion Resident is exposed less frequently due to the smaller contaminated area. Hence, the air concentrations for the intruders are judged to be smaller.
- Each individual spends 8.5 hours per day, 365 days per year asleep. For 180 days the post-intrusion resident spends 2, 4, or 8 h/d outdoors, while the all pathways farmer spends 10 h/d outdoors.
- Breathing rates are from ICRP 66 (1994) Table B.16B.

The outdoor air concentrations used in the table are discussed at length in NUREG/CR-5512, Section 6.3.1. The values chosen represent conservative bounds on likely concentrations for the activities indicated. The exposure times are also based on the NUREG/CR-5512, although the document is not as explicit as to the assumptions behind the time periods used. It appears that NUREG/CR-5512 includes a vacation period of 2 weeks away from the residence.

This is a minor (3%) reduction in the mass inhaled, and is not included. The combinations shown on Table A9 for the post-intrusion resident and all pathways farmer scenarios lead to the annual inhalation amounts shown. Dividing these by the volume of air inhaled in a year (8,094 $m^3$) gives the average concentrations shown in the table subheadings.

If the intakes are averaged over one year, and the annual average breathing rate from ICRP 66 (8,094 $m^3$/y) is applied to calculate the amount inhaled, then the average air concentration for the all pathways farmer is 0.0666 mg/$m^3$ and the average air concentration for the post-intrusion resident is 0.0158 mg/$m^3$. These are shown on Table A10.

The Columbia River population average is based on an exposure of 12 hours per day to a mass loading of 0.05 mg/$m^3$ at the daily average breathing rate. This leads to an annual inhalation of 405 milligrams of soil, as shown below. This is nearly the same intake as used in the 2001 ILAW PA (416 mg/y). In the 200 West Area Burial Ground PA (WHC-EP-0645) the annual inhalation was twice as great. This is unrealistically high, since the air concentration of contaminated material (0.1 mg/$m^3$) is a bounding value. In addition, there are other sources of airborne material that are not contaminated. Hence the estimate shown below will be used for population dose.

$$(8{,}094\ m^3/y)(0.05\ mg/m^3) = 405\ mg/y$$

**Table A10. Annual Inhalation of Contaminated Soil.**

| Exposure Scenario | Breathing Rate ($m^3$/day) | Average Air Concentration (mg/$m^3$) | Exposure Frequency (days/year) | Annual Soil Inhalation (mg/y) |
|---|---|---|---|---|
| Well-Driller | 9.68 | 0.1 | 5 | 4.84 |
| Post-Intrusion Suburban Resident | 22.175 | 0.0107 | 365 | 87 |
| Post-Intrusion Rural Resident | 22.175 | 0.0209 | 365 | 169 |
| Post-Intrusion Commercial Farm | 22.175 | 0.0397 | 365 | 321 |
| All Pathways Farmer | 22.175 | 0.0666 | 365 | 539 |
| Columbia River Population | 22.175 | 0.05 | 365 | 405 |
| HSRAM Industrial | 20 | 0.05 | 250 | 250 |
| Recreational -- Child/Adult | 10 / 20 | 0.05 | 7 | 3.5 / 7 |
| Residential -- Child/Adult | 10 / 20 | 0.05 | 365 | 182.5 / 365 |
| Agricultural -- Child/Adult | 10 / 20 | 0.05 | 365 | 182.5 / 365 |

Notes:

- Breathing rates for the Well Driller and the All Pathways Farmer are from Table B.16B of ICRP 66 for the adult mail sedentary worker. Breathing rates for the HSRAM scenarios are from the HSRAM. Two values are given for the last three HSRAM scenarios. In these scenarios, non-carcinogens are inhaled at the child's rate (10 $m^3$/d), while carcinogens are inhaled at the adult's (20 $m^3$/d).
- The Average Air Concentrations for the post-intrusion residents and the all pathways farmer are from Table A9.
- The annual soil inhalation is calculated as the product of the breathing rate, the air concentration and the exposure frequency.

In the HSRAM scenarios, the average air concentration is the national ambient air quality standard, 0.05 mg/$m^3$. The daily inhalation rate is either 10 $m^3$/d or 20 $m^3$/d. The smaller number is the breathing rate for children. The intake of non-carcinogens is evaluated using the

child's inhalation rate (10 $m^3$/d) because the child's mass is much smaller than the adult's (10 kg versus 709 kg). The inhalation of carcinogens is modeled at the adult inhalation rate (20 $m^3$/d) for a 30 year exposure period rather than the child's breathing rate for a 6 year exposure period. The difference in body mass is not as great as the total amount inhaled. Note that the child and adult are assumed to have the same toxicity parameters (reference doses and cancer induction slope factors). In the industrial scenario there are no children, so the larger breathing rate is used for all materials. In the industrial scenario, the annual inhalation time is 250 days so that the total annual inhalation is 250 mg soil. In the recreational scenario the annual inhalation time is 7 days, so the total annual inhalation is 3.5 mg soil for non-carcinogens and 7.0 mg soil for carcinogens. In the residential and agricultural scenarios the annual inhalation time is 365 days so that the total annual inhalation is 182.5 mg soil for non-carcinogens and 365 mg soil for carcinogens. The HSRAM inhalation intakes are therefore lower than the residential gardener commonly used in Hanford Site performance assessments.

### A3.2.2 Special Model for Tritium

Airborne concentrations of tritium in the irrigation scenarios are based on airborne water. The airborne water is described in the next section. The contribution from the soil is included in the airborne water, and is not calculated separately. Airborne concentrations of tritium for the intruder scenarios are calculated using an evaporation model derived from the RESRAD manual (ANL/EAD/LD-2). The tritium emanation model used to calculate inhalation dose from tritium in the intruder scenarios is the subject of this section.

The simple box model assumes there is a volume of air directly over the garden that has a tritium concentration fed by evaporation and diminished by movement of air through the volume. The air volume is the garden area times a vertical height selected to represent the average air concentration. The average wind speed observed at the Hanford Meteorology Station is used.

**Soil Water Model**

The top 15 cm of garden soil are of interest because vegetation derives most nutrients from this layer and airborne losses occur from this surface layer. Radioactive contaminants deposited on the soil surface are mechanically mixed by tilling. In addition, precipitation and irrigation drive the contaminants downward with the excess water. In the case of tritiated water (HTO) there is also loss from the surface layer through evaporation. Tritiated water follows the non-radioactive water in the soil. Hence, the soil water model used in this report is introduced here, although further discussion is postponed until Section A6.0.

As shown in Table A11, the year is divided into an irrigation period and a non-irrigation period due to the typical practices in the vicinity of the Hanford Site. The irrigation period extends from April to September (6 months). Precipitation values for the irrigating and non-irrigating periods are from PNNL-15160 (2005) for the years 1971 through 2000 (a 30-year period). The irrigation amount (I) is from the grout PA (WHC-SD-WM-EE-004). The evaporation amount (E) is selected to give an excess of 10 cm during the 6-month irrigation period. Note that the number of significant digits is due to the conversion from units of inches to units of centimeters, rather than the precision of the measurement.

The irrigation rate along the Columbia River is smaller than near the Hanford Site. Following the grout PA, an average irrigation application of 63.5 cm is used. With this change, the value for E in Table A11 becomes 59.266 cm/y. The other numbers are unchanged.

**Table A11. Water Balance for the Surface Layer near the Hanford Site.**

| Source of Water | Irrigation | Non-irrigation |
|---|---|---|
| Precipitation (P) | 5.766 cm | 11.963 cm |
| Irrigation (I) | 82.3 cm | none |
| Evaporation (E) | 78.066 cm | 11.963 cm |
| Excess (P + I - E) | 10.0 cm | none |

Notes:
- The precipitation amounts (P) are from PNNL-15160 (2005). These are the average amounts for the 30 years from 1971 to 2000.
- The irrigation amounts (I) are the depth of water applied to soil near the Hanford Site during the season. A smaller value (63.5 cm) is used for irrigation in the Columbia River population scenario.
- The evaporation amounts (E) are chosen to give an excess of 10 cm.
- The number of significant digits is due to the conversion from units of inches rather than the precision of the measurement.

For simplicity, the upper 15 cm of soil is assumed to have a uniform tritium concentration with depth. This follows from the assumption that the land is used as a garden or pasture and is periodically cultivated. Contaminants deposited on the ground surface are evenly mixed to a depth of 15 cm. The horizontal distribution of the contaminant will still be non-uniform, especially for the larger averaging area of the pasture.

The three parts to the removal rate are radioactive decay, air emissions (upward), and percolation (downward) during the two irrigation periods for a total of six cases. The loss of tritium by radioactive decay is small compared to percolation and evaporation. The decay constant shown in Table A12 uses a half life of 12.32 years.

The rate at which tritium leaves the surface layer is assumed proportional to the total present in the layer at any point in time. The constant of proportionality will be referred to as a fractional removal rate. During the year there are four fractional removal rates, two for evaporation and two for percolation. The fractional removal rate for radioactive decay is the same during both seasons. Typical numbers for fractional removal rates near the Hanford Site for water in both gardens and pastureland are shown in Table A12.

**Table A12. Tritium Removal Coefficients for the Surface Layer.**

| Water Removal | Irrigation | Non-irrigation |
|---|---|---|
| Radioactive ($\lambda_R$) | 0.05626 per year | 0.05626 per year |
| Leaching ($\lambda_S$) | 6.667 per year | none |
| Evaporation ($\lambda_E$) | 52.044 per year | 7.975 per year |
| Total removal ($\lambda_T$) | 58.767 per year | 8.032 per year |

The irrigation rate along the Columbia River is smaller than near the Hanford Site, and an average irrigation application of 63.5 cm is used. With this change, the value for $\lambda_E$ in

Table A12 becomes 39.511 per year, and the value for $\lambda_T$ is 46.177 per year. The other numbers are unchanged.

The formula used to calculate these values is shown below. It uses a soil layer of thickness "d" during both the irrigation or non-irrigation seasons. Note that the quantity (P+I-E) is the excess water applied to the soil, assumed to be 10 cm. The soil parameters are discussed further in Section A6.0.

$$\lambda_S = \frac{P + I - E}{\theta\, d\, T_{irr}} \quad \text{and} \quad \lambda_E = \frac{E}{\theta\, d\, T_{irr}} \quad \text{and} \quad \lambda_R = \frac{\ln(2)}{T_{half}}$$

Where

- $d$ = thickness of the surface soil layer from which nuclides migrate, 15 cm
- $E$ = total evaporation during the season (from Table A11), in cm
- $I$ = total irrigation water applied during the season (from Table A11), in cm
- $P$ = total precipitation during the season (from Table A11), in cm
- $T_{half}$ = radioactive decay half life for tritium (from Table A1), 12.32 years
- $T_{irr}$ = irrigation period, 0.5 y. The non-irrigation period ($T_{no}$) is also 0.5 y.
- $\lambda_E$ = evaporation coefficient (see Table A12), per year
- $\lambda_R$ = radioactive decay constant for tritium, 0.05626 per year
- $\lambda_S$ = average soil leaching coefficient for tritium (see Table A12), per year
- $\theta$ = volumetric water content of the surface soil, milliliters of water per cubic centimeter of soil. A value of 0.2 ml/cc is assumed. Because the total soil porosity is about 0.4 ml/cc, the saturation ratio is about 50%.

The quantity of tritium in the surface layer decreases with time as shown below. "Q" is the total tritium activity in the garden or pasture. (Natural levels of tritium are assumed to be zero.) Because $\lambda_T$ is large, the initial inventory of tritiated water leaves the surface layer in a few weeks.

$$\frac{dQ}{dt} = -\lambda_T Q \quad \text{and} \quad \lambda_T = \lambda_R + \lambda_S + \lambda_E$$

$$Q = Q_0 e^{-\lambda_T t}$$

**Time Dependence of the Air Concentration**

The air concentration directly over the contaminated soil depends on both the rate at which tritium is added to the air and the rate at which it is dispersed by the wind. A simple box model is used to approximate this situation. In the simple box model, the tritiated water and the air are instantaneously and uniformly distributed throughout the box. The rate at which tritium is added to the box is the product of the evaporation coefficient ($\lambda_E$) and the quantity of tritium in the surface layer (Q). The rate of removal by the wind depends on the size of the box (the width perpendicular to the wind and the box height) and the wind speed.

The assumed width of the box could be based on either the width of the contaminated soil or the entire width of the garden/pasture. The objective here is to represent the average air concentration inhaled by an individual while they are in or near the garden/pasture. Thus, the

entire width of the pasture or garden is used. The width is approximated as the square root of the area of the pasture or garden. This is the side length of a square.

Typical activities place the individual's head between 0.5 m and 1.5 m above the soil. The tritium evaporating from the ground spreads vertically by diffusion and turbulence. Near the contaminated soil the tritium spreads primarily by diffusion so the vertical spread is determined by the wind speed. At high wind speeds, the tritium is carried from the garden/pasture before rising appreciably, so very little can be inhaled. In addition, tritium is only inhaled while the individual is downwind of the contaminated soil. Thus, the amount of tritium inhaled by the individual depends on the wind speed and direction.

To simplify the analysis, it is assumed that the entire garden or pasture is contaminated, and the wind speed is the average wind speed during the year. The volume of the box is the product of the area of the garden or pasture and the assumed height of the box. The vertical height of the box is selected to represent the average vertical extent of airborne contamination. The larger the contaminated surface, the larger the vertical height. The rate of removal of tritium from the box is the air concentration times the volumetric flow rate as shown below.

$$\text{Removal Rate} = -U\,H\sqrt{A}\,C_A = -\mu\,W$$

$$\text{where} \quad C_A = \frac{W}{A\,H} \quad \text{and} \quad \mu = \frac{U}{\sqrt{A}}$$

Where

| | | |
|---|---|---|
| $A$ | = | surface area of the garden (100 $m^2$) or pasture (5,000 $m^2$) |
| $C_A$ | = | tritium air concentration in the volume (AH) above the garden, in $Ci/m^3$ |
| $H$ | = | effective vertical height above the garden for estimating air concentrations, in m |
| $U$ | = | harmonic wind speed average through the volume of interest, 2.055 m/s from PNNL-15160 for the years 1955 to 2004 (50 years) |
| $W$ | = | amount of tritium in the volume of air above the garden or pasture, in Ci |
| $\mu$ | = | effective removal constant by wind moving through a volume of air over the garden or pasture, per second |

The harmonic average wind speed is the inverse of the average of the inverse wind speeds from PNNL-15160 for the years 1955 to 2004. The inverse speeds are weighted by the fraction of the hourly readings that have wind speeds in that group. The calm group in PNNL-15160 is assumed to have a wind speed of 1 mile/hour. During the year, the average wind speed is slightly greater during the summer months, but this has a small effect on the average speed. The harmonic average is used because the formula derived for the amount of tritium inhaled (presented below) has the wind speed in the denominator.

The time dependence of the airborne tritium in the volume of interest is approximated using the linear differential equation shown below. "Q" is the total tritium activity in the garden/pasture, which is decreasing with time. "W" is the total tritium activity in the selected air volume above the garden/pasture.

$$\frac{dW}{dt} = \lambda_E\,Q - \mu\,W$$

The solution to the above equation for the activity in the volume of interest is shown below. The average air concentration is also shown. The approximate formulas are based on the typical situation of $\mu >> \lambda_T$.

$$W = \frac{\lambda_E Q_0}{\mu - \lambda_T}\left(e^{-\lambda_T t} - e^{-\mu t}\right) \cong \frac{\lambda_E Q_0}{\mu} e^{-\lambda_T t}$$

$$C_A = \frac{\lambda_E Q_0}{(\mu - \lambda_T) A H}\left(e^{-\lambda_T t} - e^{-\mu t}\right) \cong \frac{\lambda_E Q_0}{U H \sqrt{A}} e^{-\lambda_T t}$$

Where

- $A$ = surface area of the garden (100 $m^2$) or pasture (5,000 $m^2$)
- $C_A$ = tritium air concentration in the volume (AH) above the garden, in $Ci/m^3$
- $H$ = effective vertical height above the garden for estimating air concentrations, in m
- $Q_0$ = initial total tritium activity in the garden, in Ci
- $t$ = elapsed time, in years. At t=0 the well was drilled and spread in the garden and irrigation begins.
- $W$ = amount of tritium in the volume of air above the garden or pasture, in Ci
- $\lambda_E$ = tritium evaporation coefficient (from Table A12), per year
- $\lambda_R$ = radioactive decay constant for tritium, 0.05626 per year
- $\lambda_S$ = average soil leaching coefficient for tritium (see Table A12), per year
- $\lambda_T$ = total fractional removal rate from the surface layer, per year, $\lambda_T = \lambda_R + \lambda_E + \lambda_S$
- $\mu$ = effective removal constant by wind moving through a volume of air over the garden or pasture, per second

The total activity inhaled by the resident is the time integral of the product of air concentration and breathing rate. The breathing rate is assumed to be constant during the exposure period. In addition, the breathing rate is adjusted downward to account for time absent from the garden/pasture. Because the leaching and evaporation removal constants are large, this is effectively an integral from 0 to infinity. The equation for the activity of tritium inhaled by the post-intrusion resident is shown below.

$$\text{Tritium Inhaled} = \frac{\lambda_E F_{PI} BR}{\lambda_T \mu H A} Q_0 = \frac{\lambda_E F_{PI} BR}{\lambda_T U H \sqrt{A}} Q_0$$

Where

- $A$ = surface area of the garden (100 $m^2$) or pasture (5,000 $m^2$)
- $BR$ = breathing rate for the post-intrusion resident when outdoors in his garden, 1.21 $m^3/h$ from ICRP 66
- $F_{PI}$ = fraction of air that the individual breathes while located in the contaminated area. Computed as the volume of air inhaled during the hours outdoors divided by the volume inhaled in 1 day. For the suburban gardener this is $(2\ h)(1.21\ m^3/h)/(22.175\ m^3) = 0.1091$
- $H$ = effective vertical height above the garden for estimating air concentrations, in m
- $Q_0$ = initial total tritium activity in the garden, in Ci
- $U$ = harmonic wind speed average through the volume of interest, 2.05 m/s from PNNL-15160 for the years 1955 to 2004
- $\lambda_E$ = tritium evaporation coefficient (from Table A12), per year

$\lambda_R$ = radioactive decay constant for tritium, 0.05626 per year
$\lambda_S$ = average soil leaching coefficient for tritium (see Table A12), per year
$\lambda_T$ = total fractional removal rate from the surface layer, per year, $\lambda_T = \lambda_R + \lambda_E + \lambda_S$
$\mu$ = effective removal constant by wind moving through a volume of air over the contaminated area, per second

Input assumptions and calculated results for the box model are shown in Table A13. The last column shows the fraction of tritium exhumed that is inhaled by the exposed individuals. This fraction is used to calculate the inhalation dose from tritium for the post intrusion scenarios. Another method developed by EPA in the soil screening guidance is compared with the box model results in the next section.

**Table A13. Fraction of Exhumed Tritium that is Inhaled.**

| Parameter | Suburban Garden | Rural Pasture | Commercial Farm |
|---|---|---|---|
| Surface Area (A) | 100 $m^2$ | 5,000 $m^2$ | 647,000 $m^2$ |
| Box Height (H) | 1 m | 2 m | 4 m |
| Ambient Wind Fractional Loss Rate ($\mu$) | 739.8 $h^{-1}$ (17,755 $d^{-1}$) | 104.6 $h^{-1}$ (2,511 $d^{-1}$) | 9.197 $h^{-1}$ (220.7 $d^{-1}$) |
| Exposure Period | 2 h/d | 4 h/d | 8 h/d |
| Inhalation Fraction ($F_{PI}$) | 0.1091 | 0.2183 | 0.4365 |
| Fraction Inhaled during the Irrigation Season | 1.581E-06 | 2.236E-07 | 1.965E-08 |
| Fraction Inhaled during the Non-irrigation Season | 1.772E-06 | 2.507E-07 | 2.204E-08 |

**Alternate Methods for Estimating the Amount Inhaled**

Another method for calculating the amount inhaled is based on the methods adopted by EPA for evaluating human health risks from contaminants in surface soil (EPA/540/R-96/018 and EPA/540/R95/128). In the EPA risk methodology the rate of emission from the soil surface is estimated from soil characteristics. The air concentration nearby is calculated using an air transport factor obtained from the EPA plume dispersion software ISCST3 (EPA-454/B-95-003) for area sources. In ISCST3 the area of the source can be varied along with the location of the receptor point (distance, direction, and elevation). The software calculates the air transport factor ($\chi$/S') at that location using hourly wind data.

The method presented above for tritium emanations from the soil surface can be restated using this type of air transport factor. The air concentration is the product of the emission rate (Ci/s per $m^2$) and the air transport factor for an area source (s/m). Replacing the emission rate per unit area with a time-varying emission rate ($\lambda_E Q/A$) gives the formula for the time-dependent air concentration shown below. As before, a time integral must be performed to calculate the total activity inhaled. Note that the conversion factors for the different time units are not explicitly stated in the formula.

$$C_A = \frac{\lambda_E Q_0}{A} e^{-\lambda_T t} \left(\frac{\chi}{S'}\right)$$

$$\text{Tritium Inhaled} = \frac{\lambda_E \left(\frac{\chi}{S'}\right) F_{PI}\, BR}{\lambda_T A} Q_0$$

Where

| | | |
|---|---|---|
| $A$ | = | surface area of the garden (100 $m^2$) or pasture (5,000 $m^2$) |
| $BR$ | = | breathing rate for the post-intrusion resident when outdoors in his garden, 1.21 $m^3$/h from ICRP 66 |
| $C_A$ | = | tritium air concentration at various locations at or near the garden, in Ci/$m^3$ |
| $F_{PI}$ | = | fraction of air that the individual breathes while located in the contaminated area. Computed as the volume of air inhaled during the hours outdoors divided by the volume inhaled in 1 day. |
| $Q_0$ | = | initial total tritium activity in the garden, in Ci |
| $\frac{\chi}{S'}$ | = | air concentration (g/$m^3$) calculated for a unit areal release rate (g/s per $m^2$), in units of g/$m^3$ per g/s-$m^2$ (or simply s/m) calculated using the ISCST3 software. The receptor distance and direction with the largest value is used. |
| $\lambda_E$ | = | tritium evaporation coefficient, per year |
| $\lambda_R$ | = | radioactive decay constant for tritium, 0.05626 per year |
| $\lambda_S$ | = | average soil leaching coefficient for tritium (see Table A12), per year |
| $\lambda_T$ | = | total fractional removal rate from the surface layer, per year, $\lambda_T = \lambda_R + \lambda_E + \lambda_S$ |

Results of the ISCST3 calculations are shown in Table A14. Three receptor elevations were used in the ISCST3 runs to observe the effect of this parameter. The air concentrations were calculated at various distances from the center of the area source in all 36 wind transport directions. The distance with the largest air concentration is shown in the table. (The direction is not shown) The fourth column shows the largest air concentrations calculated by ISCST3.

Note that the two formulas given above for "Tritium Inhaled" can be combined and rearranged to show the effective air transport factor ($\chi$/S') used in the tritium model. This is shown in the equation below.

$$\frac{\lambda_E F_{PI}\, BR\, Q_0}{\lambda_T U H \sqrt{A}} = \frac{\lambda_E F_{PI}\, BR\, Q_0}{\lambda_T A} \left(\frac{\chi}{S'}\right)$$

$$\text{thus,} \quad \left(\frac{\chi}{S'}\right) = \frac{\sqrt{A}}{U H}$$

The atmospheric dispersion parameter used in the EPA Soil Screening Guidance documents (EPA/540/R-96/018 and EPA/540/R95/128) to relate the surface emission rate (g/$m^2$ per second) to the average air concentration at the ground surface (kg/$m^3$) is known as Q/C. It is the inverse of the air transport factor ($\chi$/S') calculated using the ISCST3 software for area sources. The value selected in the EPA risk assessment methodology for surface soil is 68.81 g/$m^2$ per second per kg/$m^3$ calculated using Los Angeles wind data and a 0.5-acre-square source. (0.5 acre = 2,023 $m^2$). It is an annual average value at an elevation of zero meters above the soil surface in the center of the contaminated area. Using the formalism developed above for tritium, the quantity Q/C is defined as shown below.

$$\left(Q/C\right) = H\mu = \frac{H\,U}{\sqrt{A}}$$

**Table A14. ISCST3 Results.**

| Source Area (Scenario) | Receptor Elevation (m) | Peak Radial Distance from Center (m) | ISCST3 Air Concentration ($g/m^3$) | Q/C ($g/m^2$-s per $kg/m^3$) | |
|---|---|---|---|---|---|
| | | | | ISCST3 | Tritium Model |
| 100 $m^2$ | 0 | 1.5 | 9.235 | 108.3 | |
| {Suburban | 0.5 | 8 | 1.200 | 833.2 | 205.5 |
| Garden} | 1 | 15 | 0.3712 | 2,694 | |
| 1/2 Acre | 0 | 8 | 19.49 | 51.30 | |
| (2,023 $m^2$) | 0.5 | 8 | 7.473 | 133.8 | na |
| (EPA Default) | 1 | 14 | 3.298 | 303.3 | |
| 5,000 $m^2$ | 0 | 12 | 23.093 | 43.30 | |
| (Rural Pasture) | 0.5 | 12 | 10.783 | 92.74 | 58.12 |
| | 1 | 15 | 5.824 | 171.7 | |

Notes:
- For input to ISCST3, the source area is square with an emission rate of 1 $g/m^2$ per second.
- Hanford Site wind data from the 200 East Area for the years 1992 to 1996 was used in the ISCST3 computations.
- The quantity Q/C is calculated as 1000 g/kg divided by the ISCST3 results.

Inserting the box height and surface area gives the Q/C values shown below for the suburban garden and rural pasture scenarios. These are also listed in Table A14.

$$\left(Q/C\right)_{\text{Garden}} = \frac{(1\,\text{m})(2.055\,\text{m/s})}{\sqrt{100\,\text{m}^2}} = 0.2055\,\text{m/s} = 205.5\,\frac{\text{g}}{\text{m}^2\,\text{s}}\,\text{per}\,\frac{\text{kg}}{\text{m}^3}$$

$$\left(Q/C\right)_{\text{Pasture}} = \frac{(2\,\text{m})(2.055\,\text{m/s})}{\sqrt{5000\,\text{m}^2}} = 0.05812\,\text{m/s} = 58.12\,\frac{\text{g}}{\text{m}^2\,\text{s}}\,\text{per}\,\frac{\text{kg}}{\text{m}^3}$$

The Q/C values using Hanford Site data collected in the 200 Areas from 1992 to 1996 are shown in the last columns of Table A14. It is clear that receptor elevation is a very important parameter in the ISCST3 calculation. The box model results used in the tritium model agree with the ISCST3 results if a small receptor elevation (less than 0.5 m) is included in the ISCST3 calculations. An example input file for ISCST3 is shown in the first attachment for reference.

The Hanford Site result for the Q/C parameter using the EPA screening model area of 0.5 acre and a receptor elevation of 0 meters is 51.31 $g/m^2$ per second per $kg/m^3$. This is somewhat smaller (more conservative) than the EPA default value of 68.81 $g/m^2$ per second per $kg/m^3$. However, the numbers from the box model use a more realistic assumption of non-zero receptor elevation. Note that the assumed receptor elevation has a significant effect on the Q/C parameter, especially for smaller areas.

### A3.2.3 Airborne Water

In the exposure scenarios that use contaminated groundwater the contaminants dissolved in the water may become airborne. Two situations are modeled. The first is inhalation of airborne contaminants from ambient sources such as overhead irrigation, wind blowing across puddles, drops falling off foliage, and indoor sources such as laundry and cooking. The second source is inhalation of spray during a shower. These moisture inhalation pathways were used in the 2001 ILAW PA (DOE/ORP-2000-24), but not in prior Hanford performance assessments.

Because tritium is modeled as water (HTO), an equilibrium approach is used for tritium. The ratio of airborne tritium to total water in the air is the same as the concentration of the tritium in the water. For other radionuclides, air concentrations are estimated using entrainment factors suitable for the processes that aerosolize the liquid. For chemicals the air concentration is estimated using Henry's Law.

The entrainment of dissolved inorganic materials into the air requires some physical process, such as a water spray during irrigation or showering, to create droplets that will remain airborne for a time. While these droplets are airborne they evaporate and leave behind any suspended solids as airborne particles. The air concentration of the dissolved materials is therefore proportional to the total water content of the air. The constant of proportionality is represented by measured entrainment factors for evaporation of aqueous solutions. There are other sources of humidity that involve no entrained contaminants, e.g., green plants and moisture carried in by regional air movements. Neglecting these lends conservatism to the air concentration estimates.

In *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, Volume 1* (DOE-HDBK-3010-94) data for aqueous solutions under various conditions are presented. Section 3.1 recommends a median entrainment factor of 6E-7 for non-boiling aqueous solutions of inorganic compounds. This number will be used for ambient conditions, as shown in Table A15. Another way of looking at the entrainment factor is that it is the fraction of dissolved contaminant that becomes airborne with the water vapor. The rest is left behind in solution. This effect is also observed in distillation operations as impurity carryover.

**Ambient Sources of Airborne Water**

Ambient sources of airborne water include overhead irrigation, wind blowing across puddles, drops falling off foliage, and indoor sources produced by laundering clothes and cooking. These activities result in small amounts of the dissolved contaminants becoming airborne. To keep inhalation exposures in the same units as the other pathways, the amount of the dissolved contaminant that is airborne or inhaled will be expressed in terms of the volume of the aqueous solution. The calculation of the amount inhaled in each exposure scenario is summarized in Tables A15 and A16. Table A15 presents the average airborne concentrations, and Table A16 shows the total amounts inhaled during the year.

In Table A15, the ambient contribution to water inhaled is divided into the irrigation months (April through September) and the non-irrigation months (October through March). Because the irrigation season is largely outdoor activity, Hanford Site averages for 1971 to 2000 (30 years) from PNNL-15160 are used for the average temperature (19.46 C) and the average relative humidity (40.2%). At 19.46 C the saturated water concentration is 2.2%. At a relative

humidity of 40.2% the water vapor concentration is 0.89%, as shown in Table A15. The conversion of vapor concentration from mole fraction to mass concentration uses the molecular weight for water (18.0153 g/gmole) and the ideal gas law, as shown below. Note that the temperature is in degrees Kelvin rather than Celsius, and also that the volume is converted from liters to cubic meters ($m^3$).

$$\text{Water Vapor Conc} = \frac{(2.2\%)(40.2\%)(18.0153\ \text{g/gmole})}{(0.082057\ \text{L}\cdot\text{atm/gmole/K})(19.46+273.15\ \text{K})} = 6.7\ \text{g/m}^3$$

During the non-irrigation season, time indoors is increased, so an average indoor temperature (20 C) and humidity (30%) is used in the calculation of waterborne air concentration.

The entrainment factors described above are next applied to the airborne water content to calculate the equivalent concentration of dissolved particulate in the air. The airborne concentration of entrained contaminants is shown in Table A15 in the row labeled "Entrained Contaminant". It is calculated as the product of the water vapor concentration and the entrainment factor. The units of $g/m^3$ should be interpreted as the mass of contaminated water, i.e., groundwater or Columbia River water, which is present in each cubic meter of air. The mass airborne can be converted to volume airborne using an assumed density for dilute aqueous solutions of 1,000 g/L.

The droplet concentration under ambient conditions is negligible. However, droplets are important in showering, as discussed below.

A dilution factor is included because some water vapor comes from uncontaminated sources such as rainfall and plant transpiration. In Table A15 the dilution factor during the irrigation season is estimated from the amounts of precipitation and irrigation water listed in Table A11. This leads to a dilution factor of 93.5% during the irrigation season. During the remainder of the year (without irrigation) the airborne water contamination is based on approximate indoor conditions. A small amount of dilution by uncontaminated water sources brought into the home leads to an assumed dilution factor of 90%.

The total concentration of the contaminated water in air is the sum of the "Entrained Contaminants" and "Droplet Concentration". The Dilution Factor is multiplied by this sum to give the "Total Contaminant Airborne". For tritium, the row labeled "Tritium Airborne" is calculated as the product of the "Dilution Factor" and the sum of the "Water Vapor Concentration" and the "Droplet Concentration". The entrainment factor is not used with tritiated water. Note that the units are grams of contaminated water per cubic meter of air.

**Airborne Water during Showering**

During the showering activity there is evaporative entrainment of dissolved inorganic chemicals that could be included but was not due to competing processes like plateout and washout. Instead, the air concentration during the shower is based on a water droplet concentration in air of 10 mg liquid per $m^3$ air, a value characteristic of fogs (Hinds 1982). This fog is only included in the shower and not the ambient case.

Most of the airborne water during the shower is present as vapor rather than droplets. The entrainment factor is quite small, so the entrained contaminant concentration is much smaller and is not shown in Table A15. The total airborne contaminant concentration is based on the droplet concentration, while the total tritium airborne is based on the estimated water vapor concentration.

**Table A15. Water Concentration in Air.**

| Parameter | Ambient April - September | Ambient October - March | Shower |
|---|---|---|---|
| Air Temperature, C | 19.46 | 20 | 40 |
| Air Temperature, F | 67.03 | 68 | 104 |
| Air Temperature, K | 292.61 | 293.15 | 313.15 |
| Relative Humidity | 40.2% | 30% | 80% |
| Water Vapor Concentration | 0.89% | 0.69% | 5.82% |
| | 6.7 g/m$^3$ | 5.1 g/m$^3$ | 40.8 g/m$^3$ |
| Entrainment Factor | 6.0E-7 | 6.0E-7 | not used |
| ***Entrained Contaminant*** | ***4.02E-6 g/m$^3$*** | ***3.06E-6 g/m$^3$*** | not used |
| ***Droplet Concentration*** | not used | not used | ***0.01 g/m$^3$*** |
| Dilution Factor | 93.5% | 90% | 100% |
| Total Contaminant Airborne | 3.76E-6 g/m$^3$ | 2.75E-6 g/m$^3$ | 0.01 g/m$^3$ |
| Tritium Airborne | 6.26 g/m$^3$ | 4.59 g/m$^3$ | 40.8 g/m$^3$ |

Notes:
- The first column of ambient conditions during the irrigation season uses air temperature, relative humidity, and rainfall dilution from Hanford meteorological data (PNNL-15160). The second column for the non-irrigating season uses reasonable assumptions based on indoor conditions. The two are similar in magnitude.
- Water Vapor Concentration is given as both a mole fraction and mass concentration.
- The Entrainment Factors is recommended for resuspension from non-boiling liquids in Section 3.1 of DOE-HDBK-3010-94, Volume I.
- The dilution factor accounts for uncontaminated sources of airborne water.
- The shower temperature is based on typical hot water settings. The relative humidity during the shower is a value selected from the likely range of 60% to 100%.
- The airborne concentrations are the effective mass of solution per cubic meter of air.

**Liquid Volume Inhaled During the Year**

The objective here is to estimate the total amount of liquid that is, in effect, inhaled during a year of exposure. In Table A15 the average air concentrations are estimated. These are multiplied by the breathing rates and exposure periods used in each scenario (see Table A10) to calculate the total amount of liquid inhaled during the year. These amounts are listed in Table A16. The assumed density of the irrigation water is 1.0 kg/L.

The All Pathways Farmer takes a shower every day that lasts 15 minutes. Since the indoor activity breathing rate is 1.18 m$^3$/h, the volume of air inhaled during the shower is 0.295 m$^3$. This volume has been subtracted from the daily air volume inhaled (22.175 m$^3$) because the air concentrations during the shower include the effect of ambient conditions. Hence, the ambient daily volume inhaled is 21.88 m$^3$. The resulting annual inhalation of 0.0011 L (48 L tritium) is considerably lower than the inhaled water amount used in the 2001 ILAW PA (DOE/ORP-2000-24), namely, 0.084 L (43.5 L tritium).

**Table A16. Water Inhalation of Radionuclides by Scenario.**

| Exposure Scenario | Daily Volume Inhaled ($m^3$/day) | Air Concentration ($g/m^3$) | | Exposure Frequency (days/year) | Annual Inhalation (L/year) | |
|---|---|---|---|---|---|---|
| | | Other | Tritium | | Other | Tritium |
| All Pathways Farmer | | | | ***Total*** | ***1.10E-03*** | ***48*** |
| Ambient | 21.88 | 3.0E-06 | 5.43 | 365 | 2.40E-05 | 43.4 |
| Shower | 0.295 | 0.01 | 40.8 | 365 | 1.08E-03 | 4.4 |
| Columbia River Population | | | | ***Total*** | ***7.43E-04*** | ***46*** |
| Ambient | 21.98 | 3.0E-06 | 5.43 | 365 | 2.41E-05 | 43.6 |
| Shower | 0.197 | 0.01 | 40.8 | 365 | 7.19E-04 | 2.9 |
| HSRAM Industrial | | | | ***Total*** | ***5.08E-04*** | ***29*** |
| Ambient | 20 | 3.0E-06 | 5.43 | 250 | 1.50E-05 | 27 |
| Shower | 0.197 | 0.01 | 40.8 | 250 | 4.93E-04 | 2.0 |
| HSRAM Recreational | | | | ***Total*** | ***1.38E-05*** | ***0.056*** |
| Ambient | 0 | 0 | 0 | 7 | 0 | 0 |
| Shower | 0.197 | 0.01 | 40.8 | 7 | 1.38E-05 | 0.056 |
| HSRAM Residential | | | | ***Total*** | ***7.35E-04*** | ***33*** |
| Ambient | 15 | 3.0E-06 | 5.43 | 365 | 1.64E-05 | 29.7 |
| Shower | 0.197 | 0.01 | 40.8 | 365 | 7.19E-04 | 2.9 |
| HSRAM Agricultural | | | | ***Total*** | ***7.35E-04*** | ***33*** |
| Ambient | 15 | 3.0E-06 | 5.43 | 365 | 1.64E-05 | 29.7 |
| Shower | 0.197 | 0.01 | 40.8 | 365 | 7.19E-04 | 2.9 |

Notes:

- The air concentrations are calculated in Table A15. The breathing rates are shown in Table A10.
- The ambient breathing rates for the non-HSRAM scenarios have been reduced to remove the breathing that takes place during the shower. In the HSRAM residential and agricultural scenarios, the average indoor breathing rate (15 $m^3$/d) is used.
- The All Pathways Farmer showers 15 minutes per day. The Columbia River Population and HSRAM individuals shower 10 minutes per day.
- In the Recreational scenario there are no significant sources of airborne water other than the shower. The annual intakes for the child in the Recreational scenario are half the values shown.
- The annual inhalation is the equivalent volume of water that is inhaled each year. It is calculated as the product of the breathing rate, the air concentration, and the exposure frequency.

The Columbia River Population is assumed to take 10-minute showers every day of the year. Since the indoor breathing rate is 1.18 $m^3$/h (ICRP 66), the volume of air inhaled during the shower is 0.197 $m^3$. This volume has been subtracted from the daily air volume inhaled because the air concentrations during the shower include the effect of ambient conditions. Hence, the ambient daily volume inhaled is 21.978 $m^3$ rather than 22.175 $m^3$. The resulting annual intake shown in Table A16 (7.43E-4 L, 46 L tritium) is smaller than the intakes used in the 2001 ILAW PA (0.084 L, 43.5 L tritium).

Dissolved chemicals are assumed to have air concentrations at 50% of the saturation value given by Henry's Law. The assumed 50% of saturation is based on the average relative humidity observed at the Hanford site, 54.6% (PNNL-15160). The temperature dependence of the saturation value is ignored to simplify. Some portions of the exposure are at higher temperatures

and concentrations. Other portions are at lower temperatures and concentrations. Room temperature values are assumed to adequately represent the annual average.

The maximum air concentration allowed is the water concentration (in mg/L) times 0.5 L/m$^3$, the bounding value given in the HSRAM. This (50% of saturation up to a maximum of 0.5 L/m$^3$) bypasses the need to classify chemicals as volatiles. The resulting annual air intakes for chemicals are shown in Table A17.

**Table A17. Annual Air Intakes by Scenario.**

| Exposure Scenario | Daily Volume Inhaled (m$^3$/day) | Exposure Frequency (days/year) | Annual Volume of Air Inhaled (m$^3$/year) |
|---|---|---|---|
| All Pathways Farmer | | ***Total*** | ***8,094*** |
| Ambient | 21.88 | 365 | 7,986 |
| Shower | 0.295 | 365 | 108 |
| Columbia River Population | | ***Total*** | ***8,094*** |
| Ambient | 21.978 | 365 | 8,022 |
| Shower | 0.197 | 365 | 72 |
| HSRAM Industrial | | ***Total*** | ***5,049*** |
| Ambient | 20 | 250 | 5,000 |
| Shower | 0.197 | 250 | 49 |
| HSRAM Recreational | | ***Total*** | ***0.69 / 1.38*** |
| Ambient | 0 | 7 | 0.00 |
| Shower | 0.0985 / 0.197 | 7 | 0.69 / 1.38 |
| HSRAM Residential | | ***Total*** | ***5,547*** |
| Ambient | 15 | 365 | 5,475 |
| Shower | 0.197 | 365 | 72 |
| HSRAM Agricultural | | ***Total*** | ***5,547*** |
| Ambient | 15 | 365 | 5,475 |
| Shower | 0.197 | 365 | 72 |

Notes:
- The breathing rates are from Table A10.
- In the HSRAM recreational scenario inhalation of volatiles occurs during the shower only. Non-carcinogens are inhaled at the child's rate (0.0985 m$^3$/d), while carcinogens are inhaled at the adult's rate (0.197 m$^3$/d).
- The annual volume of air inhaled is calculated as the product of the daily volume inhaled and the exposure frequency.

The air concentration for each chemical is calculated using the unitless Henry's Law Constants from Table A3. Owing to ventilation effects in occupied spaces, the actual air concentration will not be at the upper limit given by Henry's law. The average saturation fraction ($F_{SAT}$) is 50% in analogy with the average relative humidity.

The formula used to calculate the air concentrations ($C_A$) is shown below along with the equation for the partial pressure ($P_{GAS}$) of the vapor in equilibrium with the liquid. The ideal gas law is used to relate the partial pressure and air concentration. The ratio $C_A/C_W$ expresses the air concentration in terms of the equivalent volume of water per m$^3$ of air. This ratio is not allowed to exceed the HSRAM number (0.5 L/m$^3$). From the last equation, this means the HSRAM limit is reached when H' > 0.001, or $K_{HENRY}$ > 0.0245 L-atm/mole.

$$P_{GAS} = \frac{H' \; R \; T \; C_W}{(1000 \text{ mg/g}) M_{MOLE}}$$

$$C_A = F_{SAT} \frac{(1000 \text{ L/m}^3)(1000 \text{ mg/g}) M_{MOLE}}{R \; T} P_{GAS}$$

$$C_A = F_{SAT} (1000 \text{ L/m}^3) H' C_W$$

$$\frac{C_A}{C_W} = F_{SAT} (1000 \text{ L/m}^3) H' < 0.5 \text{ L/m}^3$$

where,

| | | |
|---|---|---|
| $C_A$ | = | concentration of the chemical in air, in mg/m$^3$ |
| $C_W$ | = | concentration of the dissolved chemical in water, in mg/L |
| $F_{SAT}$ | = | fraction of the upper limit concentration given by Henry's Law that is likely to be present on the average, 50% is assumed |
| H' | = | unitless Henry's Law Constant from Table A3 |
| $M_{MOLE}$ | = | molecular weight of the compound, in g/mole |
| $P_{GAS}$ | = | partial pressure of the chemical in the air, in atm |
| R | = | ideal gas law constant, 0.082057 L-atm/mole-K |
| T | = | absolute temperature of the gas, 298.15 K (20 C) |
| 1000 L/m$^3$ | = | volume conversion factor |
| 1000 mg/g | = | mass conversion factor |

The airborne chemical concentrations also have a lower bound calculated from the non-tritium annual water inhalation volumes (L/y) shown in Table A16 divided by the annual air inhalation volumes (m$^3$/y) shown in Table A17. In this way the inorganic chemicals with very small Henry's Law constants are treated as any inert material would be.

## A3.3 EXTERNAL EXPOSURE TIMES

The external doses from radionuclides in soil are proportional to both the radionuclide concentration (in Ci/m$^2$) and the time of exposure (in hours) in a given scenario. The constant of proportionality depends on the type and energy of the radiation given off by each nuclide as well as the geometry of the exposure setting. This section discusses the selection of the effective time of exposure for each exposure scenario.

The effective time of exposure is composed of a daily exposure time for a certain number of days per year. In addition, a reduction factor is applied to reduce the time of exposure based on geometry considerations unique to each scenario. These factors, together with the effective annual time of exposure are listed in Table A18.

During the drilling operation, the worker is exposed to varying dose rates. Until the waste is exhumed this dose rate is zero. While the waste comes from the hole, the dose rate is high. Since the volume of waste exhumed is small (less than 1 m$^3$), the dose rate varies inversely with the square of the worker's distance from the waste. The waste is soon covered with clean soil from deeper in the well, which reduces the dose rate. To represent the potential dose to the worker, the waste is assumed spread near the well to a depth of 5 cm. The volume of soil cuttings from a well 6.5 inches in diameter and 100 m deep is 2.43 m$^3$, as explained in Section

2.1.1. If this volume of soil is spread to an average depth of 5 cm, its area is 49 $m^2$. The external dose rate factors listed in Federal Guidance Report Number 12 (EPA-402-R-93-081) for an infinite slab that is 5 cm thick are used to estimate the dose from 40 hours of exposure. This approach differs from previous performance assessments, which assume the borehole cuttings are mixed with the soil in an area of 100 $m^2$ to a depth of 15 cm. The approach used in this report leads to larger external doses for the well driller.

**Table A18. Annual External Exposure Times.**

| Exposure Scenario | Daily (hours/day) | Dose Rate Reduction Factor | Exposure Frequency (days/year) | Annual Exposure Time (hours/year) |
|---|---|---|---|---|
| **Irrigated Land** | | | | |
| Well-Driller | 8 | 1 | 5 | 40 |
| Suburban Garden | 2 | 0.5 | 180 | 180 |
| Rural Pasture | 4 | 0.5 | 180 | 360 |
| Commercial Farm | 8 | 0.5 | 180 | 720 |
| All Pathways Farmer | 12 | 0.941 | 365 | 4,120 |
| Columbia River Population | 24 | 0.5 | 365 | 4,380 |
| HSRAM Industrial | 8 | 0.8 | 146 | 934 |
| HSRAM Recreational | 8 | 0.8 | 7 | 45 |
| HSRAM Residential | 24 | 0.8 | 365 | 7,008 |
| HSRAM Agricultural | 24 | 0.8 | 365 | 7,008 |
| **Shoreline Sediments** | | | | |
| All Pathways Farmer | 8 | 0.2 | 7 | 11 |
| Columbia River Population | 5 | 0.2 | 5 | 5 |
| HSRAM Recreational | 8 | 0.2 | 7 | 11 |
| HSRAM Residential | 8 | 0.2 | 7 | 11 |
| HSRAM Agricultural | 8 | 0.2 | 7 | 11 |
| **Swimming and Boating** | | | | |
| HSRAM Recreational | 2.6 | 0.5 | 7 | 9.1 |
| HSRAM Residential | 2.6 | 0.5 | 7 | 9.1 |
| HSRAM Agricultural | 2.6 | 0.5 | 7 | 9.1 |

Notes:
- The HSRAM Residential and Agricultural parameters have been assumed to match the parameters for the HSRAM Recreational Scenario. Other assumptions are described in the text.
- The annual external exposure time is calculated as the product of the daily time, the reduction factor, and the exposure frequency.

For the post-intrusion scenarios, the contamination is localized to the area contaminated by the exhumed waste. The external dose rate is greatest in the center of this area. At the edge of the contaminated area the dose rate has dropped to roughly half the value at the center. At a distance of 5 meters from the edge of the contamination the dose rate has dropped by an order of magnitude. Note that the dramatic decrease in dose rate is not the case for the airborne dust concentration. The annual average concentration of suspended dust from the garden decreases by diffusion and turbulent mixing rather slowly with distance, falling to perhaps half the peak value at a distance of 100 m in the downwind direction.

In the post-intrusion scenarios, because the external dose rate decreases rapidly with distance from the contaminated area, the time indoors or asleep (Table A9) will be assigned zero exposure. It will be assumed that the resident spends most of the time outdoors away from the contaminated area. The annual average exposure is half the peak value for an infinite plane because the exposed individual spends time in all parts of the contaminated area. Hence, the dose rate reduction factor for the post-intrusion scenarios is 0.5. For comparison with the effective annual exposure times shown in Table A18, the 2001 ILAW PA (DOE/ORP-2000-24) used 900 hours, the Grouted Waste PA (WHC-SD-WM-EE-004) used 4,383 hours, and the 200 West Area Burial Ground PA (WHC-EP-0645) used 3,260 hours. In addition, the prior Hanford PA's spread the exposure over the entire year rather than calculating the accumulated dose during the first half of the year.

In the All Pathways Farmer scenario most of the area near the person's dwelling is contaminated. The extent of the contaminated areas will affect the calculation of external dose in these situations. The exposure to soil contamination is divided into two time periods during the year. The first period is the time actually spent standing in the contamination. The second period is the total time near the contamination, or indoors. It is assumed that the entire time outdoors (1800 hours) is spent in exposure conditions similar to the center of an irrigated field. However, the dose rate indoors is reduced by a factor of 3. This factor of 3 is discussed in detail in NUREG/CR-5512, Section 6.7.4. Therefore the effective time of exposure at the unshielded dose rate is 4,120 hours per year, as shown below.

$$(1{,}800 \text{ hr}) + (3{,}102 + 3{,}858 \text{ hr})/3 = 4{,}120 \text{ hours}$$

The dose rate reduction factor shown in Table A18 is calculated from this effective exposure time to be consistent with the other scenarios. The calculation of the dose rate reduction factor for the All Pathways Farmer is shown below.

$$(4{,}120 \text{ h/y}) / (12 \text{ h/d} * 365 \text{ d/y}) = 0.941$$

The 2001 ILAW PA used the same time period for the All Pathways Farmer, 4,120 h. The Grouted Waste performance assessment used an effective time of 4,383 hours and the 200 West Area Burial Ground performance assessment used an effective time of 3,260 hours.

The annual exposure time for the Columbia River population is chosen to be 4,380 hours (12 h/d for 365 d). This is the same as used in prior performance assessments.

For the HSRAM scenarios, the external exposure parameters for irrigated land are from the HSRAM. The shoreline, swimming and boating activities for the residential and agricultural scenarios are assumed to match the recreational scenario. It should be noted that the dose received from submersion in water is small compared to the ingestion dose. Thus the external dose from submersion will be ignored. See Section A3.6.3 for further justification.

## A3.4 ABSORPTION THROUGH THE SKIN

Each exposure scenario includes dermal contact with the contaminated medium. The driller and post-intrusion resident get the contaminated soil on their skin. The groundwater scenarios have contaminated water being used for showers and saunas. This section evaluates the likely intakes due to contaminants being absorbed through the skin into body fluids.

### A3.4.1 Dermal Absorption of Radionuclides

The internal dose from radionuclides absorbed through the skin is the product of the average amount absorbed each day and an internal dose factor for dermal absorption. Internal dose factors for radionuclides absorbed through the skin can be estimated by dividing the ingestion dose factor from Federal Guidance Report Number 11 (EPA-520/1-88-020) by the gut-to-body-fluid transfer fraction (f1). This is somewhat inexact because the skin and the gut are different. Material in the gut is wet and the gut contains a variety of chemicals secreted by the body to aid in the absorption of nutrients. In addition, the interior surface area of the small intestine is larger than the skin area of the entire body by two orders of magnitude. It is likely the present approach will exaggerate the internal dose from dermal absorption.

The amount absorbed through the skin depends on the surface concentration of the contaminant, the area contaminated, and how often this happens during the year. The transfer from the skin to the body fluids is assumed proportional to the f1 parameter. The annual intake would then be multiplied by the internal dose factor constructed by dividing the ingestion dose factor by the f1. The f1 transfer fraction thus cancels out of the calculation, and dermal contact can be regarded as another type of ingestion dose.

An exception is for tritium as water vapor. The inhalation dose factor for tritium includes absorption through the skin in addition to the lungs by increasing the value by 50%. The ingestion dose factor is not modified.

<u>Contaminated Soil.</u> Soil adheres to the skin, permitting materials in the soil to be absorbed through the skin into body fluids. The adult body has a median skin area of about 20,000 $cm^2$, from Chapter 6 of the updated *Exposure Factors Handbook* (EPA/600-P-95/002Fa). The recommended area for contact with soil outdoors is 5,000 $cm^2$, which is 25% of the total. Typical soil adherence values range from 0.1 $mg/cm^2$ to 5 $mg/cm^2$ (EPA/600-P-95/002Fa). Actual soil adherence depends on soil properties such as moisture content and particle size, type of activity, and parts of the body surface exposed. The values selected for the performance assessment exposure scenarios are shown in Table A19. The numbers are at the low end of the range, but are consistent with values selected for the HSRAM and NASR scenarios.

A small fraction of the contamination present on the skin will be absorbed into the body through the skin. This fraction is assumed to be 0.001 times the f1 value based on typical values for the dermal absorption factor for inorganic chemicals (see Table A23). Table A19 summarizes the affected skin areas, soil adherence, and annual contact events for each of the exposure scenarios. The product of these factors gives the equivalent annual soil ingestion due to dermal contact. The values shown are much smaller than the values for direct ingestion of soil presented in Table A8 (less than 3%). Hence the approach taken in DOE/RL-91-45 to neglect dermal absorption of radionuclides will be adopted in this report also.

**Table A19. Dermal Absorption of Radionuclides in Soil.**

| Scenario | Soil Adherence ($mg/cm^2/day$) | Exposure Frequency (days/year) | Equivalent Ingestion (g/year) | Fraction of Inadvertent Soil Ingested |
|---|---|---|---|---|
| Well-Driller | 0.25 | 5 | 0.0063 | 1.3% |
| Post-Intrusion Scenarios | 0.25 | 180 | 0.23 | 1.3% |
| All Pathways Farmer | 0.25 | 365 | 0.46 | 1.3% |
| Columbia River Population | 0.2 | 365 | 0.37 | 1.0% |

Notes:
- The recommended adult surface area involved in outdoor soil contact is 5,000 $cm^2$ from the Exposure Factors Handbook, Chapter 6 (EPA/600-P-95/002Fa).
- The "Equivalent Ingestion" is the product of the adult surface area for outdoor contact, the soil adherence, the exposure frequency, and the assumed dermal absorption factor, 0.001.
- The fractions shown in the last column are the annual dermal intake divided by the annual inadvertent soil ingestion shown in Table A7.

Contaminated Irrigation Water. Waterborne contaminants in contact with the skin may potentially be absorbed through the skin into the body fluids. The leading dermal contact events are showers and the sauna or sweat lodge. Since these expose the entire skin surface, the potential for significant absorption exists. However, contact time is limited to 10 or 15 minutes for showers and 1 hour for the sauna or sweat lodge. The recommended adult total surface area is 20,000 $cm^2$ from the Exposure Factors Handbook, Chapter 6 (EPA/600-P-95/002Fa). Based on this area and typical values for the dermal absorption (permeability) constant (0.01 cm/h from Table A23), the dermal absorption intakes shown in Table A20 may be calculated.

The last column in Table A20 shows the ratio of the annual dermal intake to the annual average ingestion intake of water (545 L from Table A4). The dermal absorption adds less than 1 percent to the total. Therefore, the dermal absorption of radionuclides in water will not be explicitly included in the calculations in this report.

**Table A20. Dermal Absorption of Radionuclides in Water.**

| Scenario | Shower Duration (hours/day) | Exposure Frequency (days/year) | Equivalent Ingestion (L/year) | Fraction of Total Water Ingested |
|---|---|---|---|---|
| All Pathways Farmer | 0.25 | 365 | 1.8 | 0.3% |
| Columbia River Population | 0.167 | 365 | 1.2 | 0.2% |

Notes:
- The "Equivalent Ingestion" is the product of the adult surface area (20,000 $cm^2$), the daily contact time, the exposure frequency, and the assumed permeability coefficient, 0.01 cm/h.
- The fractions shown in the last column are the equivalent ingestion per year divided by the annual water ingestion from Table A4.

### A3.4.2 Dermal Absorption of Chemicals

The dermal absorption of chemicals occurs as a result of contact with contaminated soil or water. Annual dermal exposure factors are shown in Table A21 for soil and Table A22 for water. The exposure factors need to be multiplied by additional chemical-specific dermal factors. The formula for the dermal dose calculation is presented on page 78 of the main report.

Because reference doses and slope factors for dermal exposure have not been developed, a form of route-to-route extrapolation is used. The dermal exposures are treated as a form of ingestion, and the ingestion reference dose and slope factor are used. The only modification factor is the gut-to-body fluid transfer factor (f1). The exposures are adjusted to an effective amount ingested by dividing by the gut-to-body fluid transfer fraction.

**Table A21. Dermal Absorption of Chemicals in Soil.**

| Scenario | Skin Contact Area ($cm^2$) | Soil Adherence ($mg/cm^2/day$) | Exposure Frequency (days/year) | Annual Dermal Exposure (g/year) |
|---|---|---|---|---|
| **Irrigated Land** | | | | |
| All Pathways Farmer | 5,000 | 0.25 | 365 | 456 |
| Columbia River Population | 5,000 | 0.2 | 180 | 365 |
| HSRAM Industrial | 5,000 | 0.2 | 146 | 146 |
| Recreational -- Child/Adult | 2500 / 5000 | 0.2 | 7 | 3.5 / 7 |
| Residential -- Child/Adult | 2500 / 5000 | 0.2 | 180 | 90 / 180 |
| Agricultural -- Child/Adult | 2500 / 5000 | 0.2 | 180 | 90 / 180 |
| **Shoreline Sediment** | | | | |
| All Pathways Farmer | 5,000 | 0.25 | 7 | 8.8 |
| Columbia River Population | 5,000 | 0.2 | 5 | 5.0 |
| Recreational -- Child/Adult | 2500 / 5000 | 0.2 | 7 | 3.5 / 7 |
| Residential -- Child/Adult | 2500 / 5000 | 0.2 | 7 | 3.5 / 7 |
| Agricultural -- Child/Adult | 2500 / 5000 | 0.2 | 7 | 3.5 / 7 |

Notes:
- The recommended adult surface area involved in outdoor soil contact is 5,000 $cm^2$ from the *Exposure Factors Handbook*, Chapter 6 (EPA/600-P-95/002Fa). The child's surface area for contact with soil outdoors is half the adult value. For the last three HSRAM scenarios, the first 6 years are at the child's rate while the next 24 years are at the adult rate.
- Soil adherence and exposure frequency numbers for the All Pathways and Columbia River scenarios are assumed. Values for the HSRAM scenarios are from the HSRAM.
- The "Annual Dermal Exposure" is the product of the skin contact area, the soil adherence, and the exposure frequency.
- In the absence of reference doses and slope factors for dermal absorptions, the dermal route is treated as a form of ingestion. The effective amount ingested is described on pg 78 of the main report).

The chemical-specific dermal absorption factors and gastro-intestinal absorption factors shown in Table A23 are from the RAIS database. Numbers in the database are taken from a large list of technical publications. The internet address for these references is http://risk.lsd.ornl.gov/tox/giabsref.shtml. The GI absorption factors and references may also be accessed by chemical using http://risk.lsd.ornl.gov/cgi-bin/tox/TOX_select?select=nrad.

**Table A22. Dermal Absorption of Chemicals in Water.**

| Scenario | Daily Dermal Contact Time (hours/day) | Exposure Frequency (days/year) | Annual Dermal Exposure (L/year per cm/h) |
|---|---|---|---|
| All Pathways Farmer Shower | 0.25 | 365 | 1,825 |
| Columbia River Population Shower | 0.167 | 365 | 1,217 |
| HSRAM Industrial Shower | 0.167 | 250 | 833 |
| Recreational Shower | 0.167 | 7 | 23 |
| Surface Water Swimming | 2.6 | 7 | 364 |
| Residential Shower | 0.167 | 365 | 1,217 |
| Agricultural Shower | 0.167 | 365 | 1,217 |

Notes:

- The "Surface Water Swimming" is not used in the All Pathways Farmer or HSRAM Industrial scenarios. All others use this contact time in addition to contact during bathing.
- The 2.6 hours swimming is divided into 3 equal contact events each day lasting 52 minutes. The showers are assumed to be taken only once per day.
- The "Annual Dermal Exposure" is the product of the adult surface area (20,000 $cm^2$), the daily contact time, and the exposure frequency.
- In the absence of reference doses and slope factors for dermal absorptions, the dermal route is treated as a form of ingestion. The effective amount ingested is described on pg 78 of the main report).

The permeability constants for contact with contaminated water shown in Table A23 are calculated from the formula below from *Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment)* (EPA/540/R/99/005). Values for the logarithm of the octanol-water constant (Log $K_{OW}$) and molecular weights (MW) for each chemical are listed in Table A3. The formula below was used even for inorganic compounds, provided there was a value for Log $K_{OW}$. For the few chemicals with no value for Log $K_{OW}$, the default value of 0.001 cm/h was used. Note that the permeability coefficient is usually represented with the symbol $K_P$. A different symbol ($U_D$) is used here because the units for permeability are similar to those for velocity.

$$\text{Log } U_D = 0.66(\text{Log } K_{OW}) - 0.0056*MW - 2.8$$

The final column in Table A23 shows the loss factors ($F_{LOSS}$) attributed to desquamation of the stratum corneum, which is the outer layer of the epidermis. These numbers generally are only less than 1.00 for chemicals that have a long lag time. The term "lag time" refers to the time needed to reach a steady transfer rate through the stratum corneum. The initial transfer rate into the skin is larger than the steady state value because the transport through this layer is mostly by diffusion. The lag times are calculated using the formula shown below (from EPA 2004). The thickness 0.001 cm shown in the formula is the minimum thickness of the stratum corneum, 10 μm. Values for $T_{LAG}$ for each chemical are listed in Table A23a.

$$T_{LAG} = \frac{0.001\,\text{cm}}{6} 10^{2.8 + 0.0056\,MW}$$

Most of the values for the loss factors are from EPA/540/R/99/005 (2004). Loss factors were estimated for several chemicals not listed in the reference by using the loss factors for chemicals with similar lag times and octanol water constants.

**Table A23. Dermal Absorption Parameters for Chemicals.**

| CASRN | Chemical Name | Dermal Absorption Factor | GI Absorption Factor (f1) | Permeability Constant ($U_D$), cm/h | Dermal Loss ($F_{LOSS}$) |
|---|---|---|---|---|---|
| 50-32-8 | Benzo[a]pyrene | 0.13 | 0.31 | 6.805E-01 | 1 |
| 53-70-3 | Dibenz[a,h]anthracene | 0.13 | 0.31 | 1.248E+00 | 0.6 |
| 56-23-5 | Carbon tetrachloride | 0.01 | 0.65 | 1.608E-02 | 1 |
| 56-55-3 | Benz[a]anthracene | 0.13 | 0.31 | 5.286E-01 | 1 |
| 57-12-5 | Cyanide, free | 0.01 | 0.17 | 7.649E-04 | 1 |
| 57-14-7 | 1,1-Dimethylhydrazine | 0.01 | 0.5 | 1.197E-04 | 1 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 0.01 | 0.5 | 1.468E-04 | 1 |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 0.04 | 0.97 | 1.063E-02 | 0.9 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 0.01 | 0.8 | 2.357E-03 | 1 |
| 60-34-4 | Methylhydrazine | 0.01 | 0.5 | 1.774E-04 | 1 |
| 60-57-1 | Dieldrin | 0.01 | 0.5 | 4.275E-02 | 0.8 |
| 62-75-9 | N-Nitrosodimethylamine | 0.01 | 0.5 | 2.564E-04 | 1 |
| 64-18-6 | Formic acid | 0.01 | 0.5 | 3.853E-04 | 1 |
| 67-56-1 | Methanol (Methyl alcohol) | 0.01 | 0.8 | 3.254E-04 | 1 |
| 67-64-1 | Acetone (2-Propanone) | 0.01 | 0.83 | 5.204E-04 | 1 |
| 67-66-3 | Chloroform | 0.01 | 0.2 | 6.787E-03 | 1 |
| 67-72-1 | Hexachloroethane | 0.01 | 0.5 | 4.043E-02 | 1 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 0.01 | 0.5 | 2.321E-03 | 1 |
| 71-43-2 | Benzene | 0.01 | 0.97 | 1.474E-02 | 1 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 0.01 | 0.9 | 1.248E-02 | 1 |
| 72-20-8 | Endrin | 0.01 | 0.02 | 3.154E-02 | 0.8 |
| 74-83-9 | Bromomethane | 0.01 | 0.8 | 2.843E-03 | 1 |
| 74-87-3 | Methyl chloride (Chloromethane) | 0.01 | 0.8 | 3.295E-03 | 1 |
| 75-00-3 | Ethyl Chloride | 0.01 | 0.8 | 6.060E-03 | 1 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 0.01 | 1 | 8.302E-03 | 1 |
| 75-05-8 | Acetonitrile | 0.01 | 0.8 | 5.568E-04 | 1 |
| 75-07-0 | Acetaldehyde | 0.01 | 0.8 | 5.357E-04 | 1 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 0.01 | 0.95 | 3.543E-03 | 1 |
| 75-15-0 | Carbon disulfide | 0.25 | 0.63 | 1.133E-02 | 1 |
| 75-21-8 | Ethylene Oxide (Oxirane) | 0.01 | 0.8 | 5.693E-04 | 1 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 0.01 | 1 | 6.718E-03 | 1 |
| 75-35-4 | 1,1-Dichloroethylene | 0.01 | 1 | 1.156E-02 | 1 |
| 75-45-6 | Chlorodifluoromethane | 0.01 | 0.8 | 2.683E-03 | 1 |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 0.01 | 0.8 | 9.777E-03 | 1 |
| 75-69-4 | Trichlorofluoromethane | 0.01 | 0.23 | 1.260E-02 | 1 |
| 75-71-8 | Dichlorodifluoromethane | 0.01 | 0.23 | 8.882E-03 | 1 |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 0.01 | 0.8 | 1.723E-02 | 1 |
| 76-44-8 | Heptachlor | 0.01 | 0.72 | 1.366E-01 | 0.8 |
| 78-83-1 | Isobutanol | 0.01 | 0.8 | 1.934E-03 | 1 |
| 78-87-5 | 1,2-Dichloropropane | 0.01 | 0.74 | 7.483E-03 | 1 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 0.01 | 0.8 | 9.718E-04 | 1 |

**Table A23. Dermal Absorption Parameters for Chemicals.**

| CASRN | Chemical Name | Dermal Absorption Factor | GI Absorption Factor (f1) | Permeability Constant ($U_D$), cm/h | Dermal Loss ($F_{LOSS}$) |
|---|---|---|---|---|---|
| 79-00-5 | 1,1,2-Trichloroethane | 0.01 | 0.81 | 5.015E-03 | 1 |
| 79-01-6 | Trichloroethylene | 0.01 | 0.15 | 1.152E-02 | 1 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 0.01 | 0.5 | 1.065E-03 | 1 |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 0.01 | 0.7 | 6.878E-03 | 1 |
| 79-46-9 | 2-Nitropropane | 0.01 | 0.8 | 2.065E-03 | 1 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 0.01 | 0.8 | 4.060E-02 | 0.9 |
| 83-32-9 | Acenaphthene | 0.13 | 0.31 | 8.387E-02 | 1 |
| 84-66-2 | Diethyl phthalate | 0.01 | 0.9 | 3.570E-03 | 1 |
| 84-74-2 | Dibutyl phthalate | 0.01 | 1 | 4.085E-02 | 0.9 |
| 85-68-7 | Butyl benzyl phthalate | 0.01 | 0.61 | 3.737E-02 | 0.9 |
| 86-73-7 | Fluorene | 0.13 | 0.5 | 1.067E-01 | 1 |
| 86-74-8 | Carbazole | 0.01 | 0.7 | 5.234E-02 | 1 |
| 87-68-3 | Hexachlorobutadiene | 0.01 | 0.5 | 7.844E-02 | 0.9 |
| 87-86-5 | Pentachlorophenol | 0.25 | 1 | 1.224E-01 | 0.9 |
| 88-06-2 | 2,4,6-Trichlorophenol | 0.01 | 0.5 | 3.386E-02 | 1 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 0.01 | 0.5 | 1.601E-02 | 1 |
| 91-20-3 | Naphthalene | 0.13 | 0.8 | 4.573E-02 | 1 |
| 92-52-4 | 1,1'-Biphenyl | 0.01 | 0.5 | 9.188E-02 | 1 |
| 95-47-6 | o-Xylene | 0.01 | 0.8 | 4.620E-02 | 1 |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 0.01 | 0.5 | 7.611E-03 | 1 |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 0.01 | 0.8 | 4.371E-02 | 1 |
| 95-57-8 | 2-Chlorophenol | 0.01 | 0.5 | 7.926E-03 | 1 |
| 95-63-6 | 1,2,4-Trimethylbenzene | 0.01 | 0.8 | 8.369E-02 | 1 |
| 95-95-4 | 2,4,5-Trichlorophenol | 0.01 | 0.5 | 3.544E-02 | 1 |
| 98-86-2 | Acetophenone | 0.01 | 0.8 | 3.715E-03 | 1 |
| 98-95-3 | Nitrobenzene | 0.01 | 0.97 | 5.390E-03 | 1 |
| 100-00-5 | p-Chloronitrobenzene | 0.01 | 0.8 | 7.854E-03 | 1 |
| 100-02-7 | 4-Nitrophenol | 0.01 | 1 | 4.804E-03 | 1 |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 0.01 | 0.5 | 1.668E-03 | 1 |
| 100-41-4 | Ethyl benzene | 0.01 | 0.97 | 4.836E-02 | 1 |
| 100-42-5 | Styrene | 0.01 | 0.8 | 3.662E-02 | 1 |
| 100-51-6 | Benzyl alcohol | 0.01 | 0.66 | 2.091E-03 | 1 |
| 106-42-3 | p-Xylene | 0.01 | 0.8 | 4.836E-02 | 1 |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 0.01 | 0.65 | 7.496E-03 | 1 |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 0.01 | 0.9 | 4.438E-02 | 1 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 0.01 | 0.8 | 2.764E-03 | 1 |
| 106-99-0 | 1,3-Butadiene | 0.01 | 0.8 | 1.624E-02 | 1 |
| 107-02-8 | 2-Propenal (Acrolein) | 0.01 | 0.8 | 7.576E-04 | 1 |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 0.01 | 0.8 | 1.110E-02 | 1 |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 0.01 | 1 | 4.194E-03 | 1 |
| 107-13-1 | Acrylonitrile | 0.01 | 0.8 | 1.169E-03 | 1 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 0.01 | 0.8 | 3.189E-03 | 1 |

**Table A23. Dermal Absorption Parameters for Chemicals.**

| CASRN | Chemical Name | Dermal Absorption Factor | GI Absorption Factor (f1) | Permeability Constant ($U_D$), cm/h | Dermal Loss ($F_{LOSS}$) |
|---|---|---|---|---|---|
| 108-38-3 | m-Xylene | 0.01 | 0.8 | 5.217E-02 | 1 |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 0.01 | 0.5 | 7.727E-03 | 1 |
| 108-67-8 | 1,3,5-Trimethylbenzene | 0.01 | 0.8 | 6.082E-02 | 1 |
| 108-87-2 | Methyl cyclohexane | 0.01 | 0.8 | 1.078E-01 | 1 |
| 108-88-3 | Toluene (Methyl benzene) | 0.01 | 0.8 | 3.061E-02 | 1 |
| 108-90-7 | Chlorobenzene | 0.01 | 0.31 | 2.780E-02 | 1 |
| 108-94-1 | Cyclohexanone | 0.01 | 0.8 | 1.531E-03 | 1 |
| 108-95-2 | Phenol (Carbolic acid) | 0.01 | 0.9 | 4.331E-03 | 1 |
| 109-99-9 | Tetrahydrofuran | 0.01 | 0.5 | 1.258E-03 | 1 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 0.01 | 0.8 | 5.048E-03 | 1 |
| 110-54-3 | n-Hexane | 0.01 | 0.8 | 1.956E-01 | 1 |
| 110-80-5 | 2-Ethoxyethanol | 0.01 | 0.5 | 3.049E-04 | 1 |
| 110-82-7 | Cyclohexane | na | na | 9.979E-02 | 1 |
| 110-86-1 | Pyridine | 0.01 | 0.5 | 1.535E-03 | 1 |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 0.01 | 0.5 | 1.219E-03 | 1 |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 0.01 | 0.5 | 1.236E-04 | 1 |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 0.01 | 0.19 | 1.069E+00 | 0.8 |
| 117-84-0 | Di-n-octylphthalate | 0.01 | 0.9 | 2.285E+00 | 0.8 |
| 118-74-1 | Hexachlorobenzene | 0.01 | 0.5 | 2.438E-01 | 0.9 |
| 120-12-7 | Anthracene | 0.13 | 0.76 | 1.377E-01 | 1 |
| 120-82-1 | 1,2,4-Trichlorobenzene | 0.01 | 0.97 | 6.872E-02 | 1 |
| 121-14-2 | 2,4-Dinitrotoluene | 0.102 | 0.85 | 3.068E-03 | 1 |
| 121-44-8 | Triethylamine | 0.01 | 0.8 | 3.893E-03 | 1 |
| 122-39-4 | Diphenylamine | 0.01 | 0.5 | 3.650E-02 | 1 |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | 0.01 | 0.8 | 3.376E-04 | 1 |
| 126-73-8 | Tributyl Phosphate | 0.01 | 0.5 | 2.232E-02 | 0.9 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 0.01 | 0.8 | 1.875E-03 | 1 |
| 127-18-4 | Tetrachloroethylene | 0.01 | 1 | 3.276E-02 | 1 |
| 129-00-0 | Pyrene | 0.13 | 0.31 | 1.942E-01 | 1 |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 0.01 | 0.8 | 1.543E-03 | 1 |
| 156-59-2 | cis-1,2-Dichloroethylene | 0.01 | 1 | 7.669E-03 | 1 |
| 156-60-5 | trans-1,2-Dichloroethylene | 0.01 | 1 | 1.088E-02 | 1 |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | 0.13 | 0.31 | 1.187E+00 | 0.6 |
| 205-99-2 | Benzo[b]fluoranthene | 0.13 | 0.31 | 3.998E-01 | 1 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 0.13 | 0.31 | 2.971E-01 | 1 |
| 207-08-9 | Benzo[k]fluoranthene | 0.13 | 0.31 | 6.601E-01 | 1 |
| 218-01-9 | Chrysene | 0.13 | 0.31 | 5.703E-01 | 1 |
| 309-00-2 | Aldrin | 0.01 | 0.5 | 2.795E-01 | 1 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 0.01 | 0.97 | 1.200E-02 | 0.9 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 0.01 | 0.91 | 1.165E-02 | 0.9 |
| 541-73-1 | 1,3-Dichlorobenzene | 0.01 | 0.8 | 5.089E-02 | 1 |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 0.01 | 0.55 | 8.286E-03 | 1 |

**Table A23. Dermal Absorption Parameters for Chemicals.**

| CASRN | Chemical Name | Dermal Absorption Factor | GI Absorption Factor (f1) | Permeability Constant ($U_D$), cm/h | Dermal Loss ($F_{LOSS}$) |
|---|---|---|---|---|---|
| 563-68-8 | Thallium Acetate | 0.01 | 0.5 | 4.098E-05 | 1 |
| 621-64-7 | N-Nitrosodi-N-propylamine | 0.01 | 0.25 | 2.336E-03 | 1 |
| 1314-62-1 | Vanadium pentoxide | 0.001 | 0.2 | 1.386E-02 | 1 |
| 1330-20-7 | Xylenes (mixtures) | 0.01 | 0.92 | 4.620E-02 | 1 |
| 1336-36-3 | Polychlorinated Biphenyls | 0.14 | 0.9 | 5.203E-01 | 0.9 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | 0.14 | 0.9 | 5.203E-01 | 0.9 |
| 6533-73-9 | Thallium carbonate | 0.01 | 0.5 | 1.017E-06 | 1 |
| 7429-90-5 | Aluminum | 0.001 | 0.1 | 1.777E-03 | 1 |
| 7439-89-6 | Iron | 0.001 | 0.15 | 2.394E-04 | 1 |
| 7439-93-2 | Lithium | 0.001 | 0.8 | 4.497E-04 | 1 |
| 7439-96-5 | Manganese | 0.001 | 0.04 | 1.107E-03 | 1 |
| 7439-97-6 | Mercury metal vapor | 0.001 | 0.07 | 3.061E-04 | 1 |
| 7439-98-7 | Molybdenum | 0.001 | 0.38 | 6.524E-04 | 1 |
| 7440-02-0 | Nickel (soluble salts) | 0.001 | 0.27 | 3.127E-04 | 1 |
| 7440-22-4 | Silver | 0.001 | 0.18 | 5.594E-04 | 1 |
| 7440-24-6 | Strontium, Stable | 0.001 | 0.2 | 7.263E-04 | 1 |
| 7440-28-0 | Thallium metal | 0.001 | 0.15 | 1.612E-04 | 1 |
| 7440-31-5 | Tin | 0.001 | 0.1 | 2.373E-03 | 1 |
| 7440-36-0 | Antimony | 0.001 | 0.02 | 9.617E-04 | 1 |
| 7440-38-2 | Arsenic (inorganic) | 0.03 | 0.41 | 1.630E-03 | 1 |
| 7440-39-3 | Barium | 0.001 | 0.07 | 3.826E-04 | 1 |
| 7440-41-7 | Beryllium and compounds | 0.001 | 0.01 | 5.934E-04 | 1 |
| 7440-42-8 | Boron and borates only | 0.001 | 0.9 | 1.881E-03 | 1 |
| 7440-43-9 | Cadmium | 0.001 | 0.01 | 3.344E-04 | 1 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 0.001 | 0.2 | 3.691E-04 | 1 |
| 7440-48-4 | Cobalt | 0.001 | 0.8 | 1.051E-03 | 1 |
| 7440-50-8 | Copper | 0.001 | 0.3 | 2.937E-04 | 1 |
| 7440-62-2 | Vanadium metal | 0.001 | 0.01 | 1.166E-03 | 1 |
| 7440-66-6 | Zinc and compounds | 0.001 | 0.2 | 3.253E-04 | 1 |
| 7446-18-6 | Thallium Sulfate | 0.001 | 0.2 | 2.605E-05 | 1 |
| 7487-94-7 | Mercuric chloride | 0.001 | 0.07 | 3.423E-05 | 1 |
| 7664-41-7 | Ammonia | 0.001 | 0.2 | 1.563E-04 | 1 |
| 7723-14-0 | Phosphorus, white | 0.001 | 0.2 | 6.783E-04 | 1 |
| 7782-41-4 | Fluorine (soluble fluoride) | 0.001 | 0.97 | 1.356E-03 | 1 |
| 7782-49-2 | Selenium and compounds | 0.001 | 0.44 | 8.034E-04 | 1 |
| 7791-12-0 | Thallium Chloride | 0.001 | 0.2 | 1.634E-04 | 1 |
| 8001-35-2 | Toxaphene | 0.01 | 0.5 | 4.982E-02 | 0.8 |
| 10102-45-1 | Thallium (I) Nitrate | 0.001 | 0.2 | 7.028E-05 | 1 |
| 11096-82-5 | Aroclor 1260 | 0.14 | 0.9 | 2.782E+00 | 0.8 |
| 11097-69-1 | Aroclor 1254 | 0.14 | 0.9 | 7.134E-01 | 0.9 |
| 11104-28-2 | Aroclor 1221 | 0.14 | 0.9 | 1.359E-01 | 1 |
| 11141-16-5 | Aroclor 1232 | 0.14 | 0.9 | 1.359E-01 | 1 |
| 12672-29-6 | Aroclor 1248 | 0.14 | 0.9 | 5.614E-01 | 0.9 |
| 12674-11-2 | Aroclor 1016 | 0.14 | 0.9 | 2.930E-01 | 1 |
| 14797-55-8 | Nitrate | 0.001 | 0.5 | 9.804E-04 | 1 |

**Table A23. Dermal Absorption Parameters for Chemicals.**

| CASRN | Chemical Name | Dermal Absorption Factor | GI Absorption Factor (f1) | Permeability Constant ($U_D$), cm/h | Dermal Loss ($F_{LOSS}$) |
|---|---|---|---|---|---|
| 14797-65-0 | Nitrite | 0.001 | 0.5 | 9.470E-04 | 1 |
| 16065-83-1 | Chromium (III) (insoluble salts) | 0.001 | 0.005 | 1.000E-03 | 1 |
| 16984-48-8 | Fluorine anion | 0.001 | 0.97 | 1.733E-03 | 1 |
| 18540-29-9 | Chromium (VI) (soluble salts) | 0.001 | 0.02 | 2.000E-03 | 1 |
| 22967-92-6 | Methyl Mercury | 0.001 | 0.9 | 1.110E-04 | 1 |
| 53469-21-9 | Aroclor 1242 | 0.14 | 0.9 | 5.203E-01 | 0.9 |
| na | Uranium (soluble salts) | 0.001 | 0.85 | 1.000E-03 | 1 |

Notes:
- Dermal Absorption Factors and GI Absorption Factors are from the EPA references listed in the text. The listing in this table is from the Risk Assessment Information System (RAIS) as of October, 2006.
- The Permeability Constants are calculated from the molecular weight and octanol-water constants, or use the default value of 0.001 cm/h as described in the text.
- The loss factors are due to desquamation of the stratum corneum. They are only less than 1.00 for chemicals that have a long lag time for attaining a steady transfer rate through the skin.

Three additional parameters needed in the calculation of the dermal absorption of organic chemicals are listed in Table A23a. The equations for calculating these parameters are shown below. The "B" is a ratio of permeability coefficients for different layers in the model of skin used by the EPA. The "p" and "q" parameters are used to simplify the equations for "$T_{SS}$", which is the time needed to arrive at a steady state transfer rate through the epidermis. The model does not apply to inorganic chemicals, thus in Table 23a the inorganic chemicals are indicated with "na".

$$B = \frac{U_D \sqrt{MW}}{2.6} \qquad \text{and} \qquad p = B + \frac{1}{3(1+B)}$$

$$\text{when } B \le 0.6 \text{ then } T_{SS} = 2.4\, T_{LAG}$$

$$\text{when } B > 0.6 \text{ then } T_{SS} = 6\, q\, T_{LAG} \left( 1 - \sqrt{1 - \left(\frac{p}{q}\right)^2} \right)$$

$$\text{and} \quad q = \frac{2}{\pi}(1+B)^2 - p$$

**Table A23a. Dermal Absorption Parameters for Organic Chemicals.**

| CASRN | Chemical Name | Lag Time ($T_{LAG}$) h/event | Permeability Ratio (B) | p | Time to Steady State ($T_{SS}$), h/event |
|---|---|---|---|---|---|
| 50-32-8 | Benzo[a]pyrene | 2.722E+00 | 4.157E+00 | 4.222E+00 | 1.178E+01 |
| 53-70-3 | Dibenz[a,h]anthracene | 3.808E+00 | 8.008E+00 | 8.045E+00 | 1.710E+01 |
| 56-23-5 | Carbon tetrachloride | 7.643E-01 | 7.673E-02 | 3.863E-01 | 1.834E+00 |
| 56-55-3 | Benz[a]anthracene | 1.997E+00 | 3.072E+00 | 3.154E+00 | 8.453E+00 |
| 57-12-5 | Cyanide, free | na | na | na | na |
| 57-14-7 | 1,1-Dimethylhydrazine | 2.282E-01 | 3.569E-04 | 3.336E-01 | 5.478E-01 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 2.805E-01 | 4.924E-04 | 3.337E-01 | 6.733E-01 |

**Table A23a. Dermal Absorption Parameters for Organic Chemicals.**

| CASRN | Chemical Name | Lag Time ($T_{LAG}$) h/event | Permeability Ratio (B) | p | Time to Steady State ($T_{SS}$), h/event |
|---|---|---|---|---|---|
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 4.472E+00 | 6.973E-02 | 3.813E-01 | 1.073E+01 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 2.735E-01 | 7.804E-03 | 3.386E-01 | 6.563E-01 |
| 60-34-4 | Methylhydrazine | 1.905E-01 | 4.632E-04 | 3.336E-01 | 4.571E-01 |
| 60-57-1 | Dieldrin | 1.429E+01 | 3.209E-01 | 5.732E-01 | 3.429E+01 |
| 62-75-9 | N-Nitrosodimethylamine | 2.733E-01 | 8.488E-04 | 3.339E-01 | 6.560E-01 |
| 64-18-6 | Formic acid | 1.904E-01 | 1.005E-03 | 3.340E-01 | 4.569E-01 |
| 67-56-1 | Methanol (Methyl alcohol) | 1.590E-01 | 7.084E-04 | 3.338E-01 | 3.815E-01 |
| 67-64-1 | Acetone (2-Propanone) | 2.224E-01 | 1.525E-03 | 3.344E-01 | 5.337E-01 |
| 67-66-3 | Chloroform | 4.902E-01 | 2.852E-02 | 3.526E-01 | 1.176E+00 |
| 67-72-1 | Hexachloroethane | 2.226E+00 | 2.392E-01 | 5.082E-01 | 5.343E+00 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 2.735E-01 | 7.686E-03 | 3.385E-01 | 6.563E-01 |
| 71-43-2 | Benzene | 2.879E-01 | 5.009E-02 | 3.675E-01 | 6.910E-01 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 5.874E-01 | 5.545E-02 | 3.713E-01 | 1.410E+00 |
| 72-20-8 | Endrin | 1.429E+01 | 2.368E-01 | 5.063E-01 | 3.429E+01 |
| 74-83-9 | Bromomethane | 3.577E-01 | 1.065E-02 | 3.405E-01 | 8.585E-01 |
| 74-87-3 | Methyl chloride (Chloromethane) | 2.016E-01 | 9.005E-03 | 3.394E-01 | 4.840E-01 |
| 75-00-3 | Ethyl Chloride | 2.416E-01 | 1.872E-02 | 3.459E-01 | 5.799E-01 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 2.354E-01 | 2.524E-02 | 3.504E-01 | 5.650E-01 |
| 75-05-8 | Acetonitrile | 1.785E-01 | 1.372E-03 | 3.342E-01 | 4.285E-01 |
| 75-07-0 | Acetaldehyde | 1.856E-01 | 1.367E-03 | 3.342E-01 | 4.454E-01 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 3.144E-01 | 1.256E-02 | 3.418E-01 | 7.545E-01 |
| 75-15-0 | Carbon disulfide | 2.807E-01 | 3.801E-02 | 3.591E-01 | 6.736E-01 |
| 75-21-8 | Ethylene Oxide (Oxirane) | 1.856E-01 | 1.453E-03 | 3.343E-01 | 4.454E-01 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 3.767E-01 | 2.570E-02 | 3.507E-01 | 9.041E-01 |
| 75-35-4 | 1,1-Dichloroethylene | 3.670E-01 | 4.377E-02 | 3.631E-01 | 8.809E-01 |
| 75-45-6 | Chlorodifluoromethane | 3.207E-01 | 9.595E-03 | 3.398E-01 | 7.696E-01 |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 3.843E-01 | 3.770E-02 | 3.589E-01 | 9.223E-01 |
| 75-69-4 | Trichlorofluoromethane | 6.182E-01 | 5.682E-02 | 3.722E-01 | 1.484E+00 |
| 75-71-8 | Dichlorodifluoromethane | 5.000E-01 | 3.756E-02 | 3.588E-01 | 1.200E+00 |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 1.178E+00 | 9.071E-02 | 3.963E-01 | 2.827E+00 |
| 76-44-8 | Heptachlor | 1.296E+01 | 1.015E+00 | 1.180E+00 | 5.002E+01 |
| 78-83-1 | Isobutanol | 2.735E-01 | 6.405E-03 | 3.376E-01 | 6.563E-01 |
| 78-87-5 | 1,2-Dichloropropane | 4.514E-01 | 3.059E-02 | 3.540E-01 | 1.083E+00 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 2.665E-01 | 3.174E-03 | 3.355E-01 | 6.396E-01 |
| 79-00-5 | 1,1,2-Trichloroethane | 5.874E-01 | 2.228E-02 | 3.483E-01 | 1.410E+00 |
| 79-01-6 | Trichloroethylene | 5.723E-01 | 5.078E-02 | 3.680E-01 | 1.374E+00 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 2.663E-01 | 3.478E-03 | 3.357E-01 | 6.391E-01 |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 9.158E-01 | 3.427E-02 | 3.566E-01 | 2.198E+00 |
| 79-46-9 | 2-Nitropropane | 3.317E-01 | 7.496E-03 | 3.383E-01 | 7.961E-01 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 4.740E+00 | 2.683E-01 | 5.311E-01 | 1.138E+01 |
| 83-32-9 | Acenaphthene | 7.681E-01 | 4.006E-01 | 6.386E-01 | 1.843E+00 |
| 84-66-2 | Diethyl phthalate | 1.847E+00 | 2.047E-02 | 3.471E-01 | 4.432E+00 |

**Table A23a. Dermal Absorption Parameters for Organic Chemicals.**

| CASRN | Chemical Name | Lag Time ($T_{LAG}$) h/event | Permeability Ratio (B) | p | Time to Steady State ($T_{SS}$), h/event |
|---|---|---|---|---|---|
| 84-74-2 | Dibutyl phthalate | 3.807E+00 | 2.622E-01 | 5.263E-01 | 9.137E+00 |
| 85-68-7 | Butyl benzyl phthalate | 5.904E+00 | 2.540E-01 | 5.198E-01 | 1.417E+01 |
| 86-73-7 | Fluorene | 8.968E-01 | 5.289E-01 | 7.469E-01 | 2.152E+00 |
| 86-74-8 | Carbazole | 9.083E-01 | 2.603E-01 | 5.248E-01 | 2.180E+00 |
| 87-68-3 | Hexachlorobutadiene | 3.035E+00 | 4.872E-01 | 7.113E-01 | 7.283E+00 |
| 87-86-5 | Pentachlorophenol | 3.261E+00 | 7.681E-01 | 9.567E-01 | 1.257E+01 |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.341E+00 | 1.830E-01 | 4.648E-01 | 3.219E+00 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 2.329E+00 | 9.543E-02 | 3.997E-01 | 5.588E+00 |
| 91-20-3 | Naphthalene | 5.491E-01 | 1.991E-01 | 4.771E-01 | 1.318E+00 |
| 92-52-4 | 1,1'-Biphenyl | 7.681E-01 | 4.388E-01 | 6.705E-01 | 1.843E+00 |
| 95-47-6 | o-Xylene | 4.134E-01 | 1.831E-01 | 4.648E-01 | 9.922E-01 |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 4.241E-01 | 3.044E-02 | 3.539E-01 | 1.018E+00 |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 6.999E-01 | 2.038E-01 | 4.807E-01 | 1.680E+00 |
| 95-57-8 | 2-Chlorophenol | 5.518E-01 | 3.457E-02 | 3.568E-01 | 1.324E+00 |
| 95-63-6 | 1,2,4-Trimethylbenzene | 4.954E-01 | 3.529E-01 | 5.993E-01 | 1.189E+00 |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.341E+00 | 1.915E-01 | 4.713E-01 | 3.219E+00 |
| 98-86-2 | Acetophenone | 4.951E-01 | 1.566E-02 | 3.439E-01 | 1.188E+00 |
| 98-95-3 | Nitrobenzene | 5.144E-01 | 2.300E-02 | 3.488E-01 | 1.234E+00 |
| 100-00-5 | p-Chloronitrobenzene | 8.020E-01 | 3.792E-02 | 3.591E-01 | 1.925E+00 |
| 100-02-7 | 4-Nitrophenol | 6.322E-01 | 2.179E-02 | 3.480E-01 | 1.517E+00 |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 9.189E-01 | 8.318E-03 | 3.389E-01 | 2.205E+00 |
| 100-41-4 | Ethyl benzene | 4.134E-01 | 1.916E-01 | 4.714E-01 | 9.922E-01 |
| 100-42-5 | Styrene | 4.028E-01 | 1.438E-01 | 4.352E-01 | 9.667E-01 |
| 100-51-6 | Benzyl alcohol | 4.241E-01 | 8.364E-03 | 3.389E-01 | 1.018E+00 |
| 106-42-3 | p-Xylene | 4.134E-01 | 1.916E-01 | 4.714E-01 | 9.922E-01 |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 4.241E-01 | 2.998E-02 | 3.536E-01 | 1.018E+00 |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 6.999E-01 | 2.070E-01 | 4.831E-01 | 1.680E+00 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 1.185E+00 | 1.457E-02 | 3.431E-01 | 2.845E+00 |
| 106-99-0 | 1,3-Butadiene | 2.112E-01 | 4.593E-02 | 3.646E-01 | 5.069E-01 |
| 107-02-8 | 2-Propenal (Acrolein) | 2.167E-01 | 2.182E-03 | 3.348E-01 | 5.200E-01 |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 2.821E-01 | 3.734E-02 | 3.587E-01 | 6.771E-01 |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 3.767E-01 | 1.605E-02 | 3.441E-01 | 9.041E-01 |
| 107-13-1 | Acrylonitrile | 2.084E-01 | 3.275E-03 | 3.355E-01 | 5.003E-01 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 3.826E-01 | 1.228E-02 | 3.416E-01 | 9.182E-01 |
| 108-38-3 | m-Xylene | 4.134E-01 | 2.068E-01 | 4.830E-01 | 9.922E-01 |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 4.241E-01 | 3.091E-02 | 3.542E-01 | 1.018E+00 |
| 108-67-8 | 1,3,5-Trimethylbenzene | 4.954E-01 | 2.565E-01 | 5.218E-01 | 1.189E+00 |
| 108-87-2 | Methyl cyclohexane | 3.730E-01 | 4.110E-01 | 6.472E-01 | 8.952E-01 |
| 108-88-3 | Toluene (Methyl benzene) | 3.450E-01 | 1.130E-01 | 4.125E-01 | 8.280E-01 |
| 108-90-7 | Chlorobenzene | 4.489E-01 | 1.134E-01 | 4.128E-01 | 1.077E+00 |
| 108-94-1 | Cyclohexanone | 3.728E-01 | 5.834E-03 | 3.372E-01 | 8.947E-01 |
| 108-95-2 | Phenol (Carbolic acid) | 3.539E-01 | 1.616E-02 | 3.442E-01 | 8.493E-01 |
| 109-99-9 | Tetrahydrofuran | 2.665E-01 | 4.110E-03 | 3.361E-01 | 6.396E-01 |

**Table A23a. Dermal Absorption Parameters for Organic Chemicals.**

| CASRN | Chemical Name | Lag Time ($T_{LAG}$) h/event | Permeability Ratio (B) | p | Time to Steady State ($T_{SS}$), h/event |
|---|---|---|---|---|---|
| 110-00-9 | Furan (Oxacyclopentadiene) | 2.530E-01 | 1.602E-02 | 3.441E-01 | 6.072E-01 |
| 110-54-3 | n-Hexane | 3.195E-01 | 6.984E-01 | 8.947E-01 | 1.242E+00 |
| 110-80-5 | 2-Ethoxyethanol | 3.361E-01 | 1.113E-03 | 3.341E-01 | 8.067E-01 |
| 110-82-7 | Cyclohexane | 3.113E-01 | 3.521E-01 | 5.986E-01 | 7.471E-01 |
| 110-86-1 | Pyridine | 2.916E-01 | 5.250E-03 | 3.368E-01 | 6.999E-01 |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 4.827E-01 | 5.097E-03 | 3.367E-01 | 1.158E+00 |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 5.933E-01 | 5.509E-04 | 3.337E-01 | 1.424E+00 |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 1.618E+01 | 8.122E+00 | 8.159E+00 | 7.271E+01 |
| 117-84-0 | Di-n-octylphthalate | 1.618E+01 | 1.737E+01 | 1.738E+01 | 7.448E+01 |
| 118-74-1 | Hexachlorobenzene | 4.136E+00 | 1.582E+00 | 1.711E+00 | 1.651E+01 |
| 120-12-7 | Anthracene | 1.047E+00 | 7.069E-01 | 9.022E-01 | 4.064E+00 |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.091E+00 | 3.560E-01 | 6.018E-01 | 2.619E+00 |
| 121-14-2 | 2,4-Dinitrotoluene | 1.101E+00 | 1.592E-02 | 3.440E-01 | 2.643E+00 |
| 121-44-8 | Triethylamine | 3.877E-01 | 1.506E-02 | 3.435E-01 | 9.305E-01 |
| 122-39-4 | Diphenylamine | 9.323E-01 | 1.826E-01 | 4.645E-01 | 2.237E+00 |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | 3.275E-01 | 1.219E-03 | 3.341E-01 | 7.861E-01 |
| 126-73-8 | Tributyl Phosphate | 3.260E+00 | 1.401E-01 | 4.324E-01 | 7.824E+00 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 2.498E-01 | 5.908E-03 | 3.373E-01 | 5.995E-01 |
| 127-18-4 | Tetrachloroethylene | 8.923E-01 | 1.623E-01 | 4.491E-01 | 2.141E+00 |
| 129-00-0 | Pyrene | 1.427E+00 | 1.062E+00 | 1.224E+00 | 5.524E+00 |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 3.275E-01 | 5.571E-03 | 3.371E-01 | 7.861E-01 |
| 156-59-2 | cis-1,2-Dichloroethylene | 3.670E-01 | 2.904E-02 | 3.530E-01 | 8.809E-01 |
| 156-60-5 | trans-1,2-Dichloroethylene | 3.670E-01 | 4.119E-02 | 3.613E-01 | 8.809E-01 |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | 3.710E+00 | 7.590E+00 | 7.629E+00 | 1.662E+01 |
| 205-99-2 | Benzo[b]fluoranthene | 2.722E+00 | 2.442E+00 | 2.539E+00 | 1.130E+01 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 1.427E+00 | 1.625E+00 | 1.752E+00 | 5.711E+00 |
| 207-08-9 | Benzo[k]fluoranthene | 2.722E+00 | 4.033E+00 | 4.099E+00 | 1.176E+01 |
| 218-01-9 | Chrysene | 1.997E+00 | 3.314E+00 | 3.392E+00 | 8.504E+00 |
| 309-00-2 | Aldrin | 1.163E+01 | 2.054E+00 | 2.163E+00 | 4.752E+01 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 4.472E+00 | 7.874E-02 | 3.877E-01 | 1.073E+01 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 4.472E+00 | 7.638E-02 | 3.861E-01 | 1.073E+01 |
| 541-73-1 | 1,3-Dichlorobenzene | 6.999E-01 | 2.373E-01 | 5.067E-01 | 1.680E+00 |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 4.398E-01 | 3.357E-02 | 3.561E-01 | 1.056E+00 |
| 563-68-8 | Thallium Acetate | na | na | na | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | 5.635E-01 | 1.025E-02 | 3.402E-01 | 1.352E+00 |
| 1314-62-1 | Vanadium pentoxide | na | na | na | na |
| 1330-20-7 | Xylenes (mixtures) | 4.134E-01 | 1.831E-01 | 4.648E-01 | 9.922E-01 |
| 1336-36-3 | Polychlorinated Biphenyls | 4.539E+00 | 3.420E+00 | 3.495E+00 | 1.938E+01 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | 4.539E+00 | 3.420E+00 | 3.495E+00 | 1.938E+01 |
| 6533-73-9 | Thallium carbonate | na | na | na | na |
| 7429-90-5 | Aluminum | na | na | na | na |
| 7439-89-6 | Iron | na | na | na | na |

**Table A23a. Dermal Absorption Parameters for Organic Chemicals.**

| CASRN | Chemical Name | Lag Time ($T_{LAG}$) h/event | Permeability Ratio (B) | p | Time to Steady State ($T_{SS}$), h/event |
|---|---|---|---|---|---|
| 7439-93-2 | Lithium | na | na | na | na |
| 7439-96-5 | Manganese | na | na | na | na |
| 7439-97-6 | Mercury metal vapor | na | na | na | na |
| 7439-98-7 | Molybdenum | na | na | na | na |
| 7440-02-0 | Nickel (soluble salts) | na | na | na | na |
| 7440-22-4 | Silver | na | na | na | na |
| 7440-24-6 | Strontium, Stable | na | na | na | na |
| 7440-28-0 | Thallium metal | na | na | na | na |
| 7440-31-5 | Tin | na | na | na | na |
| 7440-36-0 | Antimony | na | na | na | na |
| 7440-38-2 | Arsenic (inorganic) | na | na | na | na |
| 7440-39-3 | Barium | na | na | na | na |
| 7440-41-7 | Beryllium and compounds | na | na | na | na |
| 7440-42-8 | Boron and borates only | na | na | na | na |
| 7440-43-9 | Cadmium | na | na | na | na |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | na | na | na | na |
| 7440-48-4 | Cobalt | na | na | na | na |
| 7440-50-8 | Copper | na | na | na | na |
| 7440-62-2 | Vanadium metal | na | na | na | na |
| 7440-66-6 | Zinc and compounds | na | na | na | na |
| 7446-18-6 | Thallium Sulfate | na | na | na | na |
| 7487-94-7 | Mercuric chloride | na | na | na | na |
| 7664-41-7 | Ammonia | 1.310E-01 | 2.480E-04 | 3.335E-01 | 3.144E-01 |
| 7723-14-0 | Phosphorus, white | na | na | na | na |
| 7782-41-4 | Fluorine (soluble fluoride) | na | na | na | na |
| 7782-49-2 | Selenium and compounds | na | na | na | na |
| 7791-12-0 | Thallium Chloride | na | na | na | na |
| 8001-35-2 | Toxaphene | 2.184E+01 | 3.898E-01 | 6.296E-01 | 5.241E+01 |
| 10102-45-1 | Thallium (I) Nitrate | na | na | na | na |
| 11096-82-5 | Aroclor 1260 | 1.721E+01 | 2.127E+01 | 2.129E+01 | 7.953E+01 |
| 11097-69-1 | Aroclor 1254 | 7.078E+00 | 4.958E+00 | 5.013E+00 | 3.100E+01 |
| 11104-28-2 | Aroclor 1221 | 1.198E+00 | 7.181E-01 | 9.121E-01 | 4.640E+00 |
| 11141-16-5 | Aroclor 1232 | 1.198E+00 | 7.181E-01 | 9.121E-01 | 4.640E+00 |
| 12672-29-6 | Aroclor 1248 | 4.539E+00 | 3.689E+00 | 3.761E+00 | 1.949E+01 |
| 12674-11-2 | Aroclor 1016 | 2.912E+00 | 1.809E+00 | 1.927E+00 | 1.176E+01 |
| 14797-55-8 | Nitrate | na | na | na | na |
| 14797-65-0 | Nitrite | na | na | na | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | na | na | na | na |
| 16984-48-8 | Fluorine anion | na | na | na | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | na | na | na | na |
| 22967-92-6 | Methyl Mercury | 1.696E+00 | 6.268E-04 | 3.338E-01 | 4.070E+00 |
| 53469-21-9 | Aroclor 1242 | 4.539E+00 | 3.420E+00 | 3.495E+00 | 1.938E+01 |
| na | Uranium (soluble salts) | na | na | na | na |

Note: "na" means the chemical is considered inorganic for the purposes of dermal absorption from aqueous solutions.

## A3.5 INTERNAL DOSE FACTORS FOR RADIONUCLIDES

To assist the reader in understanding the nomenclature surrounding radiation exposures, the adjectives in the table below add particular nuances to the word "dose". Note that all cases a radiation dose comes from either internal or external sources. Internal sources are inside the body, while external sources are outside the body.

| | |
|---|---|
| absorbed | The energy deposited by the radiation per unit mass of material (any material). |
| equivalent | Relates an absorbed dose in living organisms to some reference measure of biological effect. |
| committed | Infers that the dose is accumulated over a period of 50 years. A necessary condition is that the dose comes from internally deposited radionuclides. |
| effective | Infers that the dose is the weighted sum of organ doses. |
| total | Emphasizes that the dose includes both internal and external contributions. |

The quantity "absorbed dose" has units of gray (or rad), while the quantity "dose equivalent" has units of sievert (or rem). The "dose equivalent" or "equivalent dose" is the product of the "absorbed dose" and the appropriate "radiation weighting factor". The radiation weighting factors are independent of the tissue or organ under consideration, and also the biological endpoint. They only depend on something called the "linear energy transfer", which is the energy deposited in the tissue per unit length of travel of the radiation particle. The more energy deposited per unit length of travel, the greater the biological effect. Some ambiguity arises because there is a second set of scale factors that may be applied to the dose equivalent for an organ to relate the risk from the organ dose to the equivalent risk that accompanies a whole body dose of gamma rays. These scale factors are called "organ weighting factors".

The term "committed dose equivalent" (CDE) is the total dose equivalent received by an organ over a period of 50 years following an intake of radioactivity. The term "intake" refers to the amount inhaled or ingested or absorbed through the skin. The effect on the organ depends on both the total dose commitment and the rate at which the dose accumulates. For example, a CDE of 2 Sv (200 rem) received in a few days will likely impair the functioning of that organ, while a CDE of 2 Sv received over a period of several years would likely have no effect on the functioning of the organ. For either the acute or chronic dose there is a small chance that the affected organ may develop some type of cancer. The cancer risk depends on both the organ sensitivity and the magnitude of the CDE. There is also a dose rate effect, but this is normally not included when dealing with small radiation doses characteristic of environmental exposures.

Inhaled, ingested, or dermally absorbed radioactivity affects more than one organ. Not only is the activity transported by the blood to various organs, but photons emitted in one organ can give a dose to other organs. To describe the effect on the whole person, the term "committed effective dose equivalent" (CEDE) was created. The CEDE is the weighted sum of the committed dose equivalents to the various organs of the body following an intake of radioactivity. Thus, the CEDE relates the CDE calculated for the various organs to the overall risk of some "stochastic effect" (a genetic effect or cancer) on the person. The "organ weighting factors" mentioned earlier are used to calculate CEDE from the various organ CDEs.

The internal dose factors presented in this section specify the committed effective dose equivalent (CEDE) from a unit intake (ingested or inhaled) of a radionuclide. The dose is accumulated over a period of 50 years, known as the dose commitment period. This dose commitment period was set by the International Commission on Radiological Protection (ICRP) in Publication 26 (1977) when determining internal dose and relating it to an equivalent whole body exposure. It is still part of the current recommendations of the ICRP in Publication 61 (1990). It should be noted that the recommendations from 1977 have been superseded with better models for how the body retains internally deposited radionuclides.

If a nuclide has radioactive progeny with short half-lives, i.e., nuclides with a "+D" at the end of the name, then the internal dose factors for these progeny are included with the parent isotope. It is assumed that the progeny are in secular equilibrium with the parent nuclide. The internal dose factors for the progeny are multiplied by the branching ratio (see Table A1) and a decay half life factor, and added to the parent dose factor.

Four internal dose factor collections will be considered. The first was widely used in early performance assessments for the United States Department of Energy (DOE/EH-0071). The second was prepared under the sponsorship of the United States Environmental Protection Agency (EPA-520/1-88-020). This set is now recommended for use in performance assessments at DOE sites (DOE/LLW-93 and DOE M 435.1-1 Implementation Guide Chapter IV). The third was computed for the GENII software (PNNL-6584), which was often used at the Hanford Site. The GENII internal dose factors are based on the 1993 revision (WHC-SD-WM-TI-596). The fourth set of internal dose factors uses improved anatomical models and revised metabolic data adopted by the ICRP beginning in 1990. The summary compilation of internal dose factors for various age groups was released in ICRP Publication 72.

The internal dose factors from the first three collections (GENII, EPA, and DOE) are listed in Tables A24 (ingestion) and A25 (inhalation). The ICRP 72 internal dose factors for the average adult are shown in Table A26. The internal dose factors have been converted to the common units of mrem per pCi intake. For the ingestion dose factors, the assumed values for f1, which is the fraction of the activity ingested that enters body fluids is shown. For the inhalation dose factors, the assumed activity median aerodynamic diameter of the particles is 1 μm. The lung model category is shown in the tables. The "Water" for tritium stands for tritiated water vapor (HTO), and includes a 50 percent increase due to absorption through the skin. The "Organic" for C-14 means that the carbon is assumed to have an organic chemical form rather than gaseous. The "D", "W", and "Y" mean the material clears the lungs in a matter of days, weeks, or years, respectively. The improved lung model uses the designations "F", "M", and "S" which stand for fast, moderate, and slow. The chemical forms classified as "D", "W", or "Y" under the 1977 recommendations of the ICRP, have become "F", "M", or "S", respectively.

The assumed lung clearance rate for many of the radionuclides was changed to incorporate the recommendations of the ICRP in Report Number 71 (ICRP 1996). In Publication 71 the ICRP recommends default lung clearance types for particulate aerosols when no specific information is available. No recommendations were given for beryllium, silicon, titanium, vanadium, cadmium, indium, tin, promethium, gadolinium, rhenium, bismuth, actinium, or protactinium. For most of these elements, the solubility class with the largest inhalation dose factor was selected. The exceptions are described in the next paragraph.

Titanium has dose factors for all three lung clearance classes. Class Y has the largest inhalation dose factor and class W has the smallest. The slow (S or Y) lung clearance is only observed for one compound, $SrTiO_3$. Because this compound is unlikely to be found in Hanford tank waste, the titanium compounds were assumed to be class D. The worst lung class for actinium and protactinium is W (or M). However, class Y (or S) was chosen to be consistent with the selections made for the RAIS database for cancer morbidity factors. Class Y compounds of actinium and protactinium are oxides and hydroxides. The oxides are reasonably likely to be found in environmental media. Note that HNF-SD-WM-TI-707 Revision 4 used the worst-case class W for both elements. Hence, the inhalation dose factors for actinium and protactinium decrease about 30 percent in the current document.

Comparison ratios of the GENII and DOE dose factors divided by the EPA dose factors are shown in Tables A24 and A25. Dose factors that differ less than 10% from the EPA numbers are not shown in the ratio columns. The nuclides with differences greater than 30% are Co-60, Tc-97, Tc-99, Cd-109m+D, In-115, Re-187, Ra-228, and Bk-247.

The dose factor collection from the EPA (EPA-520/1-88-020) will be used in the tank waste PA. These have been used in previous performance assessments, and are approved by the DOE (DOE M 435.1-1). The difference between the GENII, EPA, and DOE internal dose factors is minor because they are all based on the methods given in ICRP 30. However, the difference between the EPA and the ICRP 72 internal dose factors is appreciable in some cases. The ratios between the EPA and ICRP 72 internal dose factors are shown in Table A26. It should be noted that the ICRP recommends using ICRP 72 rather than ICRP30 methods to estimate internal dose. ICRP 72 is the current technical standard for radiation protection purposes.

The internal dose factors for Nb-91 are not listed in any dose factor collection and were assumed bounded by the values for Nb-93m. Both nuclides emit low energy electrons and photons, as shown on the nuclear decay data summary of Table A27. For Nb-91, there is a continuous spectrum of low energy photons associated with the electron capture and positron decay. However, this continuous spectrum is a minor addition to the photon spectrum. The total electron plus photon energy for Nb-91 (15 keV) is less than that for Nb-93m (26 keV). Therefore, the internal dose factor for Nb-91 should be less than that for Nb-93m.

An additional consideration is the half-life of the two isotopes compared with expected residence times in the body. Inhalation class Y niobium is retained in the lungs for a considerable length of time. Most is removed during the first several years, but some is retained indefinitely. The organ with the largest dose for class Y Nb-93m is the lung. Most (87%) of the dose from Nb-93m accrues during the first 10 years after inhalation. Thus, the effect of Nb-93m's shorter half-life is small. It will be assumed that the internal dose factors for Nb-91 are bounded by those for Nb-93m.

In addition to Nb-91, the internal dose factors for Po-209 are not listed in any dose factor collection and were computed by comparison with Po-210. Corrections were made for the energy of the alpha particles emitted, and the decay half-life using the equation shown below.

$$\text{Dose Factor} \propto \frac{E_\alpha}{\lambda_{eff}}\left[1 - \text{Exp}\left(-\lambda_{eff} T_d\right)\right]$$

where

$E_\alpha$ = total alpha energy per decay. For Po-209 this is 4.866 Mev per decay, while for Po-210 this is 5.304 Mev per decay.

$\lambda_{eff}$ = effective removal constant, which combines both the biological elimination and the radioactive decay of the nuclide, i.e., $\lambda_{eff} = \lambda_{bio} + \lambda_{rad}$.

$T_d$ = dose commitment period used in the dose factor collections shown in Tables A24 and A25, namely, 50 years.

From ICRP 30, the biological removal half time for polonium is 50 days ($\lambda_{bio}$=Ln(2)/50d =0.01386 per day). The decay half-life of Po-209 is 102 year ($\lambda_{rad}$=Ln(2)/102y/365.25=0.00002 per day), thus its $\lambda_{eff}$ is 0.01388 per day. The decay half-life of Po-210 is 138.38 days ($\lambda_{rad}$=Ln(2)/138.38d=0.00501 per day), thus its $\lambda_{eff}$ is 0.01887 per day. Thus, the dose integration term in brackets is nearly equal to 1 after 50 years. The ratio of Po-209 to Po-210 internal dose factors is shown below. This ratio was applied to the Po-210 inhalation and ingestion dose factors to arrive at the Po-209 internal dose factors.

$$\frac{\text{Po - 209 Dose Factor}}{\text{Po - 210 Dose Factor}} = \frac{(4.866\ \text{MeV})(0.01887\ \text{per day})}{(5.304\ \text{MeV})(0.01388\ \text{per day})} = 1.247$$

Special groups of people such as children and diabetics, will have different internal dose factors due to differences in organ mass and retention times in the various tissues of the body. Internal dose factors for different age groups have been computed by the ICRP in Publication 72 (1996). Unit dose factors for individuals whose metabolic characteristics differ considerably from those of the reference individual will also differ from those presented in Tables A24 and A25. As explained in DOE M 435.1-1 Chapter IV, the use of dose factors for representative members of the public is desirable to avoid overly conservative results. A bounding case exposure scenario evaluates possible upper limits.

**Table A24. Ingestion Dose Factors, mrem/pCi Ingested.**

| Nuclide | f1 | DOE | GENII | EPA | DOE / EPA | GENII / EPA |
|---|---|---|---|---|---|---|
| H-3 | 1 | 6.30E-08 | 6.12E-08 | 6.40E-08 | | |
| Be-10 | 0.005 | 4.20E-06 | 4.70E-06 | 4.66E-06 | | |
| C-14 | 1 | 2.10E-06 | 2.06E-06 | 2.09E-06 | | |
| Na-22 | 1 | 1.20E-05 | 1.06E-05 | 1.15E-05 | | |
| Al-26 | 0.01 | 1.30E-05 | 1.42E-05 | 1.46E-05 | 0.89 | |
| Si-32+D | 0.01 | 9.40E-06 | 1.11E-05 | 1.10E-05 | 0.86 | |
| Cl-36 | 1 | 3.00E-06 | 2.95E-06 | 3.03E-06 | | |
| K-40 | 1 | 1.90E-05 | 1.79E-05 | 1.86E-05 | | |
| Ca-41 | 0.3 | 1.20E-06 | 1.20E-06 | 1.27E-06 | | |
| Ti-44+D | 0.01 | 2.04E-05 | 2.35E-05 | 2.46E-05 | 0.83 | |
| V-49 | 0.01 | 5.40E-08 | 6.04E-08 | 6.14E-08 | 0.88 | |
| Mn-53 | 0.1 | 9.90E-08 | 1.10E-07 | 1.08E-07 | | |
| Mn-54 | 0.1 | 2.70E-06 | 2.76E-06 | 2.77E-06 | | |
| Fe-55 | 0.1 | 5.80E-07 | 6.15E-07 | 6.07E-07 | | |
| Fe-60+D | 0.1 | 1.50E-04 | 1.50E-04 | 1.52E-04 | | |
| Co-60 | 0.3 | 2.60E-05 | 2.65E-05 | 2.69E-05 | | |
| Ni-59 | 0.05 | 2.00E-07 | 2.05E-07 | 2.10E-07 | | |
| Ni-63 | 0.05 | 5.40E-07 | 5.72E-07 | 5.77E-07 | | |
| Se-79 | 0.8 | 8.30E-06 | 8.33E-06 | 8.70E-06 | | |
| Rb-87 | 1 | 4.80E-06 | 4.73E-06 | 4.92E-06 | | |
| Sr-90+D | 0.3 | 1.40E-04 | 1.31E-04 | 1.53E-04 | | 0.85 |
| Zr-93 | 0.002 | 1.60E-06 | 1.64E-06 | 1.66E-06 | | |
| Nb-91 | 0.01 | 5.30E-07 | 5.05E-07 | 5.22E-07 | | |
| Nb-93m | 0.01 | 5.30E-07 | 5.05E-07 | 5.22E-07 | | |
| Nb-94 | 0.01 | 5.10E-06 | 7.25E-06 | 7.14E-06 | 0.71 | |
| Mo-93 | 0.8 | 1.30E-06 | 1.21E-06 | 1.35E-06 | | |
| Tc-97 | 0.8 | 1.50E-07 | 2.48E-07 | 1.71E-07 | 0.88 | 1.45 |
| Tc-99 | 0.8 | 1.30E-06 | 2.23E-06 | 1.46E-06 | 0.89 | 1.52 |
| Ru-106+D | 0.05 | 2.10E-05 | 2.73E-05 | 2.74E-05 | 0.77 | |
| Pd-107 | 0.005 | 1.40E-07 | 1.50E-07 | 1.49E-07 | | |
| Ag-108m+D | 0.05 | 7.50E-06 | 7.58E-06 | 7.62E-06 | | |
| Cd-109+D | 0.05 | 1.20E-05 | 2.44E-05 | 1.31E-05 | | 1.86 |
| Cd-113m | 0.05 | 1.50E-04 | 1.62E-04 | 1.61E-04 | | |
| In-115 | 0.02 | 1.40E-04 | 8.68E-05 | 1.58E-04 | 0.89 | 0.55 |
| Sn-121m+D | 0.02 | 1.99E-06 | 2.24E-06 | 2.25E-06 | 0.88 | |
| Sn-126+D | 0.02 | 1.83E-05 | 2.08E-05 | 2.10E-05 | 0.87 | |
| Sb-125 | 0.1 | 2.60E-06 | 2.83E-06 | 2.81E-06 | | |
| Te-125m | 0.2 | 3.40E-06 | 3.72E-06 | 3.67E-06 | | |
| I-129 | 1 | 2.80E-04 | 2.49E-04 | 2.76E-04 | | |
| Cs-134 | 1 | 7.40E-05 | 6.82E-05 | 7.33E-05 | | |

**Table A24. Ingestion Dose Factors, mrem/pCi Ingested.**

| Nuclide | f1 | DOE | GENII | EPA | DOE / EPA | GENII / EPA |
|---|---|---|---|---|---|---|
| Cs-135 | 1 | 7.10E-06 | 6.86E-06 | 7.07E-06 | | |
| Cs-137+D | 1 | 5.00E-05 | 4.74E-05 | 5.00E-05 | | |
| Ba-133 | 0.1 | 3.20E-06 | 3.05E-06 | 3.40E-06 | | 0.90 |
| Ce-144+D | 0.0003 | 2.01E-05 | 2.12E-05 | 2.11E-05 | | |
| Pm-147 | 0.0003 | 9.50E-07 | 1.06E-06 | 1.05E-06 | | |
| Sm-147 | 0.0003 | 1.80E-04 | 1.86E-04 | 1.85E-04 | | |
| Sm-151 | 0.0003 | 3.40E-07 | 3.87E-07 | 3.89E-07 | 0.88 | |
| Eu-150 | 0.001 | 6.20E-06 | 6.33E-06 | 6.36E-06 | | |
| Eu-152 | 0.001 | 6.00E-06 | 6.48E-06 | 6.48E-06 | | |
| Eu-154 | 0.001 | 9.10E-06 | 9.61E-06 | 9.55E-06 | | |
| Eu-155 | 0.001 | 1.30E-06 | 1.53E-06 | 1.53E-06 | 0.85 | |
| Gd-152 | 0.0003 | 1.50E-04 | 1.61E-04 | 1.61E-04 | | |
| Tb-157 | 0.0003 | 1.00E-07 | 1.25E-07 | 1.24E-07 | 0.81 | |
| Ho-166m | 0.0003 | 7.80E-06 | 8.13E-06 | 8.07E-06 | | |
| Re-187 | 0.8 | 8.30E-09 | 1.45E-08 | 9.51E-09 | 0.87 | 1.52 |
| Tl-204 | 1 | 3.20E-06 | 3.46E-06 | 3.36E-06 | | |
| Pb-205 | 0.2 | 1.50E-06 | 1.64E-06 | 1.63E-06 | | |
| Pb-210+D | 0.2 | 5.11E-03 | 5.40E-03 | 5.37E-03 | | |
| Bi-207 | 0.05 | 4.90E-06 | 5.49E-06 | 5.48E-06 | 0.89 | |
| Po-209 | 0.1 | 2.00E-03 | 2.39E-03 | 2.37E-03 | 0.84 | |
| Po-210 | 0.1 | 1.60E-03 | 1.90E-03 | 1.90E-03 | 0.84 | |
| Ra-226+D | 0.2 | 1.10E-03 | 9.51E-04 | 1.33E-03 | 0.83 | 0.72 |
| Ra-228+D | 0.2 | 1.20E-03 | 8.44E-04 | 1.44E-03 | 0.84 | 0.59 |
| Ac-227+D | 0.001 | 1.46E-02 | 1.44E-02 | 1.48E-02 | | |
| Th-228+D | 0.0002 | 7.54E-04 | 5.79E-04 | 8.11E-04 | | 0.71 |
| Th-229+D | 0.0002 | 3.91E-03 | 3.87E-03 | 4.03E-03 | | |
| Th-230 | 0.0002 | 5.30E-04 | 5.48E-04 | 5.48E-04 | | |
| Th-232 | 0.0002 | 2.80E-03 | 2.73E-03 | 2.73E-03 | | |
| Pa-231 | 0.001 | 1.10E-02 | 1.06E-02 | 1.06E-02 | | |
| U-232 | 0.05 | 1.30E-03 | 1.31E-03 | 1.31E-03 | | |
| U-233 | 0.05 | 2.70E-04 | 2.90E-04 | 2.89E-04 | | |
| U-234 | 0.05 | 2.60E-04 | 2.84E-04 | 2.83E-04 | | |
| U-235+D | 0.05 | 2.51E-04 | 2.67E-04 | 2.67E-04 | | |
| U-236 | 0.05 | 2.50E-04 | 2.69E-04 | 2.69E-04 | | |
| U-238+D | 0.05 | 2.43E-04 | 2.70E-04 | 2.68E-04 | | |
| Np-237+D | 0.001 | 3.90E-03 | 5.22E-03 | 4.44E-03 | 0.88 | 1.17 |
| Pu-236 | 0.001 | 1.30E-03 | 1.16E-03 | 1.17E-03 | 1.12 | |
| Pu-238 | 0.001 | 3.80E-03 | 3.19E-03 | 3.20E-03 | 1.19 | |
| Pu-239 | 0.001 | 4.30E-03 | 3.53E-03 | 3.54E-03 | 1.22 | |
| Pu-240 | 0.001 | 4.30E-03 | 3.53E-03 | 3.54E-03 | 1.22 | |
| Pu-241+D | 0.001 | 8.60E-05 | 6.79E-05 | 6.85E-05 | 1.26 | |

**Table A24. Ingestion Dose Factors, mrem/pCi Ingested.**

| Nuclide | f1 | DOE | GENII | EPA | DOE / EPA | GENII / EPA |
|---|---|---|---|---|---|---|
| Pu-242 | 0.001 | 4.10E-03 | 3.35E-03 | 3.36E-03 | 1.22 | |
| Pu-244+D | 0.001 | 4.00E-03 | 3.32E-03 | 3.32E-03 | 1.20 | |
| Am-241 | 0.001 | 4.50E-03 | 3.62E-03 | 3.64E-03 | 1.24 | |
| Am-242m+D | 0.001 | 4.20E-03 | 3.50E-03 | 3.52E-03 | 1.19 | |
| Am-243+D | 0.001 | 4.50E-03 | 3.62E-03 | 3.63E-03 | 1.24 | |
| Cm-242 | 0.001 | 1.10E-04 | 1.15E-04 | 1.15E-04 | | |
| Cm-243 | 0.001 | 2.90E-03 | 2.50E-03 | 2.51E-03 | 1.15 | |
| Cm-244 | 0.001 | 2.30E-03 | 2.01E-03 | 2.02E-03 | 1.14 | |
| Cm-245 | 0.001 | 4.50E-03 | 3.73E-03 | 3.74E-03 | 1.20 | |
| Cm-246 | 0.001 | 4.50E-03 | 3.70E-03 | 3.70E-03 | 1.22 | |
| Cm-247+D | 0.001 | 4.10E-03 | 3.40E-03 | 3.42E-03 | 1.20 | |
| Cm-248 | 0.001 | 1.60E-02 | 1.36E-02 | 1.36E-02 | 1.18 | |
| Cm-250+D | 0.001 | 7.77E-02 | 7.76E-02 | 7.77E-02 | | |
| Bk-247 | 0.001 | 2.30E-03 | 3.81E-03 | 4.70E-03 | 0.49 | 0.81 |
| Cf-248 | 0.001 | 2.80E-04 | 3.39E-04 | 3.34E-04 | 0.84 | |
| Cf-249 | 0.001 | 4.60E-03 | 4.75E-03 | 4.74E-03 | | |
| Cf-250 | 0.001 | 1.90E-03 | 2.13E-03 | 2.13E-03 | 0.89 | |
| Cf-251 | 0.001 | 4.60E-03 | 4.82E-03 | 4.85E-03 | | |
| Cf-252 | 0.001 | 9.40E-04 | 1.09E-03 | 1.08E-03 | 0.87 | |

Notes:

- GENII ingestion dose factors are based on the 1993 revision (WHC-SD-WM-TI-596). EPA ingestion dose factors from Federal Guidance Report Number 11, EPA-520/1-88-020, Sept 1988. DOE ingestion dose factors from DOE/EH-0071, (DE88-014297), July 1988. All doses are 50 year committed effective dose equivalent (CEDE).
- "f1" is the fraction of the ingested activity reaching body fluids.
- The short-lived radioactive progeny shown on Table A1 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been multiplied by the branching ratios in Table A1 and added to the parent dose factor to give the values shown.
- The last two columns show ratios of GENII and DOE ingestion dose factors to the EPA dose factors. Ratios of dose factors within 10% of the EPA value are not shown.

Absorption through the skin, and injection from an injury are not considered since they are not likely to add significantly to the doses computed in the intruder and irrigation scenarios. These may be computed using an internal dosimetry program such as CINDY (PNNL-7493). Values have been published (PNNL-10190) and are basically the ingestion dose factor divided by the internal transfer factor (f1).

Any special exposure pathways associated with extended dermal contact with contaminated soil or vegetation will require appropriate dermal absorption dose factors. Dermal absorption methods for radionuclides have been included in the MEPAS[1] program (PNNL-10523).

[1]MEPAS is a registered trademark of Battelle Memorial Institute.

**Table A25. Inhalation Dose Factors, mrem/pCi Inhaled.**

| Nuclide | Lung Model | DOE | GENII | EPA | DOE / EPA | GENII / EPA |
|---|---|---|---|---|---|---|
| H-3 | Water | 9.45E-08 | 9.02E-08 | 9.60E-08 | | |
| Be-10 | Y | 3.50E-04 | 3.54E-04 | 3.54E-04 | | |
| C-14 | Organic | 2.10E-06 | 2.06E-06 | 2.09E-06 | | |
| Na-22 | D | 8.00E-06 | 7.12E-06 | 7.66E-06 | | |
| Al-26 | W | 5.90E-05 | 6.95E-05 | 7.22E-05 | 0.82 | |
| Si-32+D | Y | 1.01E-03 | 1.02E-03 | 1.03E-03 | | |
| Cl-36 | W | 2.00E-05 | 2.21E-05 | 2.19E-05 | | |
| K-40 | D | 1.20E-05 | 1.19E-05 | 1.24E-05 | | |
| Ca-41 | W | 1.30E-06 | 1.29E-06 | 1.35E-06 | | |
| Ti-44+D | D | 4.50E-04 | 4.18E-04 | 4.52E-04 | | |
| V-49 | W | 2.80E-07 | 3.46E-07 | 3.45E-07 | 0.81 | |
| Mn-53 | W | 4.30E-07 | 5.00E-07 | 5.00E-07 | 0.86 | |
| Mn-54 | W | 6.40E-06 | 6.36E-06 | 6.70E-06 | | |
| Fe-55 | W | 1.20E-06 | 1.36E-06 | 1.34E-06 | | |
| Fe-60+D | W | 2.70E-04 | 2.67E-04 | 2.70E-04 | | |
| Co-60 | W | 3.00E-05 | 3.20E-05 | 3.31E-05 | | |
| Ni-59 | W | 7.00E-07 | 8.99E-07 | 9.18E-07 | 0.76 | |
| Ni-63 | W | 1.90E-06 | 2.30E-06 | 2.30E-06 | 0.83 | |
| Se-79 | D | 6.20E-06 | 6.13E-06 | 6.55E-06 | | |
| Rb-87 | D | 3.30E-06 | 3.18E-06 | 3.23E-06 | | |
| Sr-90+D | D | 2.37E-04 | 2.09E-04 | 2.47E-04 | | 0.85 |
| Zr-93 | W | 8.10E-05 | 8.16E-05 | 8.33E-05 | | |
| Nb-91 | W | 4.10E-06 | 2.88E-06 | 3.21E-06 | 1.28 | |
| Nb-93m | W | 4.10E-06 | 2.88E-06 | 3.21E-06 | 1.28 | |
| Nb-94 | W | 2.60E-05 | 3.38E-05 | 3.61E-05 | 0.72 | |
| Mo-93 | Y | 2.80E-05 | 2.80E-05 | 2.84E-05 | | |
| Tc-97 | W | 8.90E-07 | 1.07E-06 | 9.92E-07 | | |
| Tc-99 | W | 7.50E-06 | 9.00E-06 | 8.33E-06 | | |
| Ru-106+D | W | 9.30E-05 | 1.18E-04 | 1.18E-04 | 0.79 | |
| Pd-107 | Y | 1.30E-05 | 1.29E-05 | 1.28E-05 | | |
| Ag-108m+D | W | 1.90E-05 | 2.44E-05 | 2.53E-05 | 0.75 | |
| Cd-109+D | Y | 4.20E-05 | 8.40E-05 | 4.51E-05 | | 1.86 |
| Cd-113m | D | 1.40E-03 | 1.54E-03 | 1.53E-03 | | |
| In-115 | D | 3.40E-03 | 2.02E-03 | 3.74E-03 | | 0.54 |
| Sn-121m+D | W | 9.26E-06 | 1.18E-05 | 1.19E-05 | 0.78 | |
| Sn-126+D | W | 7.54E-05 | 1.00E-04 | 1.01E-04 | 0.75 | |
| Sb-125 | W | 9.80E-06 | 1.23E-05 | 1.22E-05 | 0.80 | |
| Te-125m | W | 6.70E-06 | 7.18E-06 | 7.29E-06 | | |
| I-129 | D | 1.80E-04 | 1.51E-04 | 1.74E-04 | | 0.87 |

**Table A25. Inhalation Dose Factors, mrem/pCi Inhaled.**

| Nuclide | Lung Model | DOE | GENII | EPA | DOE / EPA | GENII / EPA |
|---|---|---|---|---|---|---|
| Cs-134 | D | 4.70E-05 | 4.28E-05 | 4.63E-05 | | |
| Cs-135 | D | 4.50E-06 | 4.49E-06 | 4.55E-06 | | |
| Cs-137+D | D | 3.20E-05 | 2.98E-05 | 3.19E-05 | | |
| Ba-133 | D | 6.90E-06 | 6.01E-06 | 7.81E-06 | 0.88 | 0.77 |
| Ce-144+D | W | 1.90E-04 | 2.15E-04 | 2.16E-04 | 0.88 | |
| Pm-147 | Y | 3.40E-05 | 3.92E-05 | 3.92E-05 | 0.87 | |
| Sm-147 | W | 7.10E-02 | 7.48E-02 | 7.47E-02 | | |
| Sm-151 | W | 2.90E-05 | 3.01E-05 | 3.00E-05 | | |
| Eu-150 | W | 2.70E-04 | 2.50E-04 | 2.68E-04 | | |
| Eu-152 | W | 2.20E-04 | 2.11E-04 | 2.21E-04 | | |
| Eu-154 | W | 2.60E-04 | 2.78E-04 | 2.86E-04 | | |
| Eu-155 | W | 3.90E-05 | 4.12E-05 | 4.14E-05 | | |
| Gd-152 | D | 2.40E-01 | 2.44E-01 | 2.43E-01 | | |
| Tb-157 | W | 9.00E-06 | 9.19E-06 | 9.21E-06 | | |
| Ho-166m | W | 7.20E-04 | 7.46E-04 | 7.73E-04 | | |
| Re-187 | W | 4.90E-08 | 5.86E-08 | 5.44E-08 | | |
| Tl-204 | D | 2.30E-06 | 2.46E-06 | 2.41E-06 | | |
| Pb-205 | D | 3.70E-06 | 3.97E-06 | 3.92E-06 | | |
| Pb-210+D | D | 1.30E-02 | 1.37E-02 | 1.36E-02 | | |
| Bi-207 | W | 1.40E-05 | 1.96E-05 | 2.00E-05 | 0.70 | |
| Po-209 | W | 1.01E-02 | 1.15E-02 | 1.07E-02 | | |
| Po-210 | W | 8.10E-03 | 8.63E-03 | 8.58E-03 | | |
| Ra-226+D | W | 7.91E-03 | 8.21E-03 | 8.60E-03 | | |
| Ra-228+D | W | 4.29E-03 | 4.18E-03 | 4.86E-03 | 0.88 | 0.86 |
| Ac-227+D | Y | 1.22E+00 | 1.32E+00 | 1.31E+00 | | |
| Th-228+D | Y | 3.13E-01 | 3.47E-01 | 3.45E-01 | | |
| Th-229+D | Y | 1.72E+00 | 1.75E+00 | 1.74E+00 | | |
| Th-230 | Y | 2.60E-01 | 2.62E-01 | 2.62E-01 | | |
| Th-232 | Y | 1.10E+00 | 1.15E+00 | 1.15E+00 | | |
| Pa-231 | Y | 8.60E-01 | 8.60E-01 | 8.58E-01 | | |
| U-232 | W | 1.30E-02 | 1.52E-02 | 1.49E-02 | 0.87 | |
| U-233 | W | 7.10E-03 | 8.01E-03 | 7.99E-03 | 0.89 | |
| U-234 | W | 7.10E-03 | 7.99E-03 | 7.88E-03 | | |
| U-235+D | W | 6.70E-03 | 7.48E-03 | 7.29E-03 | | |
| U-236 | W | 6.70E-03 | 7.49E-03 | 7.44E-03 | | |
| U-238+D | W | 6.23E-03 | 7.03E-03 | 7.06E-03 | 0.88 | |
| Np-237+D | W | 4.90E-01 | 6.32E-01 | 5.40E-01 | | 1.17 |
| Pu-236 | W | 1.60E-01 | 1.45E-01 | 1.45E-01 | 1.11 | |
| Pu-238 | W | 4.60E-01 | 3.90E-01 | 3.92E-01 | 1.17 | |

**Table A25. Inhalation Dose Factors, mrem/pCi Inhaled.**

| Nuclide | Lung Model | DOE | GENII | EPA | DOE / EPA | GENII / EPA |
|---|---|---|---|---|---|---|
| Pu-239 | W | 5.10E-01 | 4.30E-01 | 4.29E-01 | 1.19 | |
| Pu-240 | W | 5.10E-01 | 4.30E-01 | 4.29E-01 | 1.19 | |
| Pu-241+D | W | 1.00E-02 | 8.17E-03 | 8.25E-03 | 1.21 | |
| Pu-242 | W | 4.80E-01 | 4.08E-01 | 4.11E-01 | 1.17 | |
| Pu-244+D | W | 4.80E-01 | 4.03E-01 | 4.03E-01 | 1.19 | |
| Am-241 | W | 5.20E-01 | 4.41E-01 | 4.44E-01 | 1.17 | |
| Am-242m+D | W | 5.10E-01 | 4.24E-01 | 4.26E-01 | 1.20 | |
| Am-243+D | W | 5.20E-01 | 4.41E-01 | 4.40E-01 | 1.18 | |
| Cm-242 | W | 1.70E-02 | 1.75E-02 | 1.73E-02 | | |
| Cm-243 | W | 3.50E-01 | 3.07E-01 | 3.07E-01 | 1.14 | |
| Cm-244 | W | 2.70E-01 | 2.48E-01 | 2.48E-01 | | |
| Cm-245 | W | 5.40E-01 | 4.55E-01 | 4.55E-01 | 1.19 | |
| Cm-246 | W | 5.40E-01 | 4.51E-01 | 4.51E-01 | 1.20 | |
| Cm-247+D | W | 4.90E-01 | 4.15E-01 | 4.14E-01 | 1.18 | |
| Cm-248 | W | 1.90E+00 | 1.65E+00 | 1.65E+00 | 1.15 | |
| Cm-250+D | W | 9.40E+00 | 9.43E+00 | 9.40E+00 | | |
| Bk-247 | W | 5.50E-01 | 4.65E-01 | 5.74E-01 | | 0.81 |
| Cf-248 | W | 3.80E-02 | 4.44E-02 | 4.44E-02 | 0.86 | |
| Cf-249 | W | 5.50E-01 | 5.77E-01 | 5.77E-01 | | |
| Cf-250 | W | 2.20E-01 | 2.63E-01 | 2.62E-01 | 0.84 | |
| Cf-251 | W | 5.60E-01 | 5.86E-01 | 5.88E-01 | | |
| Cf-252 | W | 1.20E-01 | 1.37E-01 | 1.37E-01 | 0.88 | |

Notes:

- The inhaled particulate is assumed to have an activity median aerodynamic diameter of 1 µm.
- GENII inhalation dose factors are based on the 1993 revision (WHC-SD-WM-TI-596). EPA inhalation dose factors from Federal Guidance Report Number 11, EPA-520/1-88-020, Sept 1988. DOE inhalation dose factors from DOE/EH-0071, (DE88-014297), July 1988. All doses are 50 year committed effective dose equivalent (CEDE).
- "Lung Model" refers to the ICRP 30 lung model classification, "Water" is water vapor (for which the inhalation dose factor has been increased by 50% to include absorption through the skin), "Organic" means organically bound carbon, "D" is days, "W" is weeks, and "Y" is years. The value shown are those recommended in ICRP Report Number 71 for unknown chemical types.
- The short-lived radioactive progeny shown on Table A1 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been multiplied by the branching ratios in Table A1 and added to the parent dose factor to give the values shown.
- The last two columns show ratios of GENII and DOE inhalation dose factors to the EPA dose factors. Ratios of dose factors within 10% of the EPA value are not shown.

**Table A26. Internal Dose Factors for Adults from ICRP 72, mrem/pCi.**

| Nuclide | f1 | Ingestion | EPA / ICRP 72 | Lung Model | Inhalation | EPA / ICRP 72 |
|---|---|---|---|---|---|---|
| H-3 | 1 | 6.66E-08 | | M | 1.67E-07 | 0.58 |
| Be-10 | 0.005 | 4.07E-06 | 1.15 | S | 1.30E-04 | 2.74 |
| C-14 | 1 | 2.15E-06 | | M | 7.40E-06 | 0.28 |
| Na-22 | 1 | 1.18E-05 | | F | 4.81E-06 | 1.59 |
| Al-26 | 0.01 | 1.30E-05 | 1.13 | M | 7.40E-05 | |
| Si-32+D | 0.01 | 1.10E-05 | | S | 4.20E-04 | 2.45 |
| Cl-36 | 1 | 3.44E-06 | 0.88 | M | 2.70E-05 | 0.81 |
| K-40 | 1 | 2.29E-05 | 0.81 | F | 7.77E-06 | 1.59 |
| Ca-41 | 0.3 | 7.03E-07 | 1.81 | M | 3.52E-07 | 3.83 |
| Ti-44+D | 0.01 | 2.28E-05 | | F | 2.26E-04 | 2.00 |
| V-49 | 0.01 | 6.66E-08 | | M | 1.26E-07 | 2.74 |
| Mn-53 | 0.1 | 1.11E-07 | | M | 2.00E-07 | 2.50 |
| Mn-54 | 0.1 | 2.63E-06 | | M | 5.55E-06 | 1.21 |
| Fe-55 | 0.1 | 1.22E-06 | 0.50 | M | 1.41E-06 | |
| Fe-60+D | 0.1 | 4.07E-04 | 0.37 | M | 5.18E-04 | 0.52 |
| Co-60 | 0.1 | 1.26E-05 | 2.14 | M | 3.70E-05 | 0.89 |
| Ni-59 | 0.05 | 2.33E-07 | | M | 4.81E-07 | 1.91 |
| Ni-63 | 0.05 | 5.55E-07 | | M | 1.78E-06 | 1.30 |
| Se-79 | 0.8 | 1.07E-05 | 0.81 | F | 4.07E-06 | 1.61 |
| Rb-87 | 1 | 5.55E-06 | 0.89 | F | 1.85E-06 | 1.75 |
| Sr-90+D | 0.3 | 1.14E-04 | 1.35 | M | 1.38E-04 | 1.79 |
| Zr-93 | 0.01 | 4.07E-06 | 0.41 | M | 3.70E-05 | 2.25 |
| Nb-91 | 0.01 | 4.44E-07 | 1.18 | M | 1.89E-06 | 1.70 |
| Nb-93m | 0.01 | 4.44E-07 | 1.18 | M | 1.89E-06 | 1.70 |
| Nb-94 | 0.01 | 6.29E-06 | 1.14 | M | 4.07E-05 | 0.89 |
| Mo-93 | 1 | 1.15E-05 | 0.12 | M | 2.18E-06 | 13.02 |
| Tc-97 | 0.5 | 2.52E-07 | 0.68 | M | 8.14E-07 | 1.22 |
| Tc-99 | 0.5 | 2.37E-06 | 0.62 | M | 1.48E-05 | 0.56 |
| Ru-106+D | 0.05 | 2.59E-05 | | M | 1.04E-04 | 1.14 |
| Pd-107 | 0.005 | 1.37E-07 | | S | 2.18E-06 | 5.85 |
| Ag-108m+D | 0.05 | 8.51E-06 | 0.90 | M | 2.74E-05 | |
| Cd-109+D | 0.05 | 7.40E-06 | 1.78 | S | 2.29E-05 | 1.97 |
| Cd-113m | 0.05 | 8.51E-05 | 1.89 | F | 4.07E-04 | 3.75 |
| In-115 | 0.02 | 1.18E-04 | 1.33 | F | 1.44E-03 | 2.59 |
| Sn-121m+D | 0.02 | 2.07E-06 | | M | 1.73E-05 | 0.69 |
| Sn-126+D | 0.02 | 1.88E-05 | 1.12 | M | 1.05E-04 | |
| Sb-125 | 0.1 | 4.07E-06 | 0.69 | M | 1.78E-05 | 0.69 |
| Te-125m | 0.3 | 3.22E-06 | 1.14 | M | 1.26E-05 | 0.58 |
| I-129 | 1 | 4.07E-04 | 0.68 | F | 1.33E-04 | 1.30 |

**Table A26. Internal Dose Factors for Adults from ICRP 72, mrem/pCi.**

| Nuclide | f1 | Ingestion | EPA / ICRP 72 | Lung Model | Inhalation | EPA / ICRP 72 |
|---|---|---|---|---|---|---|
| Cs-134 | 1 | 7.03E-05 | | F | 2.44E-05 | 1.89 |
| Cs-135 | 1 | 7.40E-06 | | F | 2.55E-06 | 1.78 |
| Cs-137+D | 1 | 4.81E-05 | | F | 1.70E-05 | 1.88 |
| Ba-133 | 0.2 | 5.55E-06 | 0.61 | M | 1.15E-05 | 0.68 |
| Ce-144+D | 0.0005 | 1.94E-05 | | M | 1.33E-04 | 1.62 |
| Pm-147 | 0.0005 | 9.62E-07 | | S | 1.81E-05 | 2.16 |
| Sm-147 | 0.0005 | 1.81E-04 | | M | 3.55E-02 | 2.10 |
| Sm-151 | 0.0005 | 3.63E-07 | | M | 1.48E-05 | 2.03 |
| Eu-150 | 0.0005 | 4.81E-06 | 1.32 | M | 1.96E-04 | 1.37 |
| Eu-152 | 0.0005 | 5.18E-06 | 1.25 | M | 1.55E-04 | 1.42 |
| Eu-154 | 0.0005 | 7.40E-06 | 1.29 | M | 1.96E-04 | 1.46 |
| Eu-155 | 0.0005 | 1.18E-06 | 1.29 | M | 2.55E-05 | 1.62 |
| Gd-152 | 0.0005 | 1.52E-04 | | F | 7.03E-02 | 3.46 |
| Tb-157 | 0.0005 | 1.26E-07 | | M | 4.44E-06 | 2.08 |
| Ho-166m | 0.0005 | 7.40E-06 | | M | 4.44E-04 | 1.74 |
| Re-187 | 0.8 | 1.89E-08 | 0.50 | M | 2.33E-08 | 2.33 |
| Tl-204 | 1 | 4.44E-06 | 0.76 | F | 1.44E-06 | 1.67 |
| Pb-205 | 0.2 | 1.04E-06 | 1.58 | M | 9.25E-07 | 4.24 |
| Pb-210+D | 0.2 | 2.56E-03 | 2.10 | M | 4.41E-03 | 3.08 |
| Bi-207 | 0.05 | 4.81E-06 | 1.14 | M | 2.07E-05 | |
| Po-209 | 0.5 | 5.54E-03 | 0.43 | M | 1.52E-02 | 0.70 |
| Po-210 | 0.5 | 4.44E-03 | 0.43 | M | 1.22E-02 | 0.70 |
| Ra-226+D | 0.2 | 1.04E-03 | 1.28 | M | 1.31E-02 | 0.66 |
| Ra-228+D | 0.2 | 2.55E-03 | 0.56 | M | 9.68E-03 | 0.50 |
| Ac-227+D | 0.0005 | 4.47E-03 | 3.30 | S | 3.35E-01 | 3.90 |
| Th-228+D | 0.0005 | 5.31E-04 | 1.53 | S | 1.61E-01 | 2.14 |
| Th-229+D | 0.0005 | 2.27E-03 | 1.77 | S | 3.23E-01 | 5.40 |
| Th-230 | 0.0005 | 7.77E-04 | 0.70 | S | 5.18E-02 | 5.05 |
| Th-232 | 0.0005 | 8.51E-04 | 3.21 | S | 9.25E-02 | 12.44 |
| Pa-231 | 0.0005 | 2.63E-03 | 4.03 | S | 1.26E-01 | 6.82 |
| U-232 | 0.02 | 1.22E-03 | | M | 2.89E-02 | 0.52 |
| U-233 | 0.02 | 1.89E-04 | 1.53 | M | 1.33E-02 | 0.60 |
| U-234 | 0.02 | 1.81E-04 | 1.56 | M | 1.30E-02 | 0.61 |
| U-235+D | 0.02 | 1.75E-04 | 1.53 | M | 1.15E-02 | 0.64 |
| U-236 | 0.02 | 1.74E-04 | 1.54 | M | 1.18E-02 | 0.63 |
| U-238+D | 0.02 | 1.79E-04 | 1.50 | M | 1.08E-02 | 0.66 |
| Np-237+D | 0.0005 | 4.10E-04 | 10.83 | M | 8.51E-02 | 6.35 |
| Pu-236 | 0.0005 | 3.22E-04 | 3.62 | M | 7.40E-02 | 1.96 |
| Pu-238 | 0.0005 | 8.51E-04 | 3.76 | M | 1.70E-01 | 2.30 |

**Table A26. Internal Dose Factors for Adults from ICRP 72, mrem/pCi.**

| Nuclide | f1 | Ingestion | EPA / ICRP 72 | Lung Model | Inhalation | EPA / ICRP 72 |
|---|---|---|---|---|---|---|
| Pu-239 | 0.0005 | 9.25E-04 | 3.82 | M | 1.85E-01 | 2.32 |
| Pu-240 | 0.0005 | 9.25E-04 | 3.82 | M | 1.85E-01 | 2.32 |
| Pu-241+D | 0.0005 | 1.78E-05 | 3.85 | M | 3.33E-03 | 2.48 |
| Pu-242 | 0.0005 | 8.88E-04 | 3.78 | M | 1.78E-01 | 2.31 |
| Pu-244+D | 0.0005 | 8.92E-04 | 3.73 | M | 1.74E-01 | 2.32 |
| Am-241 | 0.0005 | 7.40E-04 | 4.92 | M | 1.55E-01 | 2.86 |
| Am-242m+D | 0.0005 | 7.04E-04 | 4.99 | M | 1.37E-01 | 3.11 |
| Am-243+D | 0.0005 | 7.43E-04 | 4.88 | M | 1.52E-01 | 2.90 |
| Cm-242 | 0.0005 | 4.44E-05 | 2.58 | M | 1.92E-02 | |
| Cm-243 | 0.0005 | 5.55E-04 | 4.53 | M | 1.15E-01 | 2.68 |
| Cm-244 | 0.0005 | 4.44E-04 | 4.54 | M | 9.99E-02 | 2.48 |
| Cm-245 | 0.0005 | 7.77E-04 | 4.81 | M | 1.55E-01 | 2.93 |
| Cm-246 | 0.0005 | 7.77E-04 | 4.76 | M | 1.55E-01 | 2.90 |
| Cm-247+D | 0.0005 | 7.03E-04 | 4.86 | M | 1.44E-01 | 2.87 |
| Cm-248 | 0.0005 | 2.85E-03 | 4.78 | M | 5.55E-01 | 2.98 |
| Cm-250+D | 0.0005 | 1.63E-02 | 4.77 | M | 3.11E+00 | 3.02 |
| Bk-247 | 0.0005 | 1.30E-03 | 3.63 | M | 2.55E-01 | 2.25 |
| Cf-248 | 0.0005 | 1.04E-04 | 3.23 | M | 3.26E-02 | 1.36 |
| Cf-249 | 0.0005 | 1.30E-03 | 3.66 | M | 2.59E-01 | 2.23 |
| Cf-250 | 0.0005 | 5.92E-04 | 3.60 | M | 1.26E-01 | 2.08 |
| Cf-251 | 0.0005 | 1.33E-03 | 3.64 | M | 2.63E-01 | 2.24 |
| Cf-252 | 0.0005 | 3.33E-04 | 3.26 | M | 7.40E-02 | 1.85 |

Notes:

- The ingestion and inhalation doses are from ICRP Publication 72 for adults. All doses are 50 year committed effective dose equivalent. The inhalation dose factors assume the particle size distribution has an activity median aerodynamic diameter of 1 μm.
- "Lung Model" refers to the ICRP 66 lung model classification,"F" is fast, "M" is moderate, and "S" is slow absorption of inhaled particulate material into body fluids.
- The short-lived radioactive progeny shown on Table A1 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been multiplied by the branching ratios in Table A1 and added to the parent dose factor to give the values shown.
- The ratios of the EPA dose factors divided by the ICRP 72 dose factors are shown if the difference between them is greater than 10%.

**Table A27. Nuclear Decay Data for Nb-91 and Nb-93m.**

| Nb-91 (680 y) | Particle energy, keV | fraction of decays | Weighted energy, keV |
|---|---|---|---|
| electron capture | 1254.6 | 0.99836 | 417.51 |
| positron | 232.6 | 0.00164 | 0.13 |
| electron | 13.47 | 0.2348 | 3.16 |
| photon | 15.69 | 0.18319 | 2.87 |
| | 15.77 | 0.35027 | 5.52 |
| | 17.66 | 0.10136 | 1.79 |
| | 511 | 0.00328 | 1.68 |
| | | Total for electrons + photons: | 15 keV |
| **Nb-93m(16.13 y)** | **Particle energy, keV** | **fraction of decays** | **Weighted energy, keV** |
| isomeric transition | 30.77 | 1 | 30.77 |
| electron | 11.78 | 0.1440 | 1.70 |
| | 14.15 | 0.0365 | 0.52 |
| | 28.07 | 0.1340 | 3.76 |
| | 28.31 | 0.0262 | 0.74 |
| | 28.40 | 0.4710 | 13.38 |
| | 30.39 | 0.1360 | 4.13 |
| photon | 16.52 | 0.0310 | 0.51 |
| | 16.61 | 0.0590 | 0.98 |
| | 18.61 | 0.0175 | 0.33 |
| | 30.77 | 5.5 E-06 | 0.00 |
| | | Total for electrons + photons: | 26 keV |

Note: The last column shows the product of the particle energies and the fraction of decays with this energy particle. Although the Nb-93m half-life is short enough that the total retained in the body (and hence the dose) decreases partly by radioactive decay, its total electron plus positron energy is large enough to make up for the loss by decay. Data from ENDF/B-VI.

## A3.6 EXTERNAL DOSE-RATE FACTORS FOR RADIONUCLIDES

External dose-rate factors give the expected dose equivalent rate to an individual standing near radioactive contamination. The composition and shape of the contaminated region determines the dose equivalent rates at a given concentration in the medium. Four contaminated regions will be described in this section, a 15-cm soil layer, a large cloud of airborne activity, and at the surface of a body of water. The doses from external exposure with the radioactivity distributed in air or water will be shown to be negligible in comparison to the inhalation or ingestion dose that normally accompanies the external exposure.

### A3.6.1 External Dose-Rate Factors for Radionuclides in Surface Soil

To assist the reader in understanding the nomenclature surrounding radiation exposures, the term "external effective dose equivalent" (EEDE) will be defined and applied in a manner similar to "committed effective dose equivalent" (CEDE) from the previous section. Radiation sources outside the body give doses to various organs of the person. Each organ receives a different dose during the period that the exposure takes place. To describe the effect on the whole person, the term "external effective dose equivalent" (EEDE) will be used. The EEDE is the weighted sum of the external dose equivalents to the various organs of the body from a radiation source outside the body. The EEDE relates the external dose equivalent calculated for the various organs to the overall risk of some "stochastic effect" (a genetic effect or cancer) on the person. The "organ weighting factors" mentioned in the previous section are used to calculate EEDE from the various organ dose equivalents.

External dose rate factors specify the external effective dose equivalent (EEDE) rate from a particular distribution of the radioactivity around the person. Three often used distributions are (1) submersion in a contaminated atmospheric cloud, (2) immersion in contaminated water, and (3) standing above contaminated soil. For the present, the third external dose rate factor is most useful. The soil contamination is assumed uniformly spread over a very large area with a thickness of 15 cm (6 in.). The external dose rate factors have units of EEDE per unit area of contaminated soil. A large area is assumed so that the actual area doesn't matter. Once the contaminated area is larger than a few hundred square meters, the dose rate factors are independent of the area. The thickness of the contaminated layer affects the dose rate and must be considered. For typical exposure scenarios the soil thickness is 15 cm. Radionuclides are assumed to be uniformly distributed through this thickness as a result of cultivating the soil for the purpose of growing a garden.

External dose rates from a layer of contaminated surface soil are available from various references. Three references that have been used on the Hanford Site are the DOE surface gamma dose-rate conversion factors (DOE/EH-0070), the EPA values in Federal Guidance Report Number 12 (EPA-402-R-93-081), and the external dose factors recently computed for the GENII program. The three sets of external dose rate factors are shown in Table A28. They have been converted to the common units of mrem/hour per $Ci/m^2$ for purposes of comparison.

The DOE surface gamma conversion factors (DOE/EH-0070) are derived from an assumed contamination thickness of zero. The contamination lies on top of the soil surface in a

layer that is infinitely thin, perfectly flat, and infinite in extent. These assumptions necessarily exaggerate the dose rates. Strong beta-emitting nuclides such as Sr-90 produce no external dose since the production of bremsstrahlung radiation was ignored.

The GENII external dose rate factors (PNNL-6584) were computed using a version of the ISOSHLD program known as EXTDF, which is part of the GENII software package. Bremsstrahlung radiation is computed for all beta emitters. The dose rate factors are calculated 1 m above a contamination thickness of 0.05 m and 0.15 m. The surface soil is given a density of 1.5 grams per cubic centimeter. Again the surface layer is perfectly flat and infinite in extent. The finite thickness adds realism, since the contamination thickness assumed for the well-driller (0.05 m) is increased to 0.15 m during normal tilling operations that are part of the post-drilling scenarios. The 0.15-m dose rate factors have been used in prior Hanford Site performance assessments.

The EPA external dose rate factors (EPA-402-R-93-081) were computed using a Monte Carlo approach with the best available input data and dosimetric models, except that ICRP 30 organ weighting factors rather than ICRP 60 weighting factors were used. The EPA external dose rate factors also include exposure to the skin using a weighting factor of 0.01. These are considered to be the best external dose rate factors currently available and will be used in the tank waste PA. The EPA values shown in Table A28 are for a soil contamination thickness of 5 cm and 15 cm. The number shown for Eu-150 is listed as Eu-150b in the EPA compilation. The reference does not give values for Nb-91 and Po-210. Therefore, the values computed by EXTDF were used instead.

The GENII and EPA external dose rate factors are available as dose rate per unit concentration in the soil. The unit concentration was converted to a unit area by multiplying by the contamination thickness. The DOE dose rate factors are already in area units. Note that the EPA dose rate factors were developed for a soil density of 1.6 g/cc. However, the tank waste PA will use a soil density for the surface layer of 1.5 g/cc. Therefore, the EPA dose rate factors were multiplied by the ratio of densities (1.067) to give the values shown on Table A28.

The three external dose factor collections are compared in Table A28. What is shown on this table are ratios of the GENII (15 cm) and DOE collections divided by the EPA (15 cm) collection. Differences less than 10 percent are not shown. Ratios for dose rate factors that are zero were not computed.

The GENII external dose rate factors agree fairly well (within 27%) for nuclides that emit penetrating gamma rays and have the largest dose rate factors. Examples are Na-22, Al-26, Ti-44, Mn-54, Fe-60, Co-60, Nb-94, Ag-108m, Sn-126, Cs-134, Cs-137, Eu-150, Eu-152, Eu-154, Ho-166m, Bi-207, Ra-226, Ra-228, and Th-228. The disagreement between GENII and the EPA collections is over the low energy photon emitters. However, for these nuclides the internal doses are typically much greater than the external, so the different external dose rate factors would not affect the total doses.

**Table A28. External Dose Rate Factors, mrem/h per Ci/m$^2$.**

| Nuclide | DOE (thin layer) | GENII using EXTDF | | EPA Federal Guidance Report 12 | | DOE / EPA | | GENII / EPA | |
|---|---|---|---|---|---|---|---|---|---|
| | | 5 cm | 15 cm | 5 cm | 15 cm | 5 cm | 15 cm | 5 cm | 15 cm |
| H-3 | 0 | 1.05E-07 | 3.49E-08 | 0 | 0 | | | EPA=0 | EPA=0 |
| Be-10 | 0 | 1.06E+00 | 4.33E-01 | 1.26E+00 | 5.37E-01 | DOE=0 | DOE=0 | 0.841 | 0.807 |
| C-14 | 0 | 2.16E-02 | 7.51E-03 | 1.92E-02 | 6.82E-03 | DOE=0 | DOE=0 | 1.12 | |
| Na-22 | 2.40E+04 | 1.22E+04 | 6.75E+03 | 1.12E+04 | 5.98E+03 | 2.13 | 4.01 | | 1.13 |
| Al-26 | 2.85E+04 | 1.60E+04 | 9.15E+03 | 1.35E+04 | 7.32E+03 | 2.12 | 3.89 | 1.18 | 1.25 |
| Si-32+D | 0 | 2.03E+01 | 9.62E+00 | 1.22E+01 | 5.70E+00 | DOE=0 | DOE=0 | 1.67 | 1.69 |
| Cl-36 | 5.32E-04 | 2.03E+00 | 8.58E-01 | 2.52E+00 | 1.16E+00 | 2.1E-04 | 4.6E-04 | 0.804 | 0.742 |
| K-40 | 1.56E+03 | 8.53E+02 | 4.87E+02 | 7.90E+02 | 4.33E+02 | 1.98 | 3.61 | | 1.12 |
| Ca-41 | 2.35E-01 | 0 | 0 | 0 | 0 | EPA=0 | EPA=0 | | |
| Ti-44+D | 2.57E+04 | 1.30E+04 | 7.07E+03 | 1.15E+04 | 6.00E+03 | 2.24 | 4.28 | 1.13 | 1.18 |
| V-49 | 8.60E-01 | 0 | 0 | 0 | 0 | EPA=0 | EPA=0 | | |
| Mn-53 | 1.80E+00 | 2.90E-01 | 9.68E-02 | 0 | 0 | EPA=0 | EPA=0 | EPA=0 | EPA=0 |
| Mn-54 | 9.59E+03 | 4.64E+03 | 2.52E+03 | 4.29E+03 | 2.27E+03 | 2.24 | 4.22 | | 1.11 |
| Fe-55 | 2.52E+00 | 3.22E-01 | 1.07E-01 | 0 | 0 | EPA=0 | EPA=0 | EPA=0 | EPA=0 |
| Fe-60+D | 5.40E+01 | 2.14E+01 | 1.10E+01 | 2.06E+01 | 1.05E+01 | 2.62 | 5.13 | | |
| Co-60 | 2.59E+04 | 1.33E+04 | 7.51E+03 | 1.26E+04 | 6.87E+03 | 2.05 | 3.77 | | |
| Ni-59 | 4.75E+00 | 3.92E-01 | 1.31E-01 | 0 | 0 | EPA=0 | EPA=0 | EPA=0 | EPA=0 |
| Ni-63 | 0 | 5.71E-04 | 1.91E-04 | 0 | 0 | | | EPA=0 | EPA=0 |
| Se-79 | 0 | 1.55E-02 | 5.35E-03 | 2.64E-02 | 9.44E-03 | DOE=0 | DOE=0 | 0.588 | 0.567 |
| Rb-87 | 0 | 1.08E-01 | 4.02E-02 | 1.84E-01 | 7.13E-02 | DOE=0 | DOE=0 | 0.588 | 0.565 |
| Sr-90+D | 0 | 4.08E+01 | 1.97E+01 | 2.45E+01 | 1.17E+01 | DOE=0 | DOE=0 | 1.67 | 1.68 |
| Zr-93 | 0 | 4.02E-04 | 1.34E-04 | 0 | 0 | | | EPA=0 | EPA=0 |
| Nb-91 | 8.36E+01 | 1.09E+01 | 5.74E+00 | 1.09E+01 | 5.74E+00 | 7.68 | 14.6 | | |
| Nb-93m | 1.17E+01 | 1.30E-01 | 4.33E-02 | 1.58E-01 | 5.28E-02 | 74.2 | 223 | 0.821 | 0.821 |
| Nb-94 | 1.81E+04 | 8.61E+03 | 4.67E+03 | 8.13E+03 | 4.29E+03 | 2.23 | 4.23 | | |
| Mo-93 | 6.59E+01 | 7.29E-01 | 2.43E-01 | 8.98E-01 | 2.99E-01 | 73.4 | 220 | 0.811 | 0.811 |
| Tc-97 | 7.28E+01 | 7.60E-01 | 2.53E-01 | 1.23E+00 | 4.10E-01 | 59.1 | 177 | 0.617 | 0.617 |
| Tc-99 | 7.14E-03 | 1.35E-01 | 5.04E-02 | 1.63E-01 | 6.35E-02 | 0.044 | 0.112 | 0.828 | 0.793 |
| Ru-106+D | 2.40E+03 | 1.36E+03 | 7.32E+02 | 1.12E+03 | 5.83E+02 | 2.14 | 4.11 | 1.22 | 1.26 |
| Pd-107 | 0 | 1.25E-05 | 4.16E-06 | 0 | 0 | | | EPA=0 | EPA=0 |
| Ag-108m+D | 1.90E+04 | 1.00E+04 | 5.37E+03 | 8.39E+03 | 4.37E+03 | 2.26 | 4.33 | 1.2 | 1.23 |
| Cd-109+D | 2.10E+02 | 2.13E+01 | 7.65E+00 | 3.47E+01 | 1.35E+01 | 6.05 | 15.6 | 0.613 | 0.568 |
| Cd-113m | 0 | 1.05E+00 | 4.28E-01 | 7.70E-01 | 3.24E-01 | DOE=0 | DOE=0 | 1.36 | 1.32 |
| In-115 | 0 | 6.38E-01 | 2.56E-01 | 4.89E-01 | 2.01E-01 | DOE=0 | DOE=0 | 1.31 | 1.27 |
| Sn-121m+D | 0 | 3.12E+00 | 1.05E+00 | 3.18E+00 | 1.07E+00 | DOE=0 | DOE=0 | | |
| Sn-126+D | 2.37E+04 | 1.22E+04 | 6.56E+03 | 1.03E+04 | 5.36E+03 | 2.3 | 4.42 | 1.19 | 1.22 |
| Sb-125 | 5.05E+03 | 2.78E+03 | 1.49E+03 | 2.18E+03 | 1.12E+03 | 2.32 | 4.52 | 1.28 | 1.33 |
| Te-125m | 2.40E+02 | 2.58E+01 | 8.75E+00 | 2.27E+01 | 7.67E+00 | 10.6 | 31.2 | 1.14 | 1.14 |
| I-129 | 2.51E+02 | 1.66E+01 | 5.54E+00 | 1.97E+01 | 6.57E+00 | 12.8 | 38.2 | 0.845 | 0.844 |
| Cs-134 | 1.80E+04 | 9.71E+03 | 5.23E+03 | 8.04E+03 | 4.24E+03 | 2.24 | 4.26 | 1.21 | 1.24 |

**Table A28. External Dose Rate Factors, mrem/h per Ci/m$^2$.**

| Nuclide | DOE (thin layer) | GENII using EXTDF | | EPA Federal Guidance Report 12 | | DOE / EPA | | GENII / EPA | |
|---|---|---|---|---|---|---|---|---|---|
| | | 5 cm | 15 cm | 5 cm | 15 cm | 5 cm | 15 cm | 5 cm | 15 cm |
| Cs-135 | 0 | 4.09E-02 | 1.46E-02 | 5.26E-02 | 1.94E-02 | DOE=0 | DOE=0 | 0.779 | 0.75 |
| Cs-137+D | 6.58E+03 | 3.39E+03 | 1.82E+03 | 2.93E+03 | 1.53E+03 | 2.25 | 4.3 | 1.16 | 1.19 |
| Ba-133 | 4.78E+03 | 2.15E+03 | 1.10E+03 | 1.89E+03 | 9.36E+02 | 2.53 | 5.11 | 1.14 | 1.18 |
| Ce-144+D | 5.88E+02 | 3.17E+02 | 1.64E+02 | 2.81E+02 | 1.43E+02 | 2.09 | 4.11 | 1.13 | 1.15 |
| Pm-147 | 4.68E-02 | 7.30E-02 | 2.74E-02 | 6.51E-02 | 2.53E-02 | 0.719 | 1.85 | 1.12 | |
| Sm-147 | 0 | 0 | 0 | 0 | 0 | | | | |
| Sm-151 | 5.93E-02 | 5.85E-03 | 1.95E-03 | 1.50E-03 | 4.99E-04 | 39.6 | 119 | 3.91 | 3.91 |
| Eu-150 | 0 | 9.37E+03 | 5.04E+03 | 7.65E+03 | 3.96E+03 | DOE=0 | DOE=0 | 1.23 | 1.27 |
| Eu-152 | 1.27E+04 | 6.52E+03 | 3.57E+03 | 5.77E+03 | 3.05E+03 | 2.19 | 4.15 | 1.13 | 1.17 |
| Eu-154 | 1.38E+04 | 6.80E+03 | 3.74E+03 | 6.28E+03 | 3.34E+03 | 2.2 | 4.14 | | 1.12 |
| Eu-155 | 8.16E+02 | 2.19E+02 | 8.98E+01 | 2.26E+02 | 9.24E+01 | 3.61 | 8.83 | | |
| Gd-152 | 0 | 0 | 0 | 0 | 0 | | | | |
| Tb-157 | 5.36E+01 | 6.71E+00 | 2.25E+00 | 4.35E+00 | 1.47E+00 | 12.3 | 36.5 | 1.54 | 1.53 |
| Ho-166m | 1.88E+04 | 8.78E+03 | 4.67E+03 | 8.95E+03 | 4.64E+03 | 2.1 | 4.05 | | |
| Re-187 | 0 | 0 | 0 | 0 | 0 | | | | |
| Tl-204 | 1.48E+01 | 4.85E+00 | 1.93E+00 | 5.14E+00 | 2.04E+00 | 2.88 | 7.28 | | |
| Pb-205 | 8.61E+00 | 2.63E-01 | 8.75E-02 | 1.07E-02 | 3.58E-03 | 802 | 2405 | 24.4 | 24.4 |
| Pb-210+D | 3.42E+01 | 9.36E+00 | 3.85E+00 | 7.59E+00 | 3.00E+00 | 4.51 | 11.4 | 1.23 | 1.28 |
| Bi-207 | 1.72E+04 | 8.95E+03 | 4.92E+03 | 7.79E+03 | 4.11E+03 | 2.21 | 4.19 | 1.15 | 1.2 |
| Po-209 | 4.10E+01 | 1.72E+01 | 8.95E+00 | 1.72E+01 | 8.95E+00 | 2.38 | 4.58 | | |
| Po-210 | 9.81E-02 | 4.92E-02 | 2.67E-02 | 4.38E-02 | 2.32E-02 | 2.24 | 4.23 | 1.12 | 1.15 |
| Ra-226+D | 1.92E+04 | 1.01E+04 | 5.61E+03 | 8.92E+03 | 4.78E+03 | 2.16 | 4.02 | 1.13 | 1.17 |
| Ra-228+D | 1.04E+04 | 5.48E+03 | 3.04E+03 | 4.92E+03 | 2.62E+03 | 2.11 | 3.97 | 1.11 | 1.16 |
| Ac-227+D | 5.00E+03 | 2.16E+03 | 1.08E+03 | 1.96E+03 | 9.61E+02 | 2.55 | 5.2 | | 1.12 |
| Th-228+D | 1.66E+04 | 8.65E+03 | 4.92E+03 | 7.69E+03 | 4.20E+03 | 2.16 | 3.95 | 1.12 | 1.17 |
| Th-229+D | 4.09E+03 | 1.78E+03 | 9.04E+02 | 1.52E+03 | 7.44E+02 | 2.69 | 5.49 | 1.17 | 1.21 |
| Th-230 | 1.03E+01 | 1.06E+00 | 4.11E-01 | 1.48E+00 | 6.05E-01 | 6.97 | 17.1 | 0.717 | 0.679 |
| Th-232 | 7.60E+00 | 5.61E-01 | 2.13E-01 | 6.71E-01 | 2.63E-01 | 11.3 | 28.8 | 0.836 | 0.81 |
| Pa-231 | 4.08E+02 | 1.80E+02 | 9.09E+01 | 1.84E+02 | 9.11E+01 | 2.22 | 4.48 | | |
| U-232 | 1.17E+01 | 7.99E-01 | 3.10E-01 | 1.10E+00 | 4.52E-01 | 10.7 | 26 | 0.727 | 0.685 |
| U-233 | 5.70E+00 | 1.13E+00 | 4.78E-01 | 1.51E+00 | 6.86E-01 | 3.79 | 8.31 | 0.751 | 0.697 |
| U-234 | 9.21E+00 | 4.93E-01 | 1.89E-01 | 5.17E-01 | 2.03E-01 | 17.8 | 45.4 | | |
| U-235+D | 2.17E+03 | 5.83E+02 | 2.52E+02 | 7.98E+02 | 3.74E+02 | 2.72 | 5.8 | 0.73 | 0.675 |
| U-236 | 8.36E+00 | 2.81E-01 | 9.85E-02 | 2.87E-01 | 1.08E-01 | 29.1 | 77.4 | | |
| U-238+D | 2.87E+02 | 1.42E+02 | 7.28E+01 | 1.23E+02 | 6.02E+01 | 2.34 | 4.77 | 1.16 | 1.21 |
| Np-237+D | 3.06E+03 | 1.41E+03 | 7.13E+02 | 1.09E+03 | 5.28E+02 | 2.8 | 5.8 | 1.3 | 1.35 |
| Pu-236 | 1.13E+01 | 2.74E-01 | 9.45E-02 | 3.13E-01 | 1.14E-01 | 36.2 | 99.5 | 0.875 | 0.832 |
| Pu-238 | 9.79E+00 | 3.10E-01 | 1.06E-01 | 2.16E-01 | 7.65E-02 | 45.3 | 128 | 1.43 | 1.39 |
| Pu-239 | 4.31E+00 | 3.51E-01 | 1.59E-01 | 3.27E-01 | 1.44E-01 | 13.2 | 29.9 | | |
| Pu-240 | 9.35E+00 | 2.05E-01 | 7.29E-02 | 2.11E-01 | 7.43E-02 | 44.2 | 126 | | |

**Table A28. External Dose Rate Factors, mrem/h per Ci/m$^2$.**

| Nuclide | DOE (thin layer) | GENII using EXTDF | | EPA Federal Guidance Report 12 | | DOE / EPA | | GENII / EPA | |
|---|---|---|---|---|---|---|---|---|---|
| | | 5 cm | 15 cm | 5 cm | 15 cm | 5 cm | 15 cm | 5 cm | 15 cm |
| Pu-241+D | 4.60E-02 | 2.21E-02 | 9.76E-03 | 2.17E-02 | 9.58E-03 | 2.12 | 4.8 | | |
| Pu-242 | 7.78E+00 | 2.73E-01 | 9.57E-02 | 1.83E-01 | 6.49E-02 | 42.6 | 120 | 1.49 | 1.47 |
| Pu-244+D | 3.86E+03 | 2.16E+03 | 1.17E+03 | 1.72E+03 | 9.04E+02 | 2.24 | 4.27 | 1.25 | 1.29 |
| Am-241 | 3.41E+02 | 4.18E+01 | 1.45E+01 | 6.20E+01 | 2.22E+01 | 5.5 | 15.4 | 0.674 | 0.654 |
| Am-242m+D | 2.66E+02 | 7.97E+01 | 3.58E+01 | 7.33E+01 | 3.28E+01 | 3.63 | 8.11 | | |
| Am-243+D | 2.94E+03 | 1.01E+03 | 4.49E+02 | 9.80E+02 | 4.42E+02 | 3 | 6.67 | | |
| Cm-242 | 1.07E+01 | 1.77E-01 | 5.97E-02 | 2.44E-01 | 8.59E-02 | 43.6 | 124 | 0.725 | 0.694 |
| Cm-243 | 1.67E+03 | 6.34E+02 | 2.90E+02 | 6.08E+02 | 2.86E+02 | 2.74 | 5.82 | | |
| Cm-244 | 9.46E+00 | 1.51E-01 | 5.09E-02 | 1.92E-01 | 6.39E-02 | 49.4 | 148 | 0.789 | 0.798 |
| Cm-245 | 9.74E+02 | 3.11E+02 | 1.32E+02 | 3.89E+02 | 1.71E+02 | 2.5 | 5.71 | 0.798 | 0.775 |
| Cm-246 | 8.37E+00 | 1.26E-01 | 4.19E-02 | 1.77E-01 | 5.89E-02 | 47.4 | 142 | 0.713 | 0.711 |
| Cm-247+D | 4.16E+03 | 2.44E+03 | 1.30E+03 | 1.74E+03 | 8.74E+02 | 2.4 | 4.76 | 1.41 | 1.49 |
| Cm-248 | 6.71E+00 | 1.14E-01 | 3.83E-02 | 1.34E-01 | 4.45E-02 | 50.2 | 151 | 0.853 | 0.859 |
| Cm-250+D | 2.96E+03 | 1.45E+03 | 8.02E+02 | 1.40E+03 | 7.41E+02 | 2.11 | 3.99 | | |
| Bk-247 | 0 | 5.01E+02 | 2.32E+02 | 4.72E+02 | 2.14E+02 | DOE=0 | DOE=0 | | |
| Cf-248 | 7.68E+00 | 1.03E-01 | 3.43E-02 | 1.90E-01 | 6.32E-02 | 40.5 | 121 | 0.543 | 0.543 |
| Cf-249 | 4.02E+03 | 1.89E+03 | 9.79E+02 | 1.72E+03 | 8.71E+02 | 2.33 | 4.61 | | 1.12 |
| Cf-250 | 7.81E+00 | 1.53E-01 | 5.37E-02 | 1.80E-01 | 6.01E-02 | 43.4 | 130 | 0.848 | 0.895 |
| Cf-251 | 1.55E+03 | 5.46E+02 | 2.40E+02 | 5.68E+02 | 2.62E+02 | 2.73 | 5.93 | | |
| Cf-252 | 7.23E+00 | 1.24E-01 | 4.25E-02 | 2.46E-01 | 8.91E-02 | 29.4 | 81.2 | 0.505 | 0.477 |

Notes:

- GENII external dose rate factors were computed using the EXTDF program. EPA external dose rate factors are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). DOE external dose rate factors are from DOE/EH-0070 (July 1988). All are effective dose equivalent from radiation sources outside the body.
- Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide.
- The conversion to area units from volume units assumes a thickness of 0.05 m or 0.15 m. The density correction applied to the EPA (1993) dose rate factors is 1.067. Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used.
- The last two columns show ratios of GENII (0.15 m) and DOE external dose rate factors to the EPA (0.15 m) dose rate factors. Ratios within 10% of the EPA value are not shown.

In general, the DOE external dose rate factors are larger than the 15-cm EPA dose rate factors by more than a factor of 4. The exceptions (Be-10, C-14, Si-32, Cl-36, Se-79, Rb-87, Sr-90, Tc-99, Cd-113m, In-115, Sn-121m, Cs-135, and Pm-147) are for nuclides, which produce most of their photons through bremsstrahlung. For these nuclides, the DOE external dose rate factors are much too small. The 5-cm EPA dose rate factors are closer to DOE numbers due to the thinner source.

In all three references used in Table A28 the dose rates were computed at a height of 1 meter above the soil. The actual height has little effect on the dose rate. Table A29 demonstrates this by comparing dose rate factors computed by the EXTDF program at 100 cm and 10 cm. The table shows the ratios of the 10 cm dose rate divided by the 100 cm dose rate for nuclides where the difference between dose rate factors was greater than 10 percent. It must be

noted that all these nuclides have external dose rates that are insignificant compared with the internal. The exclusively low energy photons emitted by these nuclides are noticeably attenuated by the additional 90 cm of air.

Some of the external exposure pathways noted in Table 3 for the low water infiltration case are much smaller than internal pathways that accompany the external exposure. For example, the external exposure to an individual whose livestock drinks contaminated well water is much smaller than the internal dose resulting from the consumption of the animal products (milk, meat, poultry, and eggs). This follows from the observation that the dose resulting from a given amount of radioactivity outside the body (leading to an external dose) is orders of magnitude lower than the dose resulting from the same amount of radioactivity ingested or inhaled (leading to an internal dose). Admittedly, the individual will not eat all of the radioactivity present in an animal, since the radioactivity will be present in organs and tissues that are not normally eaten. However, the use of all four animal pathways combined with the observation that the individual is in close proximity to the animal for only short periods during the day gives assurance that this external pathway can be ignored.

**Table A29. Ratios of Dose Rate Factors at Two Elevations.**

| Nuclide | Ratio | | Nuclide | Ratio |
|---|---|---|---|---|
| H-3 | 1.61 | | U-234 | 1.16 |
| Mn-53 | 1.61 | | U-236 | 1.26 |
| Fe-55 | 1.61 | | Pu-236 | 1.34 |
| Ni-59 | 1.61 | | Pu-238 | 1.27 |
| Ni-63 | 1.18 | | Pu-240 | 1.37 |
| Zr-93 | 1.20 | | Pu-242 | 1.24 |
| Nb-93m | 1.61 | | Cm-242 | 1.46 |
| Mo-93 | 1.61 | | Cm-244 | 1.48 |
| Tc-97 | 1.61 | | Cm-246 | 1.52 |
| Pd-107 | 1.52 | | Cm-248 | 1.46 |
| Sm-151 | 1.21 | | Cf-248 | 1.55 |
| Pb-205 | 1.61 | | Cf-250 | 1.36 |
| Th-232 | 1.12 | | Cf-252 | 1.42 |
| U-232 | 1.13 | | | |

Notes:
- The ratios are the dose rate factor (DRF) at 10 cm above the soil surface divided by the dose rate factor at 1 meter above the soil. Both DRFs are from EXTDF.
- Nuclides having DRFs within 10% at the two elevations are not shown.

### A3.6.2 External Dose-Rate Factors for Radionuclides in Air

External dose rate factors for immersion in contaminated air are listed in Table A30. Values are from Federal Guidance Report Number 12 (EPA-402-R-93-081). The dose rate factors were computed assuming the individual is located at the center of a hemisphere of infinite extent. Hence these are also referred to as semi-infinite cloud dose rate factors. Values for Nb-91 and Po-209 are from the EXTDF program of the GENII software package. Several nuclides (Ca-41, V-49, Mn-53, Fe-55, Ni-59, Ni-63, Zr-93, Pd-107, Sm-147, Gd-152, and Re-187) are omitted from the table because the dose rate factors in air are all zero.

The columns labeled "Ratio" compare the external dose from submersion in contaminated air with the typical inhalation dose that accrues during the same period. The inhalation dose is computed as the product of the air concentration, the exposure time, the breathing rate (0.95 $m^3/h$), and the inhalation dose factor (Table A25). The submersion dose is computed as the product of the air concentration, the exposure time, and the submersion dose rate factor. Thus the ratio of inhalation dose to submersion dose is the product of the breathing rate and the inhalation dose factor divided by the air submersion dose rate factor. This ratio is shown in Table A30. The light activity-breathing rate could also be used, but leads to larger ratios.

For the nuclides used in this report (Table A1), the smallest ratio is 5.06 for Na-22. This is the only isotope with a ratio smaller than 10. In any exposure scenario involving Na-22 there is additional external exposure from soil contamination and ingestion doses. Thus the submersion dose is a minor contributor to the overall total dose.

In Table A30, nuclides notable for large inhalation doses, like insoluble transuranic (TRU) isotopes, have ratios greater than 1 million. Because the activity inhaled by the individual is considerably smaller than the activity ingested, the inhalation dose for non-TRU isotopes is a small part of the total. Therefore, the air submersion dose from airborne particulate will not be included in the dose calculations.

**Table A30. External Dose Rate Factors for Air, mrem/h per pCi/$m^3$.**

| Nuclide | Air DRF | Ratio | Nuclide | Air DRF | Ratio |
|---|---|---|---|---|---|
| H-3 | 4.41E-12 | 2.07E+04 | Pb-205 | 6.74E-12 | 5.53E+05 |
| Be-10 | 1.49E-10 | 2.26E+06 | Pb-210+D | 1.19E-09 | 1.09E+07 |
| C-14 | 2.98E-12 | 6.64E+05 | Bi-207 | 1.00E-06 | 1.89E+01 |
| Na-22 | 1.44E-06 | 5.06E+00 | Po-209 | 2.42E-09 | 4.60E+06 |
| Al-26 | 1.81E-06 | 4.17E+01 | Po-210 | 5.54E-12 | 1.61E+09 |
| Si-32+D | 1.33E-09 | 7.37E+05 | Ra-226+D | 1.18E-06 | 6.92E+03 |
| Cl-36 | 2.97E-10 | 7.02E+04 | Ra-228+D | 6.37E-07 | 7.26E+03 |
| K-40 | 1.07E-07 | 1.09E+02 | Ac-227+D | 2.47E-07 | 2.58E+07 |
| Ti-44+D | 1.47E-06 | 2.92E+02 | Th-228+D | 1.08E-06 | 3.05E+05 |
| Mn-54 | 5.45E-07 | 1.17E+01 | Th-229+D | 1.98E-07 | 1.04E+07 |
| Fe-60+D | 2.89E-09 | 2.45E+05 | Th-230 | 2.32E-10 | 1.33E+09 |
| Co-60 | 1.68E-06 | 1.24E+02 | Th-232 | 1.16E-10 | 1.34E+10 |
| Se-79 | 4.04E-12 | 2.32E+06 | Pa-231 | 2.29E-08 | 5.32E+07 |
| Rb-87 | 2.42E-11 | 1.27E+05 | U-232 | 1.89E-10 | 3.31E+09 |
| Sr-90+D | 2.63E-09 | 8.93E+04 | U-233 | 2.17E-10 | 5.93E+08 |
| Nb-91 | 2.05E-09 | 1.35E+04 | U-234 | 1.02E-10 | 1.24E+09 |
| Nb-93m | 5.91E-11 | 4.70E+05 | U-235+D | 1.03E-07 | 1.13E+06 |
| Nb-94 | 1.03E-06 | 3.84E+02 | U-236 | 6.67E-11 | 1.79E+09 |
| Mo-93 | 3.36E-10 | 8.04E+04 | U-238+D | 1.61E-08 | 6.98E+06 |
| Tc-97 | 4.44E-10 | 2.12E+03 | Np-237+D | 1.38E-07 | 3.71E+06 |
| Tc-99 | 2.16E-11 | 3.67E+05 | Pu-236 | 8.46E-11 | 1.62E+09 |
| Ru-106+D | 1.39E-07 | 3.27E+03 | Pu-238 | 6.50E-11 | 5.73E+09 |
| Ag-108m+D | 1.04E-06 | 2.59E+02 | Pu-239 | 5.65E-11 | 7.22E+09 |

**Table A30. External Dose Rate Factors for Air, mrem/h per pCi/m$^3$.**

| Nuclide | Air DRF | Ratio | Nuclide | Air DRF | Ratio |
|---|---|---|---|---|---|
| Cd-109+D | 6.47E-09 | 1.68E+04 | Pu-240 | 6.33E-11 | 6.44E+09 |
| Cd-113m | 9.24E-11 | 1.57E+07 | Pu-241+D | 2.96E-12 | 2.65E+09 |
| In-115 | 5.99E-11 | 5.92E+07 | Pu-242 | 5.34E-11 | 7.30E+09 |
| Sn-121m+D | 8.26E-10 | 1.37E+04 | Pu-244+D | 2.17E-07 | 1.76E+06 |
| Sn-126+D | 1.28E-06 | 7.50E+01 | Am-241 | 1.09E-08 | 3.87E+07 |
| Sb-125 | 2.69E-07 | 4.31E+01 | Am-242m+D | 1.02E-08 | 3.96E+07 |
| Te-125m | 6.03E-09 | 1.15E+03 | Am-243+D | 1.31E-07 | 3.18E+06 |
| I-129 | 5.06E-09 | 3.26E+04 | Cm-242 | 7.58E-11 | 2.17E+08 |
| Cs-134 | 1.01E-06 | 4.36E+01 | Cm-243 | 7.83E-08 | 3.72E+06 |
| Cs-135 | 7.53E-12 | 5.74E+05 | Cm-244 | 6.54E-11 | 3.60E+09 |
| Cs-137+D | 3.62E-07 | 8.37E+01 | Cm-245 | 5.27E-08 | 8.20E+06 |
| Ba-133 | 2.37E-07 | 3.13E+01 | Cm-246 | 5.94E-11 | 7.22E+09 |
| Ce-144+D | 3.74E-08 | 9.50E+03 | Cm-247+D | 2.14E-07 | 1.84E+06 |
| Pm-147 | 9.23E-12 | 4.04E+06 | Cm-248 | 4.52E-11 | 3.48E+10 |
| Sm-151 | 4.81E-13 | 5.92E+07 | Cm-250+D | 1.82E-07 | 4.91E+07 |
| Eu-150 | 9.55E-07 | 2.67E+02 | Bk-247 | 6.27E-08 | 8.68E+06 |
| Eu-152 | 7.53E-07 | 2.79E+02 | Cf-248 | 6.30E-11 | 7.64E+08 |
| Eu-154 | 8.18E-07 | 3.32E+02 | Cf-249 | 2.10E-07 | 2.61E+06 |
| Eu-155 | 3.32E-08 | 1.19E+03 | Cf-250 | 5.99E-11 | 4.15E+09 |
| Tb-157 | 9.03E-10 | 9.69E+03 | Cf-251 | 7.43E-08 | 7.52E+06 |
| Ho-166m | 1.13E-06 | 6.53E+02 | Cf-252 | 6.74E-11 | 2.21E+09 |
| Tl-204 | 7.45E-10 | 3.07E+03 | | | |

Notes:

- External dose rate factors (DRF) for submersion in contaminated air are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used. Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide. The nuclide is dispersed uniformly in a hemisphere of infinite extent. The receptor is at the center of the hemisphere. The following nuclides were omitted from the table because the DRF is zero: Ca-41, V-49, Mn-53, Fe-55, Ni-59, Ni-63, Zr-93, Pd-107, Sm-147, Gd-152, and Re-187.
- The "Ratio" columns compare the inhalation dose to the external dose. The ratio is computed as the inhalation dose factor times the daily average breathing rate (0.95 m$^3$/h) divided by the submersion dose rate factor.

### A3.6.3 External Dose-Rate Factors for Radionuclides in Water

External dose rate factors for immersion in contaminated water are from Federal Guidance Report Number 12 (EPA-402-R-93-081). The dose rate factors in this reference were computed assuming the individual is located at the center of a sphere of infinite extent. Hence these are also referred to as infinite medium dose rate factors. Values for Nb-91 and Po-209 are from the EXTDF program of the GENII software package. Several nuclides (H-3, Ca-41, V-49, Mn-53, Fe-55, Ni-59, Ni-63, Zr-93, Pd-107, Sm-147, Gd-152, and Re-187) are omitted from the table because the dose rate factors in water are all zero.

The EPA values have been converted from Sv/s per Bq/m$^3$ for an infinite medium to mrem/h per pCi/L for a semi-infinite medium. These are listed in Table A31. The semi-infinite medium corresponds to the dose rate at the surface of a body of water. It may include swimming or shoreline activities. The relationship between infinite medium dose rate factors and semi-infinite medium dose rate factors is simply a factor of two.

The columns labeled "Ratio" compare the external dose from swimming in contaminated water with the ingestion dose from drinking water. The doses are calculated according to the usage parameters for the recreational scenario given in the HSRAM Rev 3. The daily ingestion dose is computed as the product of the water concentration, the volume consumed (2 L/d), and the ingestion dose factor (Table A24). The surface water dose is computed as the product of the water concentration, the exposure time (2.6 h/d), and the dose rate factor (Table A31). Thus the ratio of ingestion dose to external dose is the ingestion dose factor times 2/2.6=0.769 L/h divided by the surface water dose rate factor. This ratio is shown in Table A31.

For the nuclides used in this report (Table A1), the smallest ratio is 3.6 for Mn-54. Nuclides with ratios less than 10 are Mn-54, Bi-207, Eu-150, Nb-94, Ho-166m, Ag-108m+D, Na-22, Al-26, Eu-152, Sb-125, and Eu-154. Each of these also has dose contributions from other pathways (mainly external) that are about the same size as the drinking water ingestion dose. Thus, the largest increase in the recreational scenario first year total dose is 14% for Mn-54. The water submersion dose increases by less than 10% for all other radionuclides being considered. This is a small enough increase it can be ignored. The recreational scenario using groundwater was chosen to maximize the effect of the water submersion dose on the total dose. All other scenarios have other pathways or increased ingestion dose which makes the water submersion contribution even less important.

**Table A31. External Dose Rate Factors for Water, mrem/h per pCi/L.**

| Nuclide | Water DRF | Ratio | Nuclide | Water DRF | Ratio |
|---|---|---|---|---|---|
| Be-10 | 1.45E-10 | 2.48E+04 | Pb-205 | 7.79E-12 | 1.61E+05 |
| C-14 | 2.92E-12 | 5.49E+05 | Pb-210+D | 1.29E-09 | 3.19E+06 |
| Na-22 | 1.57E-06 | 5.64E+00 | Bi-207 | 1.09E-06 | 3.86E+00 |
| Al-26 | 1.96E-06 | 5.73E+00 | Po-209 | 2.90E-09 | 6.30E+05 |
| Si-32+D | 1.27E-09 | 6.62E+03 | Po-210 | 6.01E-12 | 2.43E+08 |
| Cl-36 | 2.98E-10 | 7.80E+03 | Ra-226+D | 1.28E-06 | 7.95E+02 |
| K-40 | 1.16E-07 | 1.23E+02 | Ra-228+D | 6.93E-07 | 1.60E+03 |
| Ti-44+D | 1.60E-06 | 1.18E+01 | Ac-227+D | 2.71E-07 | 4.18E+04 |
| Mn-54 | 5.91E-07 | 3.60E+00 | Th-228+D | 1.17E-06 | 5.33E+02 |
| Fe-60+D | 3.17E-09 | 3.70E+04 | Th-229+D | 2.17E-07 | 1.43E+04 |
| Co-60 | 1.82E-06 | 1.14E+01 | Th-230 | 2.62E-10 | 1.61E+06 |
| Se-79 | 3.95E-12 | 1.69E+06 | Th-232 | 1.33E-10 | 1.58E+07 |
| Rb-87 | 2.36E-11 | 1.61E+05 | Pa-231 | 2.52E-08 | 3.23E+05 |
| Sr-90+D | 2.52E-09 | 4.69E+04 | U-232 | 2.14E-10 | 4.70E+06 |
| Nb-91 | 2.68E-09 | 1.49E+02 | U-233 | 2.42E-10 | 9.17E+05 |
| Nb-93m | 6.93E-11 | 5.79E+03 | U-234 | 1.17E-10 | 1.87E+06 |
| Nb-94 | 1.11E-06 | 4.94E+00 | U-235+D | 1.14E-07 | 1.81E+03 |
| Mo-93 | 3.94E-10 | 2.63E+03 | U-236 | 7.73E-11 | 2.67E+06 |

**Table A31. External Dose Rate Factors for Water, mrem/h per pCi/L.**

| Nuclide | Water DRF | Ratio | Nuclide | Water DRF | Ratio |
|---|---|---|---|---|---|
| Tc-97 | 5.21E-10 | 2.53E+02 | U-238+D | 1.74E-08 | 1.18E+04 |
| Tc-99 | 2.09E-11 | 5.38E+04 | Np-237+D | 1.52E-07 | 2.25E+04 |
| Ru-106+D | 1.49E-07 | 1.41E+02 | Pu-236 | 9.86E-11 | 9.10E+06 |
| Ag-108m+D | 1.13E-06 | 5.20E+00 | Pu-238 | 7.59E-11 | 3.24E+07 |
| Cd-109+D | 7.43E-09 | 1.36E+03 | Pu-239 | 6.39E-11 | 4.26E+07 |
| Cd-113m | 8.92E-11 | 1.39E+06 | Pu-240 | 7.39E-11 | 3.68E+07 |
| In-115 | 5.79E-11 | 2.09E+06 | Pu-241+D | 3.30E-12 | 1.60E+07 |
| Sn-121m+D | 9.63E-10 | 1.80E+03 | Pu-242 | 6.23E-11 | 4.15E+07 |
| Sn-126+D | 1.40E-06 | 1.16E+01 | Pu-244+D | 2.35E-07 | 1.09E+04 |
| Sb-125 | 2.92E-07 | 7.39E+00 | Am-241 | 1.25E-08 | 2.24E+05 |
| Te-125m | 7.06E-09 | 4.00E+02 | Am-242m+D | 1.14E-08 | 2.37E+05 |
| I-129 | 5.93E-09 | 3.58E+04 | Am-243+D | 1.46E-07 | 1.91E+04 |
| Cs-134 | 1.09E-06 | 5.16E+01 | Cm-242 | 8.86E-11 | 9.96E+05 |
| Cs-135 | 7.33E-12 | 7.42E+05 | Cm-243 | 8.66E-08 | 2.23E+04 |
| Cs-137+D | 3.94E-07 | 9.76E+01 | Cm-244 | 7.66E-11 | 2.03E+07 |
| Ba-133 | 2.60E-07 | 1.00E+01 | Cm-245 | 5.89E-08 | 4.88E+04 |
| Ce-144+D | 4.04E-08 | 4.02E+02 | Cm-246 | 6.99E-11 | 4.07E+07 |
| Pm-147 | 9.32E-12 | 8.64E+04 | Cm-247+D | 2.33E-07 | 1.13E+04 |
| Sm-151 | 5.66E-13 | 5.28E+05 | Cm-248 | 5.30E-11 | 1.98E+08 |
| Eu-150 | 1.04E-06 | 4.71E+00 | Cm-250+D | 1.97E-07 | 3.03E+05 |
| Eu-152 | 8.19E-07 | 6.08E+00 | Bk-247 | 6.99E-08 | 5.17E+04 |
| Eu-154 | 8.86E-07 | 8.29E+00 | Cf-248 | 7.39E-11 | 3.48E+06 |
| Eu-155 | 3.74E-08 | 3.15E+01 | Cf-249 | 2.30E-07 | 1.59E+04 |
| Tb-157 | 1.05E-09 | 9.12E+01 | Cf-250 | 7.06E-11 | 2.32E+07 |
| Ho-166m | 1.23E-06 | 5.06E+00 | Cf-251 | 8.26E-08 | 4.51E+04 |
| Tl-204 | 8.13E-10 | 3.18E+03 | Cf-252 | 7.86E-11 | 1.06E+07 |

Notes:

- External dose rate factors (DRF) for submersion in contaminated water are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used. Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide. The nuclide is dispersed uniformly in a hemisphere of infinite extent. The receptor is at the center of the hemisphere. The following nuclides were omitted from the table because the DRF is zero: H-3, Ca-41, V-49, Mn-53, Fe-55, Ni-59, Ni-63, Zr-93, Pd-107, Sm-147, Gd-152, and Re-187.
- The "Ratio" columns compare the ingestion dose to the external dose for the HSRAM recreational scenario. The ratio is computed as the ingestion dose factor times 0.769 L/h divided by the water submersion dose rate factor.

Nuclides notable for large ingestion doses, such as the transuranic (TRU) isotopes, have ratios greater than 100,000. Thus, the water surface external dose will not be included in the dose calculations. It should be noted that Federal Guidance Report Number 13 does not provide unit risk factors for submersion in water.

## A3.7 CANCER MORBIDITY RISK COEFFICIENTS FOR RADIONUCLIDES

The HSRAM exposure scenarios are used to determine the potential lifetime intakes of hazardous materials left in the waste. The toxicity of those intakes depends on the chemical and nuclear characteristics of the material. Of primary interest is the risk to the exposed individual of developing some type of cancer, whether or not the cancer is fatal. For radionuclides, the recommended cancer morbidity risk coefficients are found in Federal Guidance Report Number 13 (EPA-402-R-99-001).

Federal Guidance Report 13 provides both mortality (death from cancer) and morbidity (cancer induction) risk coefficients for an average member of the population. The risk is averaged over the age and gender distributions of a group of people whose survival fraction and cancer induction rates are based on recent data for the United States. While these do change with time, they will nevertheless be used to estimate cancer induction risks to persons exposed hundred of years in the future. The risk coefficients can be used for short duration exposures to an entire population, or to lifetime exposures of one individual.

For the radionuclides of interest in this report, the cancer morbidity risk coefficients from ingestion and inhalation are shown in Table A32. The ingestion risk coefficients are separated into tap water, food, and soil. The numbers for tap water and food are from Table 2.2a in Federal Guidance Report 13. The numbers for soil come from the Risk Assessment Information System (RAIS). The Oak Ridge National Laboratory (ORNL) maintains this toxicological data listing for human health risk assessments. The data may be obtained from the World Wide Web using the location http://risk.lsd.ornl.gov. The GI absorption fractions and lung clearance types in Table A32 are the same as listed in Table A26.

The ingestion and inhalation risk coefficients for Nb-91, Po-209, Cm-248, Cm-250, and Cf-252 were estimated using risk coefficients from other nuclides. The ingestion and inhalation risk coefficients for Nb-91 are assumed bounded by those for Nb-93m. In a similar manner, the ingestion and inhalation risk coefficients for Po-209 are calculated from the risk coefficients for Po-210 using the constant of proportionality, 1.247, derived in Section A3.5. The ingestion and inhalation coefficients for Cm-250 were estimated using numbers for Cm-246 because they have similar alpha energies. For Cm-250 the average alpha energy is 5.190 MeV, while for Cm-246 the average alpha energy is 5.377 MeV. An example calculation of risk coefficient for inhalation of Cm-250 is shown below.

$$
\begin{aligned}
SF_{inhale}\left(^{250}Cm\right) &= \frac{DF_{inhale}\left(^{250}Cm\right)}{DF_{inhale}\left(^{246}Cm\right)} SF_{inhale}\left(^{246}Cm\right) \\
&= \frac{3.11\ \text{mrem/pCi}}{0.155\ \text{mrem/pCi}}\left(2.77\text{x}10^{-8}\ \text{risk/pCi inhaled}\right) \\
&= 5.54\text{x}10^{-7}\ \text{risk/pCi}
\end{aligned}
$$

The soil ingestion risk coefficients for Cm-248 and Cf-252 were estimated using the food ingestion risk coefficients for Cm-246 and Cf-250 because they have similar alpha energies. The average alpha particle energies for Cm-248 and Cm-246 are 5.070 MeV and 5.377 MeV. The

power function fit. The correlation for the external factors is much better than the correlation for the internal factors, hence a correlation method was not used to estimate the internal risk coefficients.

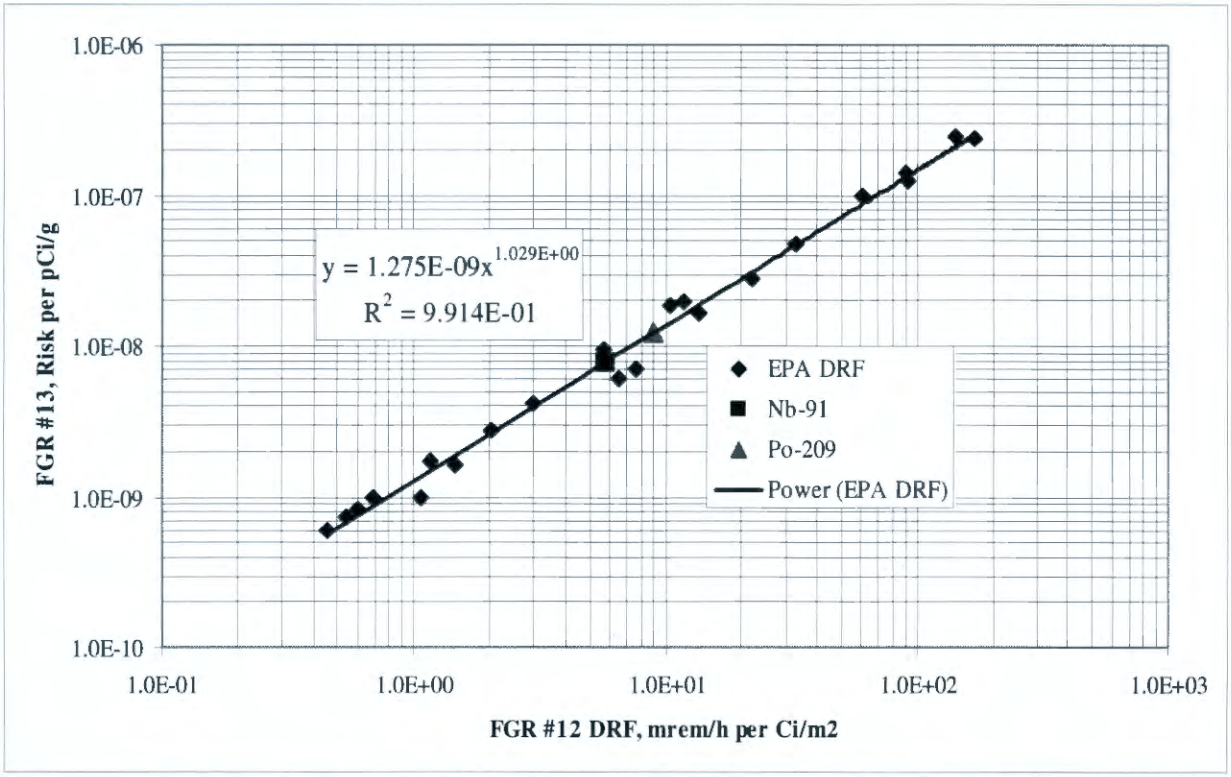


**Figure A0. Correlation between External Dose and Risk Factors.**

**Table A33. Risk Coefficients for External Exposure, risk/y per pCi/g.**

| Nuclide | Risk Coefficient | Nuclide | Risk Coefficient | Nuclide | Risk Coefficient |
|---|---|---|---|---|---|
| H-3 | 0 | Sn-121m+D | 9.86E-10 | Pa-231 | 1.39E-07 |
| Be-10 | 7.43E-10 | Sn-126+D | 8.83E-06 | U-232 | 5.98E-10 |
| C-14 | 7.83E-12 | Sb-125 | 1.81E-06 | U-233 | 9.82E-10 |
| Na-22 | 1.03E-05 | Te-125m | 6.95E-09 | U-234 | 2.52E-10 |
| Al-26 | 1.33E-05 | I-129 | 6.10E-09 | U-235+D | 5.43E-07 |
| Si-32+D | 9.43E-09 | Cs-134 | 7.10E-06 | U-236 | 1.25E-10 |
| Cl-36 | 1.74E-09 | Cs-135 | 2.36E-11 | U-238+D | 9.90E-08 |
| K-40 | 7.97E-07 | Cs-137+D | 2.54E-06 | Np-237+D | 7.97E-07 |
| Ca-41 | 0.00E+00 | Ba-133 | 1.44E-06 | Pu-236 | 1.19E-10 |
| Ti-44+D | 1.02E-05 | Ce-144+D | 2.44E-07 | Pu-238 | 7.22E-11 |
| V-49 | 0.00E+00 | Pm-147 | 3.21E-11 | Pu-239 | 2.00E-10 |
| Mn-53 | 0.00E+00 | Sm-147 | 0.00E+00 | Pu-240 | 6.98E-11 |
| Mn-54 | 3.89E-06 | Sm-151 | 3.60E-13 | Pu-241+D | 1.35E-11 |
| Fe-55 | 0.00E+00 | Eu-150 | 6.49E-06 | Pu-242 | 6.25E-11 |
| Fe-60+D | 1.86E-08 | Eu-152 | 5.30E-06 | Pu-244+D | 1.52E-06 |
| Co-60 | 1.24E-05 | Eu-154 | 5.83E-06 | Am-241 | 2.76E-08 |

power function fit. The correlation for the external factors is much better than the correlation for the internal factors, hence a correlation method was not used to estimate the internal risk coefficients.

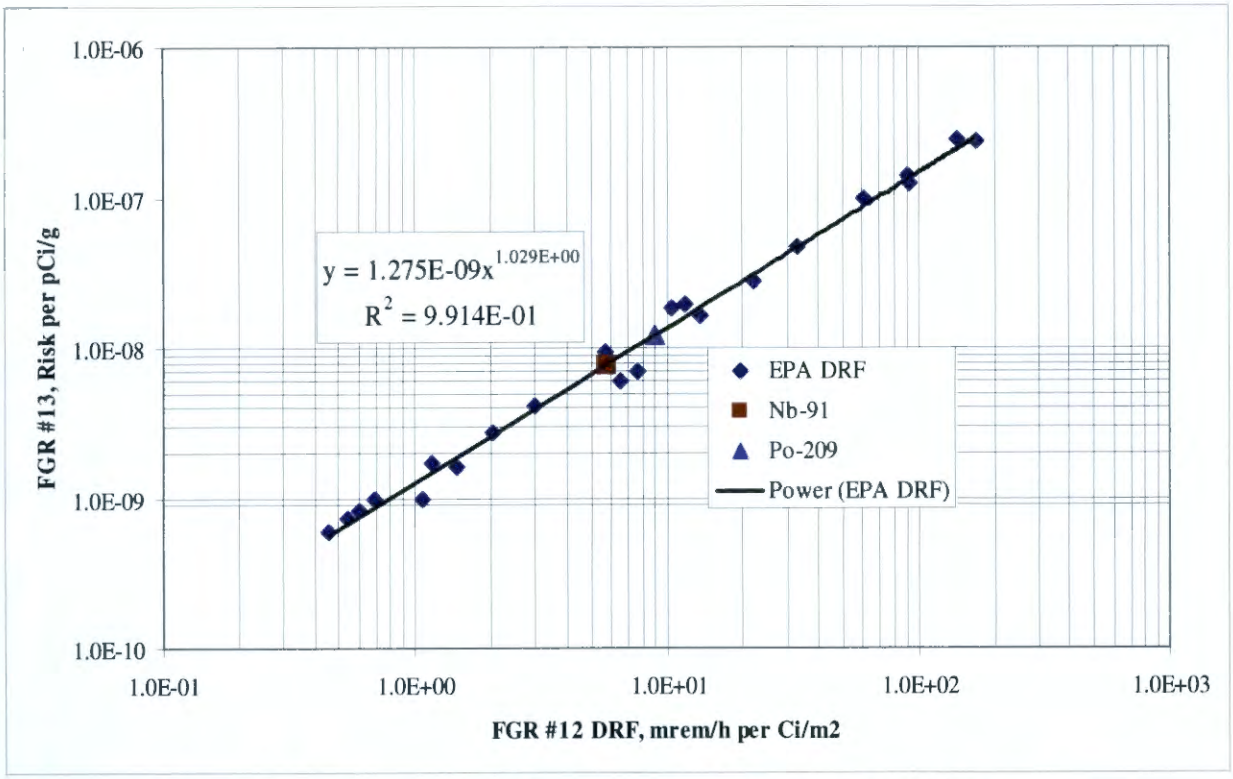


**Figure A0. Correlation between External Dose and Risk Factors.**

**Table A33. Risk Coefficients for External Exposure, risk/y per pCi/g.**

| Nuclide | Risk Coefficient | Nuclide | Risk Coefficient | Nuclide | Risk Coefficient |
|---|---|---|---|---|---|
| H-3 | 0 | Sn-121m+D | 9.86E-10 | Pa-231 | 1.39E-07 |
| Be-10 | 7.43E-10 | Sn-126+D | 8.83E-06 | U-232 | 5.98E-10 |
| C-14 | 7.83E-12 | Sb-125 | 1.81E-06 | U-233 | 9.82E-10 |
| Na-22 | 1.03E-05 | Te-125m | 6.95E-09 | U-234 | 2.52E-10 |
| Al-26 | 1.33E-05 | I-129 | 6.10E-09 | U-235+D | 5.43E-07 |
| Si-32+D | 9.43E-09 | Cs-134 | 7.10E-06 | U-236 | 1.25E-10 |
| Cl-36 | 1.74E-09 | Cs-135 | 2.36E-11 | U-238+D | 9.90E-08 |
| K-40 | 7.97E-07 | Cs-137+D | 2.54E-06 | Np-237+D | 7.97E-07 |
| Ca-41 | 0.00E+00 | Ba-133 | 1.44E-06 | Pu-236 | 1.19E-10 |
| Ti-44+D | 1.02E-05 | Ce-144+D | 2.44E-07 | Pu-238 | 7.22E-11 |
| V-49 | 0.00E+00 | Pm-147 | 3.21E-11 | Pu-239 | 2.00E-10 |
| Mn-53 | 0.00E+00 | Sm-147 | 0.00E+00 | Pu-240 | 6.98E-11 |
| Mn-54 | 3.89E-06 | Sm-151 | 3.60E-13 | Pu-241+D | 1.35E-11 |
| Fe-55 | 0.00E+00 | Eu-150 | 6.49E-06 | Pu-242 | 6.25E-11 |
| Fe-60+D | 1.86E-08 | Eu-152 | 5.30E-06 | Pu-244+D | 1.52E-06 |
| Co-60 | 1.24E-05 | Eu-154 | 5.83E-06 | Am-241 | 2.76E-08 |

**Table A33. Risk Coefficients for External Exposure, risk/y per pCi/g.**

| Nuclide | Risk Coefficient | Nuclide | Risk Coefficient | Nuclide | Risk Coefficient |
|---|---|---|---|---|---|
| Ni-59 | 0.00E+00 | Eu-155 | 1.24E-07 | Am-242m+D | 4.75E-08 |
| Ni-63 | 0.00E+00 | Gd-152 | 0.00E+00 | Am-243+D | 6.36E-07 |
| Se-79 | 1.10E-11 | Tb-157 | 1.63E-09 | Cm-242 | 7.73E-11 |
| Rb-87 | 9.11E-11 | Ho-166m | 7.69E-06 | Cm-243 | 4.19E-07 |
| Sr-90+D | 1.96E-08 | Re-187 | 0.00E+00 | Cm-244 | 4.85E-11 |
| Zr-93 | 0.00E+00 | Tl-204 | 2.76E-09 | Cm-245 | 2.38E-07 |
| Nb-91 | 7.70E-09 | Pb-205 | 3.50E-12 | Cm-246 | 4.57E-11 |
| Nb-93m | 3.83E-11 | Pb-210+D | 4.17E-09 | Cm-247+D | 1.37E-06 |
| Nb-94 | 7.29E-06 | Bi-207 | 7.08E-06 | Cm-248 | 3.42E-11 |
| Mo-93 | 2.17E-10 | Po-209 | 1.22E-08 | Cm-250+D | 1.28E-06 |
| Tc-97 | 2.94E-10 | Po-210 | 3.95E-11 | Bk-247 | 3.09E-07 |
| Tc-99 | 8.14E-11 | Ra-226+D | 8.49E-06 | Cf-248 | 4.73E-11 |
| Ru-106+D | 9.66E-07 | Ra-228+D | 4.53E-06 | Cf-249 | 1.37E-06 |
| Pd-107 | 0.00E+00 | Ac-227+D | 1.47E-06 | Cf-250 | 4.48E-11 |
| Ag-108m+D | 7.19E-06 | Th-228+D | 7.81E-06 | Cf-251 | 3.76E-07 |
| Cd-109+D | 1.64E-08 | Th-229+D | 1.16E-06 | Cf-252 | 8.66E-11 |
| Cd-113m | 4.45E-10 | Th-230 | 8.19E-10 | | |
| In-115 | 2.70E-10 | Th-232 | 3.42E-10 | | |

Notes:
- The risk coefficients for external exposure are cancer morbidity values from Federal Guidance Report Number 13 (EPA-402-R-99-001). Values for Nb-91 and Po-209 were estimated from the dose rate factors in Table A28 as described in the text.
- Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide.

## A3.8 SLOPE FACTORS AND REFERENCE DOSES FOR CHEMICALS

For chemicals, the risk to the exposed individual of developing some type of cancer as well as non-cancer effects are of interest in human health risk assessments. The cancer risk is based on cancer induction slope factors (SF), while the hazard from non-cancer effects is based on reference doses (RfD). Reference doses and cancer induction slope factors for the chemicals of interest are listed in Table A34. The source of these numbers is noted beside each.

In January 1991, EPA began to replace inhalation Reference Doses (RfD) for noncancer toxicity and inhalation slope factors for carcinogenicity, previously available on the IRIS data base, with Reference Concentrations (RfC) and inhalation unit risks, respectively. RfCs and unit risks are expressed in terms of concentration in air (mg/m$^3$), not in terms of "dose" (mg/kg-day) like the RfDs and the oral and inhalation slope factors.

EPA's decision to replace inhalation slope factors and RfDi values expressed in mg/kg-day with unit risk and RfC values expressed in mg/m$^3$ was based on two major factors: (1) the EPA workgroups felt that it was technically more accurate to base toxicity values directly on measured air concentrations instead of making the metabolic pharmacokinetic and/or surface area adjustments required to estimate an "internal dose"; and (2) there are compounds that elicit route-of-entry effects (e.g., sensitizers and irritants) where the toxic effect is to the respiratory

system or exchange boundary where a measure of "internal dose" might inappropriately imply effects to other organ systems or effects from other exposure routes.

Converting the air concentration data to a dose (in mg/kg-day) is carried out using the equations shown below. Note that the adult body weight and breathing rates are used for the conversions.

$$\text{RfDi} = \text{RfC}\frac{\text{BRa}}{\text{BWa}} \quad \text{and} \quad \text{SFi} = (\text{Unit Risk})\frac{\text{BWa}}{\text{BRa}}(1000\,\mu\text{g/mg})$$

Where

RfDi = Inhalation reference dose, in mg/kg-day, is an estimate of a daily inhalation dose to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime.

RfC = Reference concentration, in $mg/m^3$, is an estimate of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime.

BRa = standard adult breathing rate for EPA risk assessment, 20 $m^3$/day

BWa = standard adult body weight for EPA risk assessment, 70 kg

SFi = Inhalation slope factor, in risk per (mg/kg-day), gives an upper bound on the probability that some type of cancer develops as a result of a lifetime exposed to a given chemical.

Unit Risk = Unit Risk, in risk per ($\mu g/m^3$), gives an upper bound on the probability that some type of cancer develops as a result of a lifetime exposed to a given chemical.

**Table A34. Reference Doses and Cancer Induction Slope Factors for Chemicals.**

| | | Reference Dose (RfD) (mg/kg-day) | | Cancer Slope Factor (SF) $(mg/kg\text{-}day)^{-1}$ | |
|---|---|---|---|---|---|
| **CASRN** | **Chemical Name** | **Ingestion** | **Inhalation** | **Ingestion** | **Inhalation** |
| 50-32-8 | Benzo[a]pyrene | na | na | 7.30E+00 e | 3.08E+00 o |
| 53-70-3 | Dibenz[a,h]anthracene | na | na | 7.30E+00 t | 3.08E+00 t |
| 56-23-5 | Carbon tetrachloride | 7.00E-04 e | na | 1.30E-01 e | 5.20E-02 e |
| 56-55-3 | Benz[a]anthracene | na | na | 7.30E-01 t | 3.08E-01 t |
| 57-12-5 | Cyanide, free | 2.00E-02 e | na | na | na |
| 57-14-7 | 1,1-Dimethylhydrazine | na | na | 3.00E+00 o | 1.72E+01 o |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 5.00E-01 s | 8.57E-04 s | na | na |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 3.00E-04 e | na | 1.30E+00 h | na |
| 60-29-7 | Ethyl ether (Diethyl ether) | 2.00E-01 e | na | na | na |
| 60-34-4 | Methylhydrazine | na | na | 3.00E+00 o | 1.72E+01 o |
| 60-57-1 | Dieldrin | 5.00E-05 e | na | 1.60E+01 e | 1.60E+01 e |
| 62-75-9 | N-Nitrosodimethylamine | 8.00E-06 s | na | 5.10E+01 e | 4.90E+01 e |
| 64-18-6 | Formic acid | 2.00E+00 h | na | na | na |
| 67-56-1 | Methanol (Methyl alcohol) | 5.00E-01 e | na | na | na |
| 67-64-1 | Acetone (2-Propanone) | 9.00E-01 e | na | na | na |
| 67-66-3 | Chloroform | 1.00E-02 e | 8.60E-04 n | 6.10E-03 o | 8.05E-02 e |
| 67-72-1 | Hexachloroethane | 1.00E-03 e | na | 1.40E-02 e | 1.40E-02 e |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.00E-01 e | 2.60E-03 n | na | na |

**Table A34. Reference Doses and Cancer Induction Slope Factors for Chemicals.**

| CASRN | Chemical Name | Reference Dose (RfD) (mg/kg-day) | | Cancer Slope Factor (SF) $(mg/kg\text{-}day)^{-1}$ | |
|---|---|---|---|---|---|
| | | Ingestion | Inhalation | Ingestion | Inhalation |
| 71-43-2 | Benzene | 4.00E-03 e | 8.57E-03 e | 5.50E-02 e | 2.73E-02 e |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 2.00E+00 e | 1.43E+00 e | na | na |
| 72-20-8 | Endrin | 3.00E-04 e | na | na | na |
| 74-83-9 | Bromomethane | 1.40E-03 e | 1.43E-03 e | na | na |
| 74-87-3 | Methyl chloride (Chloromethane) | na | 2.57E-02 e | 1.30E-02 h | 6.30E-03 h |
| 75-00-3 | Ethyl Chloride | 4.00E-01 n | 2.86E+00 e | 2.90E-03 n | na |
| 75-01-4 | Vinyl chloride (Chloroethene) | 3.00E-03 e | 2.86E-02 e | 1.50E+00 e | 3.08E-02 e |
| 75-05-8 | Acetonitrile | na | 1.71E-02 e | na | na |
| 75-07-0 | Acetaldehyde | na | 2.57E-03 e | na | 7.70E-03 e |
| 75-09-2 | Dichloromethane (Methylene chloride) | 6.00E-02 e | 8.57E-01 h | 7.50E-03 e | 1.65E-03 e |
| 75-15-0 | Carbon disulfide | 1.00E-01 e | 2.00E-01 e | na | na |
| 75-21-8 | Ethylene Oxide (Oxirane) | na | na | 1.02E+00 h | 3.50E-01 h |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.00E-01 h | 1.43E-01 h | na | na |
| 75-35-4 | 1,1-Dichloroethylene | 5.00E-02 e | 5.71E-02 e | na | na |
| 75-45-6 | Chlorodifluoromethane | na | 1.43E+01 e | na | na |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | na | 1.43E+01 e | na | na |
| 75-69-4 | Trichlorofluoromethane | 3.00E-01 e | 2.00E-01 h | na | na |
| 75-71-8 | Dichlorodifluoromethane | 2.00E-01 e | 5.71E-02 h | na | na |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 3.00E+01 e | 8.57E+00 h | na | na |
| 76-44-8 | Heptachlor | 5.00E-04 e | na | 4.50E+00 e | 4.50E+00 e |
| 78-83-1 | Isobutanol | 3.00E-01 e | na | na | na |
| 78-87-5 | 1,2-Dichloropropane | na | 1.14E-03 e | 6.80E-02 h | na |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 6.00E-01 e | 1.43E+00 e | na | na |
| 79-00-5 | 1,1,2-Trichloroethane | 4.00E-03 e | na | 5.70E-02 e | 5.70E-02 e |
| 79-01-6 | Trichloroethylene | 3.00E-04 n | 1.14E-02 n | 4.00E-01 o | 4.00E-01 o |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 5.00E-01 e | 2.86E-04 e | na | na |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 6.00E-02 n | na | 2.00E-01 e | 2.00E-01 e |
| 79-46-9 | 2-Nitropropane | na | 5.71E-03 e | na | 9.40E+00 h |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 3.00E-03 e | na | 2.60E-01 h | na |
| 83-32-9 | Acenaphthene | 6.00E-02 e | na | na | na |
| 84-66-2 | Diethyl phthalate | 8.00E-01 e | na | na | na |
| 84-74-2 | Dibutyl phthalate | 1.00E-01 e | na | na | na |
| 85-68-7 | Butyl benzyl phthalate | 2.00E-01 e | na | na | na |
| 86-73-7 | Fluorene | 4.00E-02 e | na | na | na |
| 86-74-8 | Carbazole | na | na | 2.00E-02 o | na |
| 87-68-3 | Hexachlorobutadiene | 3.00E-04 n | na | 7.80E-02 e | 7.80E-02 e |
| 87-86-5 | Pentachlorophenol | 3.00E-02 e | na | 1.20E-01 e | na |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.00E-04 n | na | 1.10E-02 e | 1.10E-02 e |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 1.00E-03 e | na | na | na |
| 91-20-3 | Naphthalene | 2.00E-02 e | 8.57E-04 e | na | na |
| 92-52-4 | 1,1'-Biphenyl | 5.00E-02 e | na | na | na |

**Table A34. Reference Doses and Cancer Induction Slope Factors for Chemicals.**

| CASRN | Chemical Name | Reference Dose (RfD) (mg/kg-day) | | Cancer Slope Factor (SF) (mg/kg-day)$^{-1}$ | |
|---|---|---|---|---|---|
| | | Ingestion | Inhalation | Ingestion | Inhalation |
| 95-47-6 | o-Xylene | 2.00E-01 e | 2.86E-02 e | na | na |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 5.00E-02 e | na | na | na |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 9.00E-02 e | 5.71E-02 h | na | na |
| 95-57-8 | 2-Chlorophenol | 5.00E-03 e | na | na | na |
| 95-63-6 | 1,2,4-Trimethylbenzene | 5.00E-02 o | 1.71E-03 o | na | na |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.00E-01 e | na | na | na |
| 98-86-2 | Acetophenone | 1.00E-01 e | na | na | na |
| 98-95-3 | Nitrobenzene | 5.00E-04 e | 5.71E-04 b | na | na |
| 100-00-5 | p-Chloronitrobenzene | 1.00E-03 o | 1.71E-04 o | 6.70E-03 o | na |
| 100-02-7 | 4-Nitrophenol | 8.00E-03 n | na | na | na |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 1.00E-04 o | na | na | na |
| 100-41-4 | Ethyl benzene | 1.00E-01 e | 2.86E-01 e | na | 3.85E-03 n |
| 100-42-5 | Styrene | 2.00E-01 e | 2.86E-01 e | na | na |
| 100-51-6 | Benzyl alcohol | 3.00E-01 h | na | na | na |
| 106-42-3 | p-Xylene | 2.00E-01 e | 2.86E-02 e | na | na |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 5.00E-03 h | na | na | na |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 3.00E-02 n | 2.29E-01 e | 2.40E-02 h | 2.20E-02 n |
| 106-93-4 | 1,2-Dibromoetbane (Ethylene dibromide) | 9.00E-03 e | 2.57E-03 e | 2.00E+00 e | 2.10E+00 e |
| 106-99-0 | 1,3-Butadiene | na | 5.71E-04 e | na | 1.05E-01 e |
| 107-02-8 | 2-Propenal (Acrolein) | 5.00E-04 e | 5.71E-06 e | na | na |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 5.00E-02 h | 2.86E-04 e | na | na |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 2.00E-02 s | 1.40E-03 n | 9.10E-02 e | 9.10E-02 e |
| 107-13-1 | Acrylonitrile | 1.00E-03 h | 5.71E-04 e | 5.40E-01 e | 2.38E-01 e |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 8.00E-02 h | 8.57E-01 e | na | na |
| 108-38-3 | m-Xylene | 2.00E-01 e | 2.86E-02 e | na | na |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 5.00E-02 e | na | na | na |
| 108-67-8 | 1,3,5-Trimethylbenzene | 5.00E-02 o | 1.71E-03 o | na | na |
| 108-87-2 | Methyl cyclohexane | na | 8.57E-01 o | na | na |
| 108-88-3 | Toluene (Methyl benzene) | 8.00E-02 e | 1.43E+00 e | na | na |
| 108-90-7 | Chlorobenzene | 2.00E-02 e | 1.71E-02 n | na | na |
| 108-94-1 | Cyclohexanone | 5.00E+00 e | na | na | na |
| 108-95-2 | Phenol (Carbolic acid) | 3.00E-01 e | na | na | na |
| 109-99-9 | Tetrahydrofuran | 2.10E-01 n | 8.57E-02 n | 7.60E-03 n | 6.80E-03 n |
| 110-00-9 | Furan (Oxacyclopentadiene) | 1.00E-03 e | na | na | na |
| 110-54-3 | n-Hexane | 6.00E-02 h | 2.00E-01 e | na | na |
| 110-80-5 | 2-Ethoxyethanol | 4.00E-01 h | 5.71E-02 e | na | na |
| 110-82-7 | Cyclohexane | na | 1.71E+00 e | na | na |
| 110-86-1 | Pyridine | 1.00E-03 e | na | na | na |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 5.00E-01 e | 3.71E+00 e | na | na |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 6.00E-02 s | 8.60E-04 s | na | na |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 2.00E-02 e | na | 1.40E-02 e | na |
| 117-84-0 | Di-n-octylphthalate | 4.00E-02 o | na | na | na |

**Table A34. Reference Doses and Cancer Induction Slope Factors for Chemicals.**

| CASRN | Chemical Name | Reference Dose (RfD) (mg/kg-day) | | Cancer Slope Factor (SF) $(mg/kg\text{-}day)^{-1}$ | |
|---|---|---|---|---|---|
| | | Ingestion | Inhalation | Ingestion | Inhalation |
| 118-74-1 | Hexachlorobenzene | 8.00E-04 e | na | 1.60E+00 e | 1.60E+00 e |
| 120-12-7 | Anthracene | 3.00E-01 e | na | na | na |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.00E-02 e | 1.14E-03 o | na | na |
| 121-14-2 | 2,4-Dinitrotoluene | 2.00E-03 e | na | na | na |
| 121-44-8 | Triethylamine | na | 2.00E-03 e | na | na |
| 122-39-4 | Diphenylamine | 2.50E-02 e | na | na | na |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | na | na | 1.10E-02 e | na |
| 126-73-8 | Tributyl Phosphate | 2.00E-01 o | na | 5.40E-03 o | na |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.00E-04 e | 2.00E-04 h | na | na |
| 127-18-4 | Tetrachloroethylene | 1.00E-02 e | 1.71E-01 n | 5.40E-01 o | 2.07E-02 o |
| 129-00-0 | Pyrene | 3.00E-02 e | na | na | na |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 9.00E-01 e | na | na | na |
| 156-59-2 | cis-1,2-Dichloroethylene | 1.00E-02 h | na | na | na |
| 156-60-5 | trans-1,2-Dichloroethylene | 2.00E-02 e | na | na | na |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | na | na | 7.30E-01 t | 3.08E-01 t |
| 205-99-2 | Benzo[b]fluoranthene | na | na | 7.30E-01 t | 3.08E-01 t |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 4.00E-02 e | na | na | na |
| 207-08-9 | Benzo[k]fluoranthene | na | na | 7.30E-02 t | 3.08E-02 t |
| 218-01-9 | Chrysene | na | na | 7.30E-03 t | 3.08E-03 t |
| 309-00-2 | Aldrin | 3.00E-05 e | na | 1.70E+01 e | 1.70E+01 e |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 5.00E-04 n | na | 6.30E+00 e | 6.30E+00 e |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 2.00E-04 n | na | 1.80E+00 e | 1.80E+00 e |
| 541-73-1 | 1,3-Dichlorobenzene | 9.00E-04 n | na | na | na |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 3.00E-02 e | 5.71E-03 e | 1.00E-01 e | 1.40E-02 e |
| 563-68-8 | Thallium Acetate | 9.00E-05 e | na | na | na |
| 621-64-7 | N-Nitrosodi-N-propylamine | na | na | 7.00E+00 e | na |
| 1314-62-1 | Vanadium pentoxide | 9.00E-03 e | na | na | na |
| 1330-20-7 | Xylenes (mixtures) | 2.00E-01 e | 2.86E-02 e | na | na |
| 1336-36-3 | Polychlorinated Biphenyls | na | na | 4.00E-01 e | 3.50E-01 e |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | na | na | 7.00E-02 e | 7.00E-02 e |
| 6533-73-9 | Thallium carbonate | 8.00E-05 e | na | na | na |
| 7429-90-5 | Aluminum | 1.00E+00 o | 1.43E-03 o | na | na |
| 7439-89-6 | Iron | 3.00E-01 n | na | na | na |
| 7439-93-2 | Lithium | 2.00E-02 w | na | na | na |
| 7439-96-5 | Manganese | 4.67E-02 e | 1.43E-05 e | na | na |
| 7439-97-6 | Mercury metal vapor | na | 8.57E-05 e | na | na |
| 7439-98-7 | Molybdenum | 5.00E-03 e | na | na | na |
| 7440-02-0 | Nickel (soluble salts) | 2.00E-02 e | na | na | na |
| 7440-22-4 | Silver | 5.00E-03 e | na | na | na |
| 7440-24-6 | Strontium, Stable | 6.00E-01 e | na | na | na |
| 7440-28-0 | Thallium metal | 6.60E-05 ix | na | na | na |
| 7440-31-5 | Tin | 6.00E-01 h | na | na | na |
| 7440-36-0 | Antimony | 4.00E-04 e | na | na | na |

**Table A34. Reference Doses and Cancer Induction Slope Factors for Chemicals.**

| CASRN | Chemical Name | Reference Dose (RfD) (mg/kg-day) | | Cancer Slope Factor (SF) $(mg/kg\text{-}day)^{-1}$ | |
|---|---|---|---|---|---|
| | | Ingestion | Inhalation | Ingestion | Inhalation |
| 7440-38-2 | Arsenic (inorganic) | 3.00E-04 e | na | 1.50E+00 e | 1.51E+01 e |
| 7440-39-3 | Barium | 2.00E-01 e | 1.43E-04 h | na | na |
| 7440-41-7 | Beryllium and compounds | 2.00E-03 e | 5.71E-06 e | na | 8.40E+00 e |
| 7440-42-8 | Boron and borates only | 2.00E-01 e | 5.71E-03 h | na | na |
| 7440-43-9 | Cadmium | 5.00E-04 e | na | na | 6.30E+00 e |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | na | 5.71E-05 o | na | na |
| 7440-48-4 | Cobalt | 2.00E-02 o | 5.71E-06 o | na | 9.80E+00 o |
| 7440-50-8 | Copper | 4.00E-02 h | na | na | na |
| 7440-62-2 | Vanadium metal | 7.00E-03 h | na | na | na |
| 7440-66-6 | Zinc and compounds | 3.00E-01 e | na | na | na |
| 7446-18-6 | Thallium Sulfate | 8.00E-05 e | na | na | na |
| 7487-94-7 | Mercuric chloride | 3.00E-04 e | na | na | na |
| 7664-41-7 | Ammonia | na | 2.86E-02 e | na | na |
| 7723-14-0 | Phosphorus, white | 2.00E-05 e | na | na | na |
| 7782-41-4 | Fluorine (soluble fluoride) | 6.00E-02 e | na | na | na |
| 7782-49-2 | Selenium and compounds | 5.00E-03 e | na | na | na |
| 7791-12-0 | Thallium Chloride | 8.00E-05 e | na | na | na |
| 8001-35-2 | Toxaphene | na | na | 1.10E+00 e | 1.12E+00 e |
| 10102-45-1 | Thallium (I) Nitrate | 9.00E-05 e | na | na | na |
| 11096-82-5 | Aroclor 1260 | na | na | 4.00E-01 e | 3.50E-01 e |
| 11097-69-1 | Aroclor 1254 | 2.00E-05 e | na | 4.00E-01 e | 3.50E-01 e |
| 11104-28-2 | Aroclor 1221 | na | na | 4.00E-01 e | 3.50E-01 e |
| 11141-16-5 | Aroclor 1232 | na | na | 4.00E-01 e | 3.50E-01 e |
| 12672-29-6 | Aroclor 1248 | na | na | 4.00E-01 e | 3.50E-01 e |
| 12674-11-2 | Aroclor 1016 | 7.00E-05 e | na | 7.00E-02 e | 7.00E-02 e |
| 14797-55-8 | Nitrate | 1.60E+00 e | na | na | na |
| 14797-65-0 | Nitrite | 1.00E-01 e | na | na | na |
| 16065-83-1 | Chromium (III) (insoluble salts) | 1.50E+00 e | na | na | na |
| 16984-48-8 | Fluorine anion | 6.00E-02 e | na | na | na |
| 18540-29-9 | Chromium (VI) (soluble salts) | 3.00E-03 e | 2.29E-06 e | na | 4.20E+01 e |
| 22967-92-6 | Methyl Mercury | 1.00E-04 e | na | na | na |
| 53469-21-9 | Aroclor 1242 | na | na | 4.00E-01 e | 3.50E-01 e |
| na | Uranium (soluble salts) | 6.00E-04 c | na | na | na |

**Table A34. Reference Doses and Cancer Induction Slope Factors for Chemicals.**

| CASRN | Chemical Name | Reference Dose (RfD) (mg/kg-day) | | Cancer Slope Factor (SF) $(mg/kg\text{-}day)^{-1}$ | |
|---|---|---|---|---|---|
| | | Ingestion | Inhalation | Ingestion | Inhalation |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- "e" means the number is from Integrated Risk Information System (IRIS) as of August, 2007. Internet address is http://www.epa.gov/iris/
- "o" means the number is from Oak Ridge Risk Assessment Information System (RAIS) as of October, 2006. Internet address is http://risk.lsd.ornl.gov
- "h" means the number is from the Health Effects Assessment Summary Tables (HEAST) FY 1997 Update (EPA-540/R-97/036).
- "n" means National Center for Environmental Assessment (NCEA). Internet address is http://www.epa.gov/ncea.
- "c" means the RfD for Uranium is from the Federal Register, December 2000
- "s" means the number is from the EPA Superfund Risk Assessment web site. Internet address is http://www.epa.gov/superfund/index.htm
- "t" means the number was estimated using toxicity equivalency factors for PAH from EPA
- "w" means the RfD for Lithium (7439-93-2) was withdrawn by EPA
- "ix" means this is provisional guidance from EPA Region 9 for Thallium metal (CAS 7440-28-0). Internet address is www.epa.gov/docs/region09/waste/sfund/prg/index.html
- **Slope factors** give an upper bound on the probability that some type of cancer develops as a result of a lifetime exposed to a given chemical. The slope factor is multiplied by the lifetime average daily chemical dose to give the lifetime risk. Two special cases are noted below.
- The slope factors for vinyl chloride (CAS 75-01-4) apply to the general population. When applying these to occupationally exposed individuals (industrial exposure scenario), the values are reduced by a factor of 2.
- The slope factors for PCBs (CAS 1336-36-3) and the Aroclors are reduced for population (collective) exposures. The slope factors used for normal and lowest risk PCBs are 0.3 (1.0 for dietary intakes) and 0.04 per mg/kg per day.
- **Reference dose** is an estimate of a daily dose to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. Special cases are noted below.
- The RfD for manganese in dietary pathways is 3 times the drinking water RfD shown on the table.
- The RfD for dietary cadmium is twice the drinking water RfD shown on the table.
- The RfD for airborne particulate containing chromium (VI) is 2.86E-05 mg/kg per day.

Values for reference doses and slope factors adopted by the EPA are listed in the Integrated Risk Information System (IRIS) database, which may be examined at http://www.epa.gov/IRIS. This is the primary reference, but is incomplete. Additional toxicity parameters are available from the EPA-540/R-97/036, *Health Effects Assessment Summary Tables (HEAST) FY 1997*. Additional toxicity parameters not available in IRIS or HEAST were found in the table of preliminary remediation goals from EPA Region 9. This table may be obtained at the internet address www.epa.gov/docs/region09/waste/sfund/prg/index.html. A few additional numbers were obtained from the EPA Superfund risk assessment web site, for which the address is http://www.epa.gov/superfund/index.htm. Data for additional chemicals is available from the Risk Assessment Information System (RAIS). The Oak Ridge National Laboratory (ORNL) maintains this toxicological data listing for human health risk assessments. The data may be obtained from the World Wide Web using the location http://risk.lsd.ornl.gov.

The reference dose and cancer slope factors are expressed in terms of the average daily dose. This dose is normalized to the mass of the recipient, and has units of mg/kg per day. The routes of intake are ingestion and inhalation. Reference doses and cancer induction slope factors

for dermal absorption use the ingestion values. The reference doses and cancer induction slope factors for children and adults are assumed to be the same.

Several chemicals have a reference dose or slope factor given for ingestion, but none for inhalation, or vice-versa. Rather than omit this chemical, the calculations were carried out with only the given route of exposure (inhalation or ingestion/dermal). The missing route was ignored. This omission can grossly underestimate the risk from a chemical.

## A4.0 ANIMAL PARAMETERS

The animal parameters discussed here pertain to the eventual concentration of a contaminant in animal products consumed as food, such as fish, milk, meat, poultry, and eggs. The model used to represent various animals assumes contaminant intakes by inhalation, ingestion, and dermal absorption at a rate that changes little during the year. The concentration in the animal reaches a steady-state maximum related to the concentration in its environment. This is a type of equilibrium in which the intake rate of a contaminant is the same as the loss rate, hence, the concentration in the animal product is constant.

Note that the radiological and toxicological doses received by the animals are assumed low enough to not affect their health or metabolism. In equilibrium, the contaminant concentration in the animal product is proportional to the ingestion rate of contamination by the animal. The constants of proportionality are called bioaccumulation factors, or equilibrium transfer factors.

Not all animals have transfer factors developed for them. The focus of research continues to be foods consumed by a significant share of the population. Animal products that are rarely consumed, such as bottom-dwelling fish, crustaceans and mollusks are consumed in minimal amounts. If a group of people is identified who consume significant quantities of these creatures then efforts will be made to quantify the transfer factors that would apply to them. Other land animals such as pigs or goats or deer are assumed to have transfer factors that differ very little from cattle.

The cattle and poultry diets are discussed in the next section. The equilibrium transfer factors for these animals are discussed afterward.

### A4.1 GENERAL ANIMAL PARAMETERS AND PASTURE AREA

The daily intake rates assumed for cattle and poultry are listed in Table A35. These are from NUREG/CR-5512, Section 6.5.1. No distinction is made between the diets of poultry raised for food and egg-laying hens. For comparison with prior Hanford Site performance assessments, the default intake rates used by the GENII program (PNNL-6584) are also shown in Table A35. The water intake rates are the same for both. Note that the GENII program does not distinguish between the two types of stored feed (i.e., hay or grain), nor does it allow the animals to ingest soil directly.

To calculate the contaminant concentrations in the animal foods, it is necessary to introduce a "dry-to-wet ratio". The "dry-to-wet ratio" is a unitless quantity measured as the ratio

of the dry weight of the item to its wet weight. The "dry-to-wet ratio" for stored hay applies at the time of harvest. (In practice the hay is dried before being fed to cattle. Thus the "dry-to-wet ratio" for sun-cured hay is reported as approximately 0.9, similar to stored grain.)

**Table A35. Animal Feed, Water, and Soil Intake Rates.**

| Values from NUREG/CR-5512 for use in the tank waste PA | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Type of Feed** | **dry-to-wet ratio** | **Beef, kg/d** | | **Milk, kg/d** | | **Poultry, kg/d** | |
| | | **dry** | **wet** | **dry** | **wet** | **dry** | **wet** |
| Fresh Forage | 0.22 | 3 | 27 | 8 | 36 | 0.0275 | 0.13 |
| Stored Hay | 0.22 | 6 | 14 | 6 | 29 | 0 | 0 |
| Stored Grain | 0.91 | 3 | 3 | 2 | 2 | 0.0825 | 0.09 |
| | Total Feed, kg/d: | 12 | 44 | 16 | 67 | 0.110 | 0.22 |
| | Soil Ingestion Rate: | 0.6 kg/d | | 0.8 kg/d | | 0.011 kg/d | |
| | Drinking Water: | 50 L/d | | 60 L/d | | 0.3 L/d | |
| Values from GENII Version 1.485 (PNNL-6584) used in previous Hanford Site PAs | | | | | | | |
| **Type of Feed** | **dry-to-wet ratio** | **Beef, kg/d** | | **Milk, kg/d** | | **Poultry, kg/d** | |
| | | **dry** | **wet** | **dry** | **wet** | **dry** | **wet** |
| Fresh Forage | 0.20 | 10 | 51 | 8 | 41 | 0 | 0 |
| Stored Hay | 0.18 | 3 | 17 | 2 | 14 | 0.022 | 0.12 |
| Stored Grain | NA | NA | NA | NA | NA | NA | NA |
| | Total Feed, kg/d: | 13 | 68 | 10 | 55 | 0.022 | 0.12 |
| | Soil Ingestion Rate: | NA | | NA | | NA | |
| | Drinking Water: | 50 L/d | | 60 L/d | | 0.3 L/d | |

Notes:

- The wet weights for fresh forage and stored hay are at the time of harvest or grazing.
- The GENII software (Version 1.485) has one type of stored feed that uses the soil-to-plant concentration factors for grains. Hence the "NA" for "Stored Grain". In addition, GENII does not consider ingestion of soil by grazing animals.

The intake rates found in NUREG/CR-5512 will be used in the current performance assessment, as they were in the 2001 ILAW PA (DOE/ORP-2000-24). The principal reason for this change from prior Hanford performance assessments is the extra detail provided for the diet. Previous performance assessments relied on the GENII software Version 1.485, which is unable to accommodate this detail.

The exposure of special groups living near waste sites or near locations where the groundwater enters the Columbia River would probably include the consumption of some type of native game animals. These animals could acquire radioactivity from drinking and grazing near locations were groundwater enters the river. The larger examples of these, such as deer, would

graze over a large area. Thus only a small portion of the deer's plant intakes would be contaminated. Similarly, the smaller animals might derive all of their nourishment from a contaminated area. However, such animals would have to be harvested from many locations over the course of a year. The average concentration from all such animals would be much lower due to the large forage area needed for hunting and gathering. For the cases where the ground water is the main source of contamination, it will be assumed that the game animals are contaminated at such a low level compared with the domesticated animals that the dose from game animals can be ignored. For the cases where the Columbia River is the main source of contaminated water, the animals will be assumed to obtain all of their drinking water from the river, but their vegetation intakes will be assumed uncontaminated. The transfer factors for beef will be used to represent transfer to the edible portion of the deer. The daily water intake for the deer is assumed to be 25% that of the milk cow. Waterfowl are similarly represented using the poultry data, except there is no difference in the daily water intake.

It should be noted that animals killed by native hunters would be more efficiently scavenged than common farm animals. Some of the internal organs would be eaten. The animal skins could be used for clothing, and larger bones could be used as tools or ceremonial items. The more extensive use of animal parts could increase the exposed person's radiation dose. Nevertheless, it will be assumed that this dose is small compared with that from farm animals.

The land area needed to support a cow can be calculated from the consumption rates given in Table A35. A search of the internet for "pasture size" or "animal unit month" uncovers numerous reports dealing with estimating how much land is needed to support grazing cows. One common factor in the calculations is the fraction of the grass lost to trampling. The usual factor is 40%, which will be used here also. An additional consideration is the fraction of the standing biomass that the cow can eat. The usual factor is 50%, which will be used here also. Additional factors, such as the standing biomass and growing period are presented in Table A42 below. An irrigation period of 0.5 y means that there are 6 crops of grass (30 d each). The irrigation period (i.e., the grazing period) cancels out of the equation below.

$$A_{Grass} = \frac{M_{Grass}\, T_{Grow,Grass}}{Y_{Grass}\, F_{Eaten}\left(1 - F_{Trample}\right)} = \frac{(36\ \text{kg/d})(30\ \text{d})}{(1.5\ \text{kg/m}^2)(0.5)(1-0.4)} = 2{,}400\ \text{m}^2$$

where,

$A_{Grass}$ = pasture grass area needed for the milk cow, 2,400 $m^2$
$F_{Eaten}$ = fraction of standing biomass eaten by the cow while grazing, 0.5
$F_{Trample}$ = fraction of the standing biomass trampled by the cow while grazing, 0.4
$M_{Grass}$ = mass of grass eaten each day by the cow from Table A35, 36 kg (wet)/d
$T_{Grow,Grass}$ = growing period for the grass from Table A42, 30 days
$Y_{Grass}$ = standing biomass for mature grass from Table A42, 1.5 $kg/m^2$

A similar equation is needed for the hay field. The hay grows during the irrigation period and is consumed by the cow during the remainder of the year, the no-irrigation period. An irrigation period of 0.5 y means there are 4 crops of hay (45 d each). Since the hay growing period is the same length as the hay consumption period, it cancels out of the equation below. The loss from trampling is not needed, but the fraction harvested is used. The harvested fraction is assumed to be the same as the fraction that the cow eats while grazing, 50%.

$$A_{Hay} = \frac{M_{Hay}\ T_{Grow,Hay}}{Y_{Hay}\ F_{Harvest}} = \frac{(29\ kg/d)(45\ d)}{(1.0\ kg/m^2)(0.5)} = 2{,}600\ m^2$$

where,

$A_{Hay}$ = hay field area needed for the milk cow, 2,600 $m^2$
$F_{Harvest}$ = fraction of standing biomass harvested for the cow, 0.5
$M_{Hay}$ = mass of hay eaten each day by the cow from Table A35, 29 kg (wet)/d
$T_{Grow,Hay}$ = growing period for the grass from Table A42, 45 days
$Y_{Hay}$ = standing biomass for mature grass from Table A42, 1.5 $kg/m^2$

## A4.2 EQUILIBRIUM TRANSFER FACTORS FOR RADIONUCLIDES

The equilibrium transfer factors for cattle and poultry relate the rate of intake of a radionuclide to the eventual steady-state concentration in meat or milk or eggs. These parameters are the ratio of the equilibrium concentration of a nuclide in the animal product to the daily intake by the animal. For beef, poultry and eggs the units are Ci/kg per Ci/d (equivalent to d/kg), while for milk the units are Ci/L(milk) per Ci/d (equivalent to d/L). Transfer factors for organs such as liver or brain are not available. Since some elements may be found in higher concentrations in these tissues, individuals who consume the organs would receive higher doses from the radioactive isotopes of the elements.

The concentration of waterborne contaminants in fish is assumed to be proportional to the concentration of the contaminant in the water environment of the fish. The constant of proportionality for fish is called a "bioaccumulation" factor. It is the average concentration of the contaminant in the edible portion of the fish divided by the concentration in the water. This parameter has units of L/kg. The transfer factors used in the present report for cows, chickens and fish are shown in Table A36. Bioaccumulation factors include the effects of contaminants in sediments, plant life, and other aquatic organisms contribute to contamination in the edible portions of the fish.

There are several sources for these transfer factors, as indicated by the letter beside each number in Table A36. The following hierarchy is used for selecting values. The first values are chosen from PNWD-2023. This report compiled Hanford-specific data developed for dose reconstruction of historical atmospheric releases from the Hanford Site. For elements that are not discussed in PNWD-2023, values from IAEA Technical Report 364 were chosen. The IAEA report is a compilation from many sources. For elements not discussed in the IAEA report, values from ORNL-5786 were used. For elements not discussed in these reports, values from NUREG/CR-5512 Volume 1 were chosen. For elements not discussed in those reports, values from NCRP-123 were used. A few elements still had no assigned values. In these cases values were assumed based on chemical similarities.

For cows and chickens it was necessary to assume values for berkelium (Bk). These were assumed to be the same as americium (Am). For the chicken it was necessary to assume values for boron (B), aluminum (Al), titanium (Ti), and vanadium (V). These were assumed to be the same as silicon (Si), gallium (Ga), scandium (Sc), and chromium (Cr), respectively.

For accumulation in cows and chickens, the PNWD-2023 report only supplied a value for

transfer of iodine (I) to milk. The transfer factors for the other animal products are specified as a range and this range covers the values given in the IAEA report. For accumulation in fish, PNWD-2023 provides values for the elements sodium (Na), phosphorus (P), arsenic (As), and neptunium (Np). It is assumed that plutonium (Pu), americium (Am), and curium (Cm) share the same accumulation factor as Np.

**Table A36. Transfer Factors for Radionuclides to Cows, Chickens, and Fish.**

| Element | Meat (day/kg) | Milk (day/L) | Poultry (day/kg) | Eggs (day/kg) | Fish (L/kg) | Atomic Number |
|---|---|---|---|---|---|---|
| H | na | na | na | na | 1.0 b | 1 |
| Be | 1.0E-03 c | 9.0E-07 c | 0.40 d | 0.020 d | 100 b | 4 |
| B | 8.0E-04 c | 1.5E-03 c | 0.20 d | 0.80 d | 5.0 e | 5 |
| C | 0.0489 f | 0.0105 f | 4.16 f | 3.12 f | 50,000 b | 6 |
| F | 0.15 c | 1.0E-03 c | 0.010 d | 2.0 d | 10 d | 9 |
| Na | 0.080 b | 0.016 b | 0.010 d | 6.0 b | 8.0 a | 11 |
| Al | 1.5E-03 c | 2.0E-04 c | 0.30 d | 0.80 d | 500 e | 13 |
| Si | 4.0E-05 c | 2.0E-05 c | 0.20 d | 0.80 d | 20 e | 14 |
| P | 0.050 b | 0.016 b | 0.19 d | 10 d | 1,500 a | 15 |
| Cl | 0.020 b | 0.017 b | 0.030 d | 2.0 d | 50 d | 17 |
| K | 0.020 b | 7.2E-03 b | 0.40 d | 1.0 b | 1,000 d | 19 |
| Ca | 2.0E-03 b | 3.0E-03 b | 0.040 b | 0.40 b | 40 d | 20 |
| Ti | 0.030 c | 0.010 c | 4.0E-03 d | 3.0E-03 d | 1,000 e | 22 |
| V | 2.5E-03 c | 2.0E-05 c | 0.20 d | 0.80 d | 200 e | 23 |
| Mn | 5.0E-04 b | 3.0E-05 b | 0.050 b | 0.060 b | 400 b | 25 |
| Fe | 0.020 b | 3.0E-05 b | 1.0 b | 1.0 b | 200 b | 26 |
| Co | 0.010 b | 3.0E-04 b | 2.0 b | 0.10 b | 300 b | 27 |
| Ni | 5.0E-03 b | 0.016 b | 1.0E-03 d | 0.10 d | 100 b | 28 |
| As | 2.0E-03 c | 6.0E-05 c | 0.83 d | 0.80 d | 244 a | 33 |
| Se | 0.015 c | 4.0E-03 c | 9.0 b | 9.0 b | 170 d | 34 |
| Rb | 0.010 b | 0.012 b | 2.0 d | 3.0 d | 2,000 b | 37 |
| Sr | 8.0E-03 b | 2.8E-03 b | 0.080 b | 0.20 b | 60 b | 38 |
| Y | 1.0E-03 b | 2.0E-05 c | 0.010 b | 2.0E-03 b | 30 b | 39 |
| Zr | 1.0E-06 b | 5.5E-07 b | 6.0E-05 b | 2.0E-04 b | 300 b | 40 |
| Nb | 3.0E-07 b | 4.1E-07 b | 3.0E-04 b | 1.0E-03 b | 300 b | 41 |
| Mo | 1.0E-03 b | 1.7E-03 b | 1.0 b | 0.90 b | 10 b | 42 |
| Tc | 1.0E-04 b | 1.4E-04 b | 0.030 b | 3.0 b | 20 b | 43 |
| Ru | 0.050 b | 3.3E-06 b | 0.24 b | 5.0E-03 b | 10 b | 44 |
| Pd | 4.0E-03 c | 0.010 c | 3.0E-04 d | 4.0E-03 d | 10 d | 46 |
| Ag | 3.0E-03 b | 5.0E-05 b | 2.0 b | 0.50 d | 5.0 b | 47 |
| Cd | 4.0E-04 b | 1.0E-03 c | 0.80 b | 0.10 b | 200 d | 48 |
| In | 8.0E-03 c | 1.0E-04 c | 0.30 d | 0.80 d | 100,000 d | 49 |
| Sn | 0.080 c | 1.0E-03 c | 0.20 d | 0.80 d | 3,000 b | 50 |
| Sb | 4.0E-05 b | 2.5E-05 b | 6.0E-03 d | 0.070 d | 100 b | 51 |
| Te | 7.0E-03 b | 4.5E-04 b | 0.60 b | 5.0 b | 400 b | 52 |
| I | 0.040 b | 0.012 a | 0.010 b | 3.0 b | 40 b | 53 |
| Cs | 0.050 b | 7.9E-03 b | 2.0 b | 0.40 b | 2,000 b | 55 |
| Ba | 2.0E-04 b | 4.8E-04 b | 9.0E-03 b | 0.90 b | 4.0 b | 56 |
| Ce | 2.0E-05 b | 3.0E-05 b | 4.0E-03 b | 9.0E-05 b | 30 b | 58 |
| Pm | 5.0E-03 c | 2.0E-05 c | 2.0E-03 b | 0.020 b | 30 b | 61 |

**Table A36. Transfer Factors for Radionuclides to Cows, Chickens, and Fish.**

| Element | Meat (day/kg) | Milk (day/L) | Poultry (day/kg) | Eggs (day/kg) | Fish (L/kg) | Atomic Number |
|---|---|---|---|---|---|---|
| Sm | 5.0E-03 c | 2.0E-05 c | 4.0E-03 d | 7.0E-03 d | 25 d | 62 |
| Eu | 5.0E-03 c | 2.0E-05 c | 4.0E-03 d | 7.0E-03 d | 50 b | 63 |
| Gd | 3.5E-03 c | 2.0E-05 c | 4.0E-03 d | 7.0E-03 d | 25 d | 64 |
| Tb | 4.5E-03 c | 2.0E-05 c | 4.0E-03 d | 7.0E-03 d | 25 d | 65 |
| Ho | 4.5E-03 c | 2.0E-05 c | 4.0E-03 d | 7.0E-03 d | 25 d | 67 |
| Re | 8.0E-03 c | 1.5E-03 c | 0.040 d | 0.40 d | 120 d | 75 |
| Hg | 0.25 c | 4.7E-04 b | 0.030 b | 0.20 d | 1,000 b | 80 |
| Tl | 0.040 c | 2.0E-03 c | 0.30 d | 0.80 d | 10,000 e | 81 |
| Pb | 4.0E-04 b | 2.5E-04 c | 0.20 d | 0.80 d | 300 b | 82 |
| Bi | 4.0E-04 c | 5.0E-04 c | 0.10 d | 0.80 d | 10 b | 83 |
| Po | 5.0E-03 b | 3.4E-04 b | 0.90 d | 7.0 d | 50 b | 84 |
| Ra | 9.0E-04 b | 1.3E-03 b | 0.030 d | 2.0E-05 d | 50 b | 88 |
| Ac | 2.5E-05 c | 2.0E-05 c | 4.0E-03 d | 2.0E-03 d | 25 d | 89 |
| Th | 6.0E-06 c | 5.0E-06 c | 4.0E-03 d | 2.0E-03 d | 100 b | 90 |
| Pa | 1.0E-05 c | 5.0E-06 c | 4.0E-03 d | 2.0E-03 d | 10 b | 91 |
| U | 3.0E-04 b | 4.0E-04 b | 1.0 b | 1.0 b | 10 b | 92 |
| Np | 1.0E-03 b | 5.0E-06 b | 4.0E-03 d | 2.0E-03 d | 21 a | 93 |
| Pu | 1.0E-05 b | 1.1E-06 b | 3.0E-03 b | 5.0E-04 b | 21 a | 94 |
| Am | 4.0E-05 b | 1.5E-06 b | 6.0E-03 b | 4.0E-03 b | 21 a | 95 |
| Cm | 3.5E-06 c | 2.0E-05 c | 4.0E-03 d | 2.0E-03 d | 21 a | 96 |
| Bk | 4.0E-05 b | 1.5E-06 b | 6.0E-03 b | 4.0E-03 b | 25 e | 97 |
| Cf | 5.0E-03 d | 7.5E-07 d | 4.0E-03 d | 2.0E-03 d | 25 d | 98 |

Notes:

- All of the transfer factors are derived using the wet weights. Note that Egg values are for egg contents rather than the whole egg.
- Cow and chicken parameters were selected using the following hierarchy: (a) PNWD-2023, (b) IAEA #364, (c) ORNL-5786, and (d) NUREG/CR-5512. Bk is assumed the same as Am for all cow and chicken parameters. Cow and chicken transfer factors for carbon were computed from the equilibrium model described in the text (f). Values for hydrogen are not used in the calculations (na) because an equilibrium transfer model is used instead.
- For the Poultry and Egg (i.e., chicken), the values for Si are used for B, the values for Ga are used for Al, the values for Sc are used for Ti, and the values for Cr are used for V.
- Fish bioaccumulation factors were selected using the following hierarchy: (a) PNWD-2023, (b) IAEA #364, (c) ORNL-5786, (d) NUREG/CR-5512, and (e) NCRP #123.

Transfer factors for tritium (H-3) are not needed because the animal concentration is calculated using the equilibrium model described in the discussion of scenario dose factors. The transfer factors for C-14 are computed from an equilibrium model. The ratio of radioactive C-14 to the non-radioactive carbon in the animal's diet is assumed to be reproduced in the food product. The equilibrium transfer factor is then the fraction of carbon in the food product divided by the daily intake of carbon. The assumed element fractions are listed in Table A37 below. Values in this table were taken from NUREG/CR-5512. The formula to describe the calculation of C-14 transfer factors is shown below. Note that the carbon content of water is assumed insignificant.

$$B_{A,q,C-14} = \frac{F_{C,q}}{F_{C,s}M_{S,q} + \sum_{p} F_{C,p}M_{V,p,q}}$$

where,

$B_{A,q,C-14}$ = animal transfer factor for C-14 into animal product type q shown in Table A36, in day/kg

$F_{C,p}$ = mass fraction of carbon in fodder type p from Table A37

$F_{C,q}$ = mass fraction of carbon in animal product type q from Table A37

$F_{C,s}$ = mass fraction of carbon in garden soil from Table A37

$M_{S,q}$ = daily mass of soil ingested by animal type q in Table A35, in kg/d

$M_{V,p,q}$ = daily mass of animal fodder type p eaten by animal type q, in kg (wet)/d. These amounts are shown in Table A35.

p = index to the various types of animal fodder shown in Table A42

q = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

**Table A37. Hydrogen and Carbon Fractions for Equilibrium Models.**

| Food Pathway Item | Hydrogen Fraction | Carbon Fraction |
|---|---|---|
| Garden Soil | 0.0149 | 0.03 |
| Leafy Vegetables | 0.10 | 0.09 |
| Other Vegetables | 0.10 | 0.09 |
| Fruit | 0.10 | 0.09 |
| Grain | 0.068 | 0.40 |
| Fresh Forage | 0.10 | 0.09 |
| Stored Hay | 0.10 | 0.09 |
| Stored Grain | 0.068 | 0.40 |
| Beef | 0.10 | 0.24 |
| Milk | 0.11 | 0.07 |
| Poultry | 0.10 | 0.20 |
| Eggs | 0.11 | 0.15 |

Notes:

- All fractions listed above are based on the wet weight of the item. The effective water fraction is the hydrogen fraction times 8.94, which is the ratio of molecular weights for water and hydrogen.
- All fractions are taken from NUREG/CR-5512, except for the hydrogen fraction in garden soil, which is calculated as the product of the soil moisture content (20% by volume) and the density of water (1.0 kg/L) divided by the product of the soil density (1.5 kg/L) and 8.94.
- Hydrogen fractions include organically bound hydrogen as well as water.
- The carbon fraction for garden soil assumes the presence of organic matter not found in subsurface Hanford soil.

The bioaccumulation factors shown in Table A36 are used to estimate total population dose from fish consumption to people living near the Columbia River. The edible portion of fish is the muscle normally cooked and consumed. The rest of the fish is assumed to be discarded. If there are individuals who eat or otherwise use other parts of the fish they could receive additional dose.

A subject requiring research is the equilibrium transfer factors for wild animals consuming native vegetation. These species may be "harvested" by humans for food. In addition, since standard uptake factors are for muscle tissue only, there would need to be organ-specific uptake factors for those organ meats that are consumed by special groups of people.

## A4.3 EQUILIBRIUM TRANSFER FACTORS FOR CHEMICALS

As with radionuclides, the equilibrium transfer factors for cattle and poultry relate the rate of intake of a chemical to the eventual steady-state concentration in meat or milk or eggs. These parameters are the ratio of the equilibrium concentration of a chemical in the animal product to the daily intake by the animal. The units are g/kg per g/d (equivalent to d/kg). Transfer factors for chemicals are scarce. The need to estimate concentrations in the animal products consumed by people motivated the creation of methods to estimate these parameters. For organic chemicals, the transfer factors for beef, milk, and eggs were estimated from the octanol-water partition coefficient ($K_{OW}$) of the chemical using formulas presented by McKone (1994). Values for Log $K_{OW}$ are given in Table A3. Numbers for the accumulation of organic chemicals in fish were obtained from the EPI Suite software version 3.20. In particular, the program named BCFwin was used to calculate the transfer factors for fish. The transfer factors for fish are known as bioconcentration factors, abbreviated BCF.

$$F_{BEEF} = (2.5 \times 10^{-8})\ K_{OW}$$

$$F_{MILK} = (7.9 \times 10^{-9})\ K_{OW}$$

$$F_{EGG} = (8.0 \times 10^{-6})\ K_{OW}$$

For inorganic chemicals, the transfer coefficients are obtained from Table A36. No method was found to estimate the transfer of organic chemicals into poultry. The missing values were assigned values of zero for the calculations of unit risk factors. It is assumed that the poultry contribution to the total hazard index or cancer risk is small because poultry is only considered along with beef, milk, and eggs. The list of equilibrium transfer factors for the chemicals of interest in the representative animal products is shown in Table A38.

**Table A38. Transfer Factors for Chemicals into Cows, Chickens, and Fish.**

| CASRN | Chemical | Beef (d/kg) | Milk (d/kg) | Poultry (d/kg) | Eggs (d/kg) | Fish (L/kg) |
|---|---|---|---|---|---|---|
| 50-32-8 | Benzo[a]pyrene | 3.37E-02 | 1.07E-02 | na | 1.08E+01 | 1.05E+04 |
| 53-70-3 | Dibenz[a,h]anthracene | 1.41E-01 | 4.44E-02 | na | 4.50E+01 | 3.14E+04 |
| 56-23-5 | Carbon tetrachloride | 1.69E-05 | 5.34E-06 | na | 5.41E-03 | 3.01E+01 |
| 56-55-3 | Benz[a]anthracene | 1.44E-02 | 4.55E-03 | na | 4.60E+00 | 5.44E+03 |
| 57-12-5 | Cyanide, free | 1.41E-08 | 4.44E-09 | na | 4.50E-06 | 3.16E+00 |
| 57-14-7 | 1,1-Dimethylhydrazine | 1.61E-09 | 5.10E-10 | na | 5.17E-07 | 3.16E+00 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 3.01E-09 | 9.50E-10 | na | 9.62E-07 | 3.16E+00 |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 1.31E-04 | 4.15E-05 | na | 4.20E-02 | 1.46E+02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 1.94E-07 | 6.13E-08 | na | 6.21E-05 | 3.16E+00 |
| 60-34-4 | Methylhydrazine | 2.23E-09 | 7.04E-10 | na | 7.13E-07 | 3.16E+00 |
| 60-57-1 | Dieldrin | 6.28E-03 | 1.98E-03 | na | 2.01E+00 | 2.87E+03 |

**Table A38. Transfer Factors for Chemicals into Cows, Chickens, and Fish.**

| CASRN | Chemical | Beef (d/kg) | Milk (d/kg) | Poultry (d/kg) | Eggs (d/kg) | Fish (L/kg) |
|---|---|---|---|---|---|---|
| 62-75-9 | N-Nitrosodimethylamine | 6.73E-09 | 2.13E-09 | na | 2.15E-06 | 3.16E+00 |
| 64-18-6 | Formic acid | 7.21E-09 | 2.28E-09 | na | 2.31E-06 | 3.16E+00 |
| 67-56-1 | Methanol (Methyl alcohol) | 4.25E-09 | 1.34E-09 | na | 1.36E-06 | 3.16E+00 |
| 67-64-1 | Acetone (2-Propanone) | 1.44E-08 | 4.55E-09 | na | 4.60E-06 | 3.16E+00 |
| 67-66-3 | Chloroform | 2.33E-06 | 7.37E-07 | na | 7.47E-04 | 6.56E+00 |
| 67-72-1 | Hexachloroethane | 3.45E-04 | 1.09E-04 | na | 1.10E-01 | 3.07E+02 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.90E-07 | 5.99E-08 | na | 6.07E-05 | 3.16E+00 |
| 71-43-2 | Benzene | 3.37E-06 | 1.07E-06 | na | 1.08E-03 | 8.71E+00 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 7.73E-06 | 2.44E-06 | na | 2.47E-03 | 1.65E+01 |
| 72-20-8 | Endrin | 3.96E-03 | 1.25E-03 | na | 1.27E+00 | 2.01E+03 |
| 74-83-9 | Bromomethane | 3.87E-07 | 1.22E-07 | na | 1.24E-04 | 1.65E+00 |
| 74-87-3 | Methyl chloride (Chloromethane) | 2.03E-07 | 6.42E-08 | na | 6.50E-05 | 3.16E+00 |
| 75-00-3 | Ethyl Chloride | 6.73E-07 | 2.13E-07 | na | 2.15E-04 | 2.52E+00 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 1.04E-06 | 3.29E-07 | na | 3.33E-04 | 3.53E+00 |
| 75-05-8 | Acetonitrile | 1.14E-08 | 3.61E-09 | na | 3.66E-06 | 3.16E+00 |
| 75-07-0 | Acetaldehyde | 1.14E-08 | 3.61E-09 | na | 3.66E-06 | 3.16E+00 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 4.45E-07 | 1.40E-07 | na | 1.42E-04 | 1.83E+00 |
| 75-15-0 | Carbon disulfide | 2.18E-06 | 6.88E-07 | na | 6.97E-04 | 6.22E+00 |
| 75-21-8 | Ethylene Oxide (Oxirane) | 1.25E-08 | 3.96E-09 | na | 4.01E-06 | 3.16E+00 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 1.54E-06 | 4.87E-07 | na | 4.93E-04 | 4.77E+00 |
| 75-35-4 | 1,1-Dichloroethylene | 3.37E-06 | 1.07E-06 | na | 1.08E-03 | 8.71E+00 |
| 75-45-6 | Chlorodifluoromethane | 3.01E-07 | 9.50E-08 | na | 9.62E-05 | 1.35E+00 |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 2.81E-06 | 8.86E-07 | na | 8.98E-04 | 7.56E+00 |
| 75-69-4 | Trichlorofluoromethane | 8.47E-06 | 2.68E-06 | na | 2.71E-03 | 1.77E+01 |
| 75-71-8 | Dichlorodifluoromethane | 3.61E-06 | 1.14E-06 | na | 1.16E-03 | 9.19E+00 |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 3.61E-05 | 1.14E-05 | na | 1.16E-02 | 5.41E+01 |
| 76-44-8 | Heptachlor | 3.15E-02 | 9.95E-03 | na | 1.01E+01 | 9.93E+03 |
| 78-83-1 | Isobutanol | 1.44E-07 | 4.55E-08 | na | 4.60E-05 | 3.16E+00 |
| 78-87-5 | 1,2-Dichloropropane | 2.39E-06 | 7.54E-07 | na | 7.64E-04 | 6.68E+00 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 4.87E-08 | 1.54E-08 | na | 1.56E-05 | 3.16E+00 |
| 79-00-5 | 1,1,2-Trichloroethane | 1.94E-06 | 6.13E-07 | na | 6.21E-04 | 5.69E+00 |
| 79-01-6 | Trichloroethylene | 6.58E-06 | 2.08E-06 | na | 2.10E-03 | 1.46E+01 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 5.60E-08 | 1.77E-08 | na | 1.79E-05 | 3.16E+00 |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 6.14E-06 | 1.94E-06 | na | 1.96E-03 | 1.38E+01 |
| 79-46-9 | 2-Nitropropane | 2.13E-07 | 6.72E-08 | na | 6.81E-05 | 3.16E+00 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 1.09E-03 | 3.45E-04 | na | 3.49E-01 | 7.46E+02 |
| 83-32-9 | Acenaphthene | 2.08E-04 | 6.57E-05 | na | 6.65E-02 | 2.08E+02 |
| 84-66-2 | Diethyl phthalate | 6.58E-06 | 2.08E-06 | na | 2.10E-03 | 1.46E+01 |
| 84-74-2 | Dibutyl phthalate | 7.91E-04 | 2.50E-04 | na | 2.53E-01 | 5.82E+02 |
| 85-68-7 | Butyl benzyl phthalate | 1.34E-03 | 4.24E-04 | na | 4.30E-01 | 8.75E+02 |
| 86-73-7 | Fluorene | 3.78E-04 | 1.20E-04 | na | 1.21E-01 | 3.30E+02 |
| 86-74-8 | Carbazole | 1.31E-04 | 4.15E-05 | na | 4.20E-02 | 1.46E+02 |
| 87-68-3 | Hexachlorobutadiene | 1.51E-03 | 4.76E-04 | na | 4.82E-01 | 9.56E+02 |

**Table A38. Transfer Factors for Chemicals into Cows, Chickens, and Fish.**

| CASRN | Chemical | Beef (d/kg) | Milk (d/kg) | Poultry (d/kg) | Eggs (d/kg) | Fish (L/kg) |
|---|---|---|---|---|---|---|
| 87-86-5 | Pentachlorophenol | 3.30E-03 | 1.04E-03 | na | 1.05E+00 | 6.96E+02 |
| 88-06-2 | 2,4,6-Trichlorophenol | 1.22E-04 | 3.87E-05 | na | 3.92E-02 | 5.51E+01 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 9.08E-05 | 2.87E-05 | na | 2.90E-02 | 1.10E+02 |
| 91-20-3 | Naphthalene | 4.99E-05 | 1.58E-05 | na | 1.60E-02 | 6.93E+01 |
| 92-52-4 | 1,1'-Biphenyl | 2.39E-04 | 7.54E-05 | na | 7.64E-02 | 2.32E+02 |
| 95-47-6 | o-Xylene | 3.30E-05 | 1.04E-05 | na | 1.05E-02 | 5.04E+01 |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 2.23E-06 | 7.04E-07 | na | 7.13E-04 | 6.33E+00 |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 6.73E-05 | 2.13E-05 | na | 2.15E-02 | 8.73E+01 |
| 95-57-8 | 2-Chlorophenol | 3.53E-06 | 1.12E-06 | na | 1.13E-03 | 9.03E+00 |
| 95-63-6 | 1,2,4-Trimethylbenzene | 1.07E-04 | 3.37E-05 | na | 3.41E-02 | 1.24E+02 |
| 95-95-4 | 2,4,5-Trichlorophenol | 1.31E-04 | 4.15E-05 | na | 4.20E-02 | 5.81E+01 |
| 98-86-2 | Acetophenone | 9.50E-07 | 3.00E-07 | na | 3.04E-04 | 4.75E-01 |
| 98-95-3 | Nitrobenzene | 1.77E-06 | 5.59E-07 | na | 5.66E-04 | 5.30E+00 |
| 100-00-5 | p-Chloronitrobenzene | 6.14E-06 | 1.94E-06 | na | 1.96E-03 | 1.38E+01 |
| 100-02-7 | 4-Nitrophenol | 2.03E-06 | 6.42E-07 | na | 6.50E-04 | 5.90E+00 |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 7.21E-07 | 2.28E-07 | na | 2.31E-04 | 2.66E+00 |
| 100-41-4 | Ethyl benzene | 3.53E-05 | 1.12E-05 | na | 1.13E-02 | 5.31E+01 |
| 100-42-5 | Styrene | 2.23E-05 | 7.04E-06 | na | 7.13E-03 | 3.73E+01 |
| 100-51-6 | Benzyl alcohol | 3.15E-07 | 9.95E-08 | na | 1.01E-04 | 3.14E-01 |
| 106-42-3 | p-Xylene | 3.53E-05 | 1.12E-05 | na | 1.13E-02 | 5.31E+01 |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 2.18E-06 | 6.88E-07 | na | 6.97E-04 | 6.22E+00 |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 6.89E-05 | 2.18E-05 | na | 2.20E-02 | 8.89E+01 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 2.28E-06 | 7.20E-07 | na | 7.30E-04 | 6.44E+00 |
| 106-99-0 | 1,3-Butadiene | 2.44E-06 | 7.72E-07 | na | 7.82E-04 | 6.80E+00 |
| 107-02-8 | 2-Propenal (Acrolein) | 2.44E-08 | 7.72E-09 | na | 7.82E-06 | 3.16E+00 |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 2.13E-06 | 6.72E-07 | na | 6.81E-04 | 6.11E+00 |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 7.55E-07 | 2.39E-07 | na | 2.42E-04 | 2.75E+00 |
| 107-13-1 | Acrylonitrile | 4.45E-08 | 1.40E-08 | na | 1.42E-05 | 3.16E+00 |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 5.10E-07 | 1.61E-07 | na | 1.63E-04 | 2.04E+00 |
| 108-38-3 | m-Xylene | 3.96E-05 | 1.25E-05 | na | 1.27E-02 | 5.81E+01 |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 2.28E-06 | 7.20E-07 | na | 7.30E-04 | 6.44E+00 |
| 108-67-8 | 1,3,5-Trimethylbenzene | 6.58E-05 | 2.08E-05 | na | 2.10E-02 | 8.58E+01 |
| 108-87-2 | Methyl cyclohexane | 1.02E-04 | 3.22E-05 | na | 3.26E-02 | 1.20E+02 |
| 108-88-3 | Toluene (Methyl benzene) | 1.34E-05 | 4.24E-06 | na | 4.30E-03 | 2.52E+01 |
| 108-90-7 | Chlorobenzene | 1.73E-05 | 5.47E-06 | na | 5.53E-03 | 3.07E+01 |
| 108-94-1 | Cyclohexanone | 1.61E-07 | 5.10E-08 | na | 5.17E-05 | 3.16E+00 |
| 108-95-2 | Phenol (Carbolic acid) | 7.21E-07 | 2.28E-07 | na | 2.31E-04 | 2.66E+00 |
| 109-99-9 | Tetrahydrofuran | 7.21E-08 | 2.28E-08 | na | 2.31E-05 | 3.16E+00 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 5.47E-07 | 1.73E-07 | na | 1.75E-04 | 2.15E+00 |
| 110-54-3 | n-Hexane | 1.99E-04 | 6.28E-05 | na | 6.35E-02 | 2.01E+02 |
| 110-80-5 | 2-Ethoxyethanol | 1.20E-08 | 3.78E-09 | na | 3.83E-06 | 3.16E+00 |
| 110-82-7 | Cyclohexane | 6.89E-05 | 2.18E-05 | na | 2.20E-02 | 8.89E+01 |
| 110-86-1 | Pyridine | 1.12E-07 | 3.53E-08 | na | 3.57E-05 | 3.16E+00 |

**Table A38. Transfer Factors for Chemicals into Cows, Chickens, and Fish.**

| CASRN | Chemical | Beef (d/kg) | Milk (d/kg) | Poultry (d/kg) | Eggs (d/kg) | Fish (L/kg) |
|---|---|---|---|---|---|---|
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 1.69E-07 | 5.34E-08 | na | 5.41E-05 | 3.16E+00 |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 7.21E-09 | 2.28E-09 | na | 2.31E-06 | 3.16E+00 |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 9.95E-01 | 3.15E-01 | na | 3.18E+02 | 3.08E+02 |
| 117-84-0 | Di-n-octylphthalate | 3.15E+00 | 9.95E-01 | na | 1.01E+03 | 6.35E+01 |
| 118-74-1 | Hexachlorobenzene | 1.34E-02 | 4.24E-03 | na | 4.30E+00 | 5.15E+03 |
| 120-12-7 | Anthracene | 7.05E-04 | 2.23E-04 | na | 2.25E-01 | 5.33E+02 |
| 120-82-1 | 1,2,4-Trichlorobenzene | 2.62E-04 | 8.27E-05 | na | 8.38E-02 | 2.49E+02 |
| 121-14-2 | 2,4-Dinitrotoluene | 2.39E-06 | 7.54E-07 | na | 7.64E-04 | 6.68E+00 |
| 121-44-8 | Triethylamine | 7.05E-07 | 2.23E-07 | na | 2.25E-04 | 2.61E+00 |
| 122-39-4 | Diphenylamine | 7.91E-05 | 2.50E-05 | na | 2.53E-02 | 9.89E+01 |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | 1.34E-08 | 4.24E-09 | na | 4.30E-06 | 3.16E+00 |
| 126-73-8 | Tributyl Phosphate | 2.50E-04 | 7.90E-05 | na | 8.00E-02 | 3.98E+01 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.20E-07 | 3.78E-08 | na | 3.83E-05 | 3.16E+00 |
| 127-18-4 | Tetrachloroethylene | 6.28E-05 | 1.98E-05 | na | 2.01E-02 | 8.28E+01 |
| 129-00-0 | Pyrene | 1.90E-03 | 5.99E-04 | na | 6.07E-01 | 1.14E+03 |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.34E-07 | 4.24E-08 | na | 4.30E-05 | 3.16E+00 |
| 156-59-2 | cis-1,2-Dichloroethylene | 1.81E-06 | 5.72E-07 | na | 5.80E-04 | 5.40E+00 |
| 156-60-5 | trans-1,2-Dichloroethylene | 3.08E-06 | 9.72E-07 | na | 9.84E-04 | 8.12E+00 |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | 1.25E-01 | 3.96E-02 | na | 4.01E+01 | 2.88E+04 |
| 205-99-2 | Benzo[b]fluoranthene | 1.51E-02 | 4.76E-03 | na | 4.82E+00 | 5.63E+03 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 3.61E-03 | 1.14E-03 | na | 1.16E+00 | 1.88E+03 |
| 207-08-9 | Benzo[k]fluoranthene | 3.22E-02 | 1.02E-02 | na | 1.03E+01 | 1.01E+04 |
| 218-01-9 | Chrysene | 1.61E-02 | 5.10E-03 | na | 5.17E+00 | 5.94E+03 |
| 309-00-2 | Aldrin | 7.91E-02 | 2.50E-02 | na | 2.53E+01 | 2.02E+04 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 1.58E-04 | 4.98E-05 | na | 5.05E-02 | 1.68E+02 |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 1.51E-04 | 4.76E-05 | na | 4.82E-02 | 1.62E+02 |
| 541-73-1 | 1,3-Dichlorobenzene | 8.47E-05 | 2.68E-05 | na | 2.71E-02 | 1.04E+02 |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 2.68E-06 | 8.47E-07 | na | 8.57E-04 | 7.30E+00 |
| 563-68-8 | Thallium Acetate | 4.00E-02 | 2.00E-03 | 3.00E-01 | 8.00E-01 | 1.00E+04 |
| 621-64-7 | N-Nitrosodi-N-propylamine | 5.73E-07 | 1.81E-07 | na | 1.83E-04 | 2.22E+00 |
| 1314-62-1 | Vanadium pentoxide | 2.50E-03 | 2.00E-05 | 2.00E-01 | 8.00E-01 | 2.00E+02 |
| 1330-20-7 | Xylenes (mixtures) | 3.30E-05 | 1.04E-05 | na | 1.05E-02 | 5.04E+01 |
| 1336-36-3 | Polychlorinated Biphenyls | 4.87E-02 | 1.54E-02 | na | 1.56E+01 | 5.80E+04 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | 4.87E-02 | 1.54E-02 | na | 1.56E+01 | 5.80E+04 |
| 6533-73-9 | Thallium carbonate | 4.00E-02 | 2.00E-03 | 3.00E-01 | 8.00E-01 | 1.00E+04 |
| 7429-90-5 | Aluminum | 1.50E-03 | 2.00E-04 | 3.00E-01 | 8.00E-01 | 5.00E+02 |
| 7439-89-6 | Iron | 2.00E-02 | 3.00E-05 | 1.00E+00 | 1.00E+00 | 2.00E+02 |
| 7439-93-2 | Lithium | 1.00E-02 | 2.00E-02 | 1.00E-02 | 6.00E+00 | 1.00E+00 |
| 7439-96-5 | Manganese | 5.00E-04 | 3.00E-05 | 5.00E-02 | 6.00E-02 | 4.00E+02 |
| 7439-97-6 | Mercury metal vapor | 2.50E-01 | 4.70E-04 | 3.00E-02 | 2.00E-01 | 1.00E+03 |
| 7439-98-7 | Molybdenum | 1.00E-03 | 1.70E-03 | 1.00E+00 | 9.00E-01 | 1.00E+01 |
| 7440-02-0 | Nickel (soluble salts) | 5.00E-03 | 1.60E-02 | 1.00E-03 | 1.00E-01 | 1.00E+02 |

**Table A38. Transfer Factors for Chemicals into Cows, Chickens, and Fish.**

| CASRN | Chemical | Beef (d/kg) | Milk (d/kg) | Poultry (d/kg) | Eggs (d/kg) | Fish (L/kg) |
|---|---|---|---|---|---|---|
| 7440-22-4 | Silver | 3.00E-03 | 5.00E-05 | 2.00E+00 | 5.00E-01 | 5.00E+00 |
| 7440-24-6 | Strontium, Stable | 8.00E-03 | 2.80E-03 | 8.00E-02 | 2.00E-01 | 6.00E+01 |
| 7440-28-0 | Thallium metal | 4.00E-02 | 2.00E-03 | 3.00E-01 | 8.00E-01 | 1.00E+04 |
| 7440-31-5 | Tin | 8.00E-02 | 1.00E-03 | 2.00E-01 | 8.00E-01 | 3.00E+03 |
| 7440-36-0 | Antimony | 4.00E-05 | 2.50E-05 | 6.00E-03 | 7.00E-02 | 1.00E+02 |
| 7440-38-2 | Arsenic (inorganic) | 2.00E-03 | 6.00E-05 | 8.30E-01 | 8.00E-01 | 2.44E+02 |
| 7440-39-3 | Barium | 2.00E-04 | 4.80E-04 | 9.00E-03 | 9.00E-01 | 4.00E+00 |
| 7440-41-7 | Beryllium and compounds | 1.00E-03 | 9.00E-07 | 4.00E-01 | 2.00E-02 | 1.00E+02 |
| 7440-42-8 | Boron and borates only | 8.00E-04 | 1.50E-03 | 2.00E-01 | 8.00E-01 | 5.00E+00 |
| 7440-43-9 | Cadmium | 4.00E-04 | 1.00E-03 | 8.00E-01 | 1.00E-01 | 2.00E+02 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 2.00E-05 | 3.00E-05 | 4.00E-03 | 9.00E-05 | 3.00E+01 |
| 7440-48-4 | Cobalt | 1.00E-02 | 3.00E-04 | 2.00E+00 | 1.00E-01 | 3.00E+02 |
| 7440-50-8 | Copper | 9.00E-03 | 1.50E-03 | 5.00E-01 | 5.00E-01 | 2.00E+02 |
| 7440-62-2 | Vanadium metal | 2.50E-03 | 2.00E-05 | 2.00E-01 | 8.00E-01 | 2.00E+02 |
| 7440-66-6 | Zinc and compounds | 1.00E-01 | 1.00E-02 | 7.00E+00 | 3.00E+00 | 2.52E+02 |
| 7446-18-6 | Thallium Sulfate | 4.00E-02 | 2.00E-03 | 3.00E-01 | 8.00E-01 | 1.00E+04 |
| 7487-94-7 | Mercuric chloride | 2.50E-01 | 4.70E-04 | 3.00E-02 | 2.00E-01 | 1.00E+03 |
| 7664-41-7 | Ammonia | 1.04E-09 | 3.29E-10 | na | 3.33E-07 | 3.16E+00 |
| 7723-14-0 | Phosphorus, white | 5.00E-02 | 1.60E-02 | 1.90E-01 | 1.00E+01 | 1.50E+03 |
| 7782-41-4 | Fluorine (soluble fluoride) | 1.50E-01 | 1.00E-03 | 1.00E-02 | 2.00E+00 | 1.00E+01 |
| 7782-49-2 | Selenium and compounds | 1.50E-02 | 4.00E-03 | 9.00E+00 | 9.00E+00 | 1.70E+02 |
| 7791-12-0 | Thallium Chloride | 4.00E-02 | 2.00E-03 | 3.00E-01 | 8.00E-01 | 1.00E+04 |
| 8001-35-2 | Toxaphene | 1.51E-02 | 4.76E-03 | na | 4.82E+00 | 5.63E+03 |
| 10102-45-1 | Thallium (I) Nitrate | 4.00E-02 | 2.00E-03 | 3.00E-01 | 8.00E-01 | 1.00E+04 |
| 11096-82-5 | Aroclor 1260 | 4.66E+00 | 1.47E+00 | na | 1.49E+03 | 4.90E+03 |
| 11097-69-1 | Aroclor 1254 | 1.54E-01 | 4.87E-02 | na | 4.93E+01 | 1.41E+05 |
| 11104-28-2 | Aroclor 1221 | 8.47E-04 | 2.68E-04 | na | 2.71E-01 | 6.14E+02 |
| 11141-16-5 | Aroclor 1232 | 8.47E-04 | 2.68E-04 | na | 2.71E-01 | 6.14E+02 |
| 12672-29-6 | Aroclor 1248 | 5.47E-02 | 1.73E-02 | na | 1.75E+01 | 6.34E+04 |
| 12674-11-2 | Aroclor 1016 | 1.04E-02 | 3.29E-03 | na | 3.33E+00 | 1.77E+04 |
| 14797-55-8 | Nitrate | na | na | na | na | 3.16E+00 |
| 14797-65-0 | Nitrite | na | na | na | na | 3.16E+00 |
| 16065-83-1 | Chromium (III) (insoluble salts) | 9.00E-03 | 1.00E-05 | 2.00E-01 | 8.00E-01 | 2.00E+02 |
| 16984-48-8 | Fluorine anion | 1.50E-01 | 1.00E-03 | 1.00E-02 | 2.00E+00 | 1.00E+01 |
| 18540-29-9 | Chromium (VI) (soluble salts) | 9.00E-03 | 1.00E-05 | 2.00E-01 | 8.00E-01 | 2.00E+02 |
| 22967-92-6 | Methyl Mercury | 2.50E-01 | 4.70E-04 | 3.00E-02 | 2.00E-01 | 1.00E+03 |
| 53469-21-9 | Aroclor 1242 | 4.87E-02 | 1.54E-02 | na | 1.56E+01 | 5.80E+04 |
| na | Uranium (soluble salts) | 3.00E-04 | 4.00E-04 | 1.00E+00 | 1.00E+00 | 1.00E+01 |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The transfer factors into beef, milk, and eggs for organic chemicals are calculated from the octanol-water coefficients in Table A3. The numbers for fish are from the EPI Suite software version 3.20. All numbers for the inorganic chemicals are from Table A35.
- Missing values are indicated with "na", which means "not available".

## A5.0 PLANT PARAMETERS

Living plants eaten by people fall into two broad categories, aquatic plants and terrestrial plants. It will be assumed that aquatic plants contribute very little to the typical human diet. If exceptions are identified then a suitable set of parameters and models for contaminant uptake by aquatic plants and subsequent consumptions by humans will be utilized. All plants eaten are assumed to be terrestrial rather than aquatic.

The calculation of radionuclide concentrations in living terrestrial plants uses three main routes, (1) root uptake, (2) resuspension to leaves (also called "rain splash"), and (3) direct deposition of irrigation water on foliage. Each of these will be considered separately below. The three uptake routes are then combined to obtain the total concentration in edible portions of plants.

### A5.1 ROOT UPTAKE

The model for root uptake of a contaminant into terrestrial plants assumes that the concentration in the edible portion is proportional to the concentration in the soil at the time of harvest. The constants of proportionality are known as the soil-to-plant concentration ratios. These concentration ratios are measured as the concentration of the dry produce item divided by the soil concentration. They have no units, since the soil and food items have the same mass-based concentration units, e.g., pCi/kg.

Because the human consumption rates for plants shown in Table A4 are the wet weights, it is necessary to select suitable constants to convert to dry weight. These constants are known as "dry-to-wet ratios". They are simply the dry weight of the food item divided by the wet weight of the item. The "dry-to-wet ratios" from three sources are listed in Table A39. The values chosen for the tank waste PA are from PNWD-2023 for leafy vegetables and NUREG/CR-5512 for the others. The chosen values for the tank waste PA appear in the last column of Table A39. The values under the "GENII" column have been used in prior Hanford Site performance assessments.

**Table A39. Dry-to-Wet Ratios for Vegetation Consumed by Humans.**

| Type of Produce | GENII | ORNL-5786 | Tank Waste PA |
|---|---|---|---|
| Leafy Vegetables | 0.10 | 0.067 | 0.09 |
| Other (protected) | 0.25 | 0.222 | 0.25 |
| Fruit (exposed) | 0.18 | 0.126 | 0.18 |
| Grains | 0.18 | 0.888 | 0.91 |

Notes:
- The tank waste PA values are from PNWD-2023 and NUREG/CR-5512.
- The dry-to-wet ratio used for uptake of chemicals is 0.2 based on the weighted sum of the above values. The weighting factors are the mass of each type of vegetation consumed annually. Note that grains are not irrigated and therefore not included in the weighed sum.

The GENII dry-to-wet ratios for grains differ greatly from the other collections. However, it has been assumed in prior performance assessments that grains would be unlikely to become contaminated in the intruder or irrigation scenarios. The intruder would probably not raise grains

in his home garden, and the principal grain crop in this area (dry-land wheat) would not be irrigated. For the tank waste PA, grains are not included as contaminated vegetable intakes.

Root uptake for radionuclides will be calculated using concentration ratios listed in Table A40. The ratios for four types of vegetables are given on this table. The definition of the four types was presented with the consumption rates and will not be repeated here. The value for the iodine concentration ratio in leafy vegetables is from the more recent HEDR assessment (PNWD-2023 1994). The values for hydrogen were calculated using an equilibrium assumption. The ratio of tritium to hydrogen in the soil is assumed to also exist in the plant. Thus, the effective soil-to-plant transfer factor is the hydrogen concentration in the plant divided by the hydrogen concentration in the soil and the dry-to-wet ratio for the plant.

The soil-to-plant concentration ratios were selected using the following hierarchy: PNWD-2023, IAEA Technical Report Number 364, ORNL-5786, and NUREG/CR-5512. The letter next to the number in Table A40 shows the source for each number.

**Table A40. Transfer Factors for Radionuclides into Plants.**

| Element | Plant/Soil Concentration Ratios (dry) | | | | Atomic Number |
|---|---|---|---|---|---|
| | Leafy | Root | Fruit | Grain | |
| H | na | na | na | na | 1 |
| Be | 0.010 c | 1.5E-03 c | 1.5E-03 c | 1.5E-03 c | 4 |
| B | 4.0 c | 2.0 c | 2.0 c | 2.0 c | 5 |
| C | 0.70 d | 0.70 d | 0.70 d | 0.70 d | 6 |
| F | 0.060 c | 6.0E-03 c | 6.0E-03 c | 6.0E-03 c | 9 |
| Na | 0.30 b | 0.30 b | 0.30 b | 0.30 b | 11 |
| Al | 4.0E-03 c | 6.5E-04 c | 6.5E-04 c | 6.5E-04 c | 13 |
| Si | 0.35 c | 0.070 c | 0.070 c | 0.070 c | 14 |
| P | 3.5 c | 3.5 c | 3.5 c | 3.5 c | 15 |
| Cl | 70 c | 70 c | 70 c | 70 c | 17 |
| K | 1.0 c | 0.55 c | 0.55 c | 0.55 c | 19 |
| Ca | 3.5 c | 0.35 c | 0.35 c | 0.35 c | 20 |
| Ti | 5.5E-03 c | 3.0E-03 c | 3.0E-03 c | 3.0E-03 c | 22 |
| V | 5.5E-03 c | 3.0E-03 c | 3.0E-03 c | 3.0E-03 c | 23 |
| Mn | 0.69 b | 0.28 b | 0.19 b | 0.30 b | 25 |
| Fe | 4.0E-03 b | 4.0E-03 b | 4.0E-03 b | 4.0E-03 b | 26 |
| Co | 0.22 b | 0.068 b | 7.0E-03 c | 3.7E-03 b | 27 |
| Ni | 0.060 c | 0.060 c | 0.060 c | 0.030 b | 28 |
| As | 0.040 c | 6.0E-03 c | 6.0E-03 c | 6.0E-03 c | 33 |
| Se | 0.025 c | 0.025 c | 0.025 c | 0.025 c | 34 |
| Rb | 0.90 b | 0.90 b | 0.90 b | 0.90 b | 37 |
| Sr | 3.0 b | 0.61 b | 0.20 b | 0.21 b | 38 |
| Y | 0.010 b | 0.010 b | 0.010 b | 0.010 b | 39 |
| Zr | 1.0E-03 b | 1.0E-03 b | 1.0E-03 b | 1.0E-03 b | 40 |
| Nb | 0.017 b | 0.017 b | 0.017 b | 0.017 b | 41 |
| Mo | 0.80 b | 0.80 b | 0.80 b | 0.80 b | 42 |
| Tc | 180 b | 0.77 b | 1.5 c | 0.73 b | 43 |
| Ru | 0.20 b | 0.040 b | 0.040 b | 5.0E-03 b | 44 |
| Pd | 0.15 c | 0.040 c | 0.040 c | 0.040 c | 46 |
| Ag | 2.7E-04 b | 1.3E-03 b | 8.0E-04 b | 0.15 b | 47 |

**Table A40. Transfer Factors for Radionuclides into Plants.**

| Element | Plant/Soil Concentration Ratios (dry) | | | | Atomic Number |
|---|---|---|---|---|---|
| | Leafy | Root | Fruit | Grain | |
| Cd | 0.55 c | 0.15 c | 0.15 c | 0.15 c | 48 |
| In | 4.0E-03 c | 4.0E-04 c | 4.0E-04 c | 4.0E-04 c | 49 |
| Sn | 0.030 c | 6.0E-03 c | 6.0E-03 c | 6.0E-03 c | 50 |
| Sb | 0.20 c | 5.6E-04 b | 0.030 c | 0.030 c | 51 |
| Te | 0.025 c | 4.0E-03 c | 4.0E-03 c | 4.0E-03 c | 52 |
| I | 0.050 a | 0.020 b | 0.020 b | 0.020 b | 53 |
| Cs | 0.46 b | 0.13 b | 0.22 b | 0.026 b | 55 |
| Ba | 0.15 c | 0.030 b | 0.030 b | 0.030 b | 56 |
| Ce | 0.030 b | 0.030 b | 0.030 b | 0.030 b | 58 |
| Pm | 0.010 c | 4.0E-03 c | 4.0E-03 c | 4.0E-03 c | 61 |
| Sm | 0.010 c | 4.0E-03 c | 4.0E-03 c | 4.0E-03 c | 62 |
| Eu | 0.010 c | 4.0E-03 c | 4.0E-03 c | 4.0E-03 c | 63 |
| Gd | 0.010 c | 4.0E-03 c | 4.0E-03 c | 4.0E-03 c | 64 |
| Ho | 0.010 c | 4.0E-03 c | 4.0E-03 c | 4.0E-03 c | 67 |
| Re | 1.5 c | 0.35 c | 0.35 c | 0.35 c | 75 |
| Hg | 0.90 c | 0.20 c | 0.20 c | 0.20 c | 80 |
| Tl | 4.0E-03 c | 4.0E-04 c | 4.0E-04 c | 4.0E-04 c | 81 |
| Pb | 0.010 b | 6.2E-03 b | 9.0E-03 c | 4.7E-03 b | 82 |
| Bi | 0.035 c | 5.0E-03 c | 5.0E-03 c | 5.0E-03 c | 83 |
| Po | 1.2E-03 b | 7.0E-03 b | 4.0E-04 c | 2.3E-03 b | 84 |
| Ra | 0.049 b | 2.5E-03 b | 6.1E-03 b | 1.2E-03 b | 88 |
| Ac | 3.5E-03 c | 3.5E-04 c | 3.5E-04 c | 3.5E-04 c | 89 |
| Th | 1.8E-03 b | 2.5E-04 b | 8.5E-05 c | 3.4E-05 b | 90 |
| Pa | 2.5E-03 c | 2.5E-04 c | 2.5E-04 c | 2.5E-04 c | 91 |
| U | 8.3E-03 b | 0.012 b | 4.0E-03 c | 1.3E-03 b | 92 |
| Np | 0.037 b | 0.014 b | 0.010 c | 2.7E-03 b | 93 |
| Pu | 6.0E-05 b | 5.8E-04 b | 9.0E-05 b | 8.6E-06 b | 94 |
| Am | 4.3E-04 b | 4.1E-04 b | 2.5E-04 c | 2.2E-05 b | 95 |
| Cm | 7.7E-04 b | 4.6E-04 b | 1.5E-05 c | 2.1E-05 b | 96 |
| Bk | 4.3E-04 b | 4.1E-04 b | 2.5E-04 c | 2.2E-05 b | 97 |
| Cf | 0.010 d | 0.010 d | 0.010 d | 0.010 d | 98 |

Notes:

- These parameters were selected using the following hierarchy: (a) PNWD-2023, (b) IAEA Technical Report Number 364, (c) ORNL-5786, and (d) NUREG/CR-5512. The values for Leafy and Root in IAEA #364 are weighted sums of leafy or protected crops discussed in the text.
- Transfer factors for Bk are assumed to be the same as Am.
- Transfer factors for hydrogen are not shown (na) because a different model is used to calculate tritium concentrations in plants.

The transfer factors for manganese (Mn), cobalt (Co), and technetium (Tc) into leafy vegetables from IAEA Technical Report Number 364, are the weighted sum of concentration ratios for cabbage, lettuce, and spinach. The weighting is based on the USDA consumption rates found in Statistical Bulletin Number 965 (Putnam and Allshouse, 1999). In this bulletin the average individual eats 10.6 lb cabbage, 28.2 lb lettuce, and 0.5 lb of spinach annually. In terms of percentages these correspond to 27.0%, 71.8%, and 1.3%. The mean transfer factors for

cabbage, lettuce and spinach were multiplied by these percentages to arrive at the weighted transfer factor.

Similarly, for several nuclides in IAEA Technical Report Number 364 the transfer factors into root vegetables are the weighted sum of concentration ratios for root vegetables, e.g., onions, carrots, radishes, potatoes, pods, corn. The weighting is based on the USDA consumption rates found in Statistical Bulletin Number 965 (Putnam and Allshouse, 1999). In this bulletin the average individual eats 16.8 lb onions, 12.1 lb carrots, 0.4 lb radishes, 82.9 lb potatoes, 3.5 lb pods, 7.4 lb corn, and 67.5 lb others annually. The mean transfer factors for the root crops that are listed in the IAEA report are weighted by these consumption rates to arrive at the weighted transfer factor shown in Table A40. The elements for which this was carried out are manganese (Mn), cobalt (Co), zinc (Zn), strontium (Sr), technetium (Tc), cesium (Cs), lead (Pb), radium (Ra), thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm).

Concentration ratios for berkelium (Bk) were assumed to be the same as those for americium (Am), because none of the references supplied any values for berkelium.

Animal fodder is not shown separately in Table A40. Pasture grass (fresh) and hay (stored) are represented using the transfer factors for leafy vegetables. The stored grain is represented using the factors for grain.

Root uptake for chemicals into plants will be calculated using concentration ratios listed in Table A41. The ratios for just one type of plant are given on this table. The concentration ratios for organic chemicals are from the octanol-water constants shown in Table A3. The formula used to calculate the soil-to-plant (wet) factors is from McKone (1994) and is shown below. The factors for the dry plant are calculated by dividing the wet plant numbers by the dry-to-wet ratio, 0.2 from Table A39.

$$F_{PLANTS} = 7.7 \ (K_{OW})^{-0.58}$$

The concentration ratios for the inorganic chemicals are obtained from Table A40. The concentration ratios for the four plant types were combined into one using the USDA consumption amounts shown in Table A4 and the dry-to-wet ratios shown in Table A39. Grains were omitted from the weighting because they are assumed to have no contaminated irrigation water. For this generic garden crop a dry-to-wet ratio of 0.2 is assumed.

The last three columns in Table A41 are used in Section A6.0 to model the garden soil. The soil-water partition coefficients were calculated as the product of the organic carbon partition coefficient (from EPI Suite version 3.20) and the assumed carbon fraction in soil, 3%, discussed in Section A6.1. The PCKOCwin program was used to calculate the organic carbon partition coefficients. Leaching factors and soil-water partition coefficients (Kd) for inorganic chemicals are from Table A43. Numbers for Nitrate, Nitrite, and Chromium (VI) are the same as for tritium due to their high mobility. The leaching factors were calculated as described in Section A6.1.

**Table A41. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.**

| CASRN | Chemical | Soil-to-Plant (dry) Transfer Factor | Leaching Factor (per year) | Soil-Water Partition Coefficient | Organic Carbon Partition Coefficient |
|---|---|---|---|---|---|
| 50-32-8 | Benzo[a]pyrene | 1.07E-02 | 1.88E-05 | 2.36E+04 | 7.87E+05 |
| 53-70-3 | Dibenz[a,h]anthracene | 4.68E-03 | 5.65E-06 | 7.87E+04 | 2.62E+06 |
| 56-23-5 | Carbon tetrachloride | 8.79E-01 | 2.79E-01 | 1.46E+00 | 4.86E+01 |
| 56-55-3 | Benz[a]anthracene | 1.76E-02 | 6.40E-05 | 6.94E+03 | 2.31E+05 |
| 57-12-5 | Cyanide, free | 5.38E+01 | 4.43E-02 | 9.90E+00 | 2.71E+00 |
| 57-14-7 | 1,1-Dimethylhydrazine | 1.89E+02 | 6.12E-01 | 5.93E-01 | 1.98E+01 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 1.32E+02 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 2.68E-01 | 4.38E-03 | 1.01E+02 | 3.38E+03 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 1.17E+01 | 1.68E+00 | 1.32E-01 | 4.40E+00 |
| 60-34-4 | Methylhydrazine | 1.56E+02 | 6.65E-01 | 5.35E-01 | 1.78E+01 |
| 60-57-1 | Dieldrin | 2.84E-02 | 1.40E-03 | 3.18E+02 | 1.06E+04 |
| 62-75-9 | N-Nitrosodimethylamine | 8.24E+01 | 3.47E-01 | 1.15E+00 | 3.82E+01 |
| 64-18-6 | Formic acid | 7.92E+01 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 67-56-1 | Methanol (Methyl alcohol) | 1.08E+02 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 67-64-1 | Acetone (2-Propanone) | 5.30E+01 | 2.31E+00 | 5.94E-02 | 1.98E+00 |
| 67-66-3 | Chloroform | 2.77E+00 | 3.75E-01 | 1.05E+00 | 3.50E+01 |
| 67-72-1 | Hexachloroethane | 1.53E-01 | 6.47E-02 | 6.74E+00 | 2.25E+02 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 1.19E+01 | 2.15E+00 | 7.33E-02 | 2.44E+00 |
| 71-43-2 | Benzene | 2.24E+00 | 8.72E-02 | 4.97E+00 | 1.66E+02 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 1.38E+00 | 2.79E-01 | 1.46E+00 | 4.86E+01 |
| 72-20-8 | Endrin | 3.71E-02 | 1.40E-03 | 3.18E+02 | 1.06E+04 |
| 74-83-9 | Bromomethane | 7.86E+00 | 7.90E-01 | 4.29E-01 | 1.43E+01 |
| 74-87-3 | Methyl chloride (Chloromethane) | 1.14E+01 | 7.90E-01 | 4.29E-01 | 1.43E+01 |
| 75-00-3 | Ethyl Chloride | 5.70E+00 | 5.26E-01 | 7.12E-01 | 2.37E+01 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 4.42E+00 | 5.26E-01 | 7.12E-01 | 2.37E+01 |
| 75-05-8 | Acetonitrile | 6.06E+01 | 1.66E+00 | 1.35E-01 | 4.50E+00 |
| 75-07-0 | Acetaldehyde | 6.06E+01 | 2.49E+00 | 4.49E-02 | 1.50E+00 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 7.25E+00 | 5.26E-01 | 7.12E-01 | 2.37E+01 |
| 75-15-0 | Carbon disulfide | 2.89E+00 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 75-21-8 | Ethylene Oxide (Oxirane) | 5.75E+01 | 2.52E+00 | 4.31E-02 | 1.44E+00 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 3.53E+00 | 3.75E-01 | 1.05E+00 | 3.50E+01 |
| 75-35-4 | 1,1-Dichloroethylene | 2.24E+00 | 3.75E-01 | 1.05E+00 | 3.50E+01 |
| 75-45-6 | Chlorodifluoromethane | 9.10E+00 | 3.75E-01 | 1.05E+00 | 3.50E+01 |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 2.49E+00 | 2.79E-01 | 1.46E+00 | 4.86E+01 |
| 75-69-4 | Trichlorofluoromethane | 1.31E+00 | 2.79E-01 | 1.46E+00 | 4.86E+01 |
| 75-71-8 | Dichlorodifluoromethane | 2.15E+00 | 2.79E-01 | 1.46E+00 | 4.86E+01 |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 5.66E-01 | 6.47E-02 | 6.74E+00 | 2.25E+02 |
| 76-44-8 | Heptachlor | 1.12E-02 | 2.83E-04 | 1.57E+03 | 5.24E+04 |
| 78-83-1 | Isobutanol | 1.40E+01 | 2.28E+00 | 6.14E-02 | 2.05E+00 |
| 78-87-5 | 1,2-Dichloropropane | 2.74E+00 | 2.05E-01 | 2.03E+00 | 6.77E+01 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 2.61E+01 | 1.79E+00 | 1.15E-01 | 3.83E+00 |

**Table A41. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.**

| CASRN | Chemical | Soil-to-Plant (dry) Transfer Factor | Leaching Factor (per year) | Soil-Water Partition Coefficient | Organic Carbon Partition Coefficient |
|---|---|---|---|---|---|
| 79-00-5 | 1,1,2-Trichloroethane | 3.09E+00 | 2.05E-01 | 2.03E+00 | 6.77E+01 |
| 79-01-6 | Trichloroethylene | 1.52E+00 | 2.05E-01 | 2.03E+00 | 6.77E+01 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 2.41E+01 | 2.62E+00 | 3.60E-02 | 1.20E+00 |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 1.58E+00 | 1.33E-01 | 3.20E+00 | 1.07E+02 |
| 79-46-9 | 2-Nitropropane | 1.11E+01 | 5.04E-01 | 7.49E-01 | 2.50E+01 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 7.84E-02 | 6.15E-03 | 7.22E+01 | 2.41E+03 |
| 83-32-9 | Acenaphthene | 2.05E-01 | 2.42E-03 | 1.84E+02 | 6.12E+03 |
| 84-66-2 | Diethyl phthalate | 1.52E+00 | 1.13E-01 | 3.79E+00 | 1.26E+02 |
| 84-74-2 | Dibutyl phthalate | 9.45E-02 | 1.01E-02 | 4.38E+01 | 1.46E+03 |
| 85-68-7 | Butyl benzyl phthalate | 6.95E-02 | 1.58E-03 | 2.81E+02 | 9.36E+03 |
| 86-73-7 | Fluorene | 1.45E-01 | 1.31E-03 | 3.39E+02 | 1.13E+04 |
| 86-74-8 | Carbazole | 2.68E-01 | 1.31E-03 | 3.39E+02 | 1.13E+04 |
| 87-68-3 | Hexachlorobutadiene | 6.50E-02 | 1.48E-02 | 2.98E+01 | 9.94E+02 |
| 87-86-5 | Pentachlorophenol | 4.13E-02 | 4.38E-03 | 1.01E+02 | 3.38E+03 |
| 88-06-2 | 2,4,6-Trichlorophenol | 2.79E-01 | 1.24E-02 | 3.56E+01 | 1.19E+03 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 3.32E-01 | 4.18E-03 | 1.06E+02 | 3.54E+03 |
| 91-20-3 | Naphthalene | 4.69E-01 | 8.05E-03 | 5.51E+01 | 1.84E+03 |
| 92-52-4 | 1,1'-Biphenyl | 1.89E-01 | 2.37E-03 | 1.88E+02 | 6.25E+03 |
| 95-47-6 | o-Xylene | 5.97E-01 | 3.31E-02 | 1.33E+01 | 4.43E+02 |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 2.85E+00 | 3.31E-02 | 1.33E+01 | 4.43E+02 |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 3.95E-01 | 3.31E-02 | 1.33E+01 | 4.43E+02 |
| 95-57-8 | 2-Chlorophenol | 2.18E+00 | 3.31E-02 | 1.33E+01 | 4.43E+02 |
| 95-63-6 | 1,2,4-Trimethylbenzene | 3.02E-01 | 2.05E-02 | 2.15E+01 | 7.18E+02 |
| 95-95-4 | 2,4,5-Trichlorophenol | 2.68E-01 | 1.24E-02 | 3.56E+01 | 1.19E+03 |
| 98-86-2 | Acetophenone | 4.67E+00 | 2.93E-01 | 1.39E+00 | 4.62E+01 |
| 98-95-3 | Nitrobenzene | 3.25E+00 | 7.59E-02 | 5.72E+00 | 1.91E+02 |
| 100-00-5 | p-Chloronitrobenzene | 1.58E+00 | 4.73E-02 | 9.27E+00 | 3.09E+02 |
| 100-02-7 | 4-Nitrophenol | 3.00E+00 | 4.73E-02 | 9.27E+00 | 3.09E+02 |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 5.48E+00 | 6.60E-02 | 6.60E+00 | 2.20E+02 |
| 100-41-4 | Ethyl benzene | 5.73E-01 | 2.84E-02 | 1.55E+01 | 5.18E+02 |
| 100-42-5 | Styrene | 7.49E-01 | 2.84E-02 | 1.55E+01 | 5.18E+02 |
| 100-51-6 | Benzyl alcohol | 8.86E+00 | 7.37E-01 | 4.70E-01 | 1.57E+01 |
| 106-42-3 | p-Xylene | 5.73E-01 | 3.38E-02 | 1.30E+01 | 4.34E+02 |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 2.89E+00 | 3.38E-02 | 1.30E+01 | 4.34E+02 |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 3.89E-01 | 3.38E-02 | 1.30E+01 | 4.34E+02 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 2.81E+00 | 3.07E-01 | 1.31E+00 | 4.38E+01 |
| 106-99-0 | 1,3-Butadiene | 2.70E+00 | 3.07E-01 | 1.31E+00 | 4.38E+01 |
| 107-02-8 | 2-Propenal (Acrolein) | 3.90E+01 | 2.06E+00 | 8.29E-02 | 2.76E+00 |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 2.92E+00 | 3.07E-01 | 1.31E+00 | 4.38E+01 |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 5.33E+00 | 3.07E-01 | 1.31E+00 | 4.38E+01 |
| 107-13-1 | Acrylonitrile | 2.76E+01 | 1.16E+00 | 2.49E-01 | 8.30E+00 |

**Table A41. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.**

| CASRN | Chemical | Soil-to-Plant (dry) Transfer Factor | Leaching Factor (per year) | Soil-Water Partition Coefficient | Organic Carbon Partition Coefficient |
|---|---|---|---|---|---|
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 6.69E+00 | 9.65E-01 | 3.27E-01 | 1.09E+01 |
| 108-38-3 | m-Xylene | 5.36E-01 | 3.38E-02 | 1.30E+01 | 4.34E+02 |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 2.81E+00 | 3.38E-02 | 1.30E+01 | 4.34E+02 |
| 108-67-8 | 1,3,5-Trimethylbenzene | 4.00E-01 | 2.09E-02 | 2.11E+01 | 7.03E+02 |
| 108-87-2 | Methyl cyclohexane | 3.10E-01 | 5.44E-02 | 8.04E+00 | 2.68E+02 |
| 108-88-3 | Toluene (Methyl benzene) | 1.00E+00 | 5.44E-02 | 8.04E+00 | 2.68E+02 |
| 108-90-7 | Chlorobenzene | 8.67E-01 | 5.44E-02 | 8.04E+00 | 2.68E+02 |
| 108-94-1 | Cyclohexanone | 1.31E+01 | 7.56E-01 | 4.55E-01 | 1.52E+01 |
| 108-95-2 | Phenol (Carbolic acid) | 5.48E+00 | 5.44E-02 | 8.04E+00 | 2.68E+02 |
| 109-99-9 | Tetrahydrofuran | 2.08E+01 | 3.20E+00 | 5.70E-03 | 4.88E+00 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 6.43E+00 | 1.57E-01 | 2.69E+00 | 8.97E+01 |
| 110-54-3 | n-Hexane | 2.11E-01 | 9.65E-02 | 4.47E+00 | 1.49E+02 |
| 110-80-5 | 2-Ethoxyethanol | 5.90E+01 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 110-82-7 | Cyclohexane | 3.89E-01 | 8.72E-02 | 4.97E+00 | 1.66E+02 |
| 110-86-1 | Pyridine | 1.62E+01 | 3.96E-01 | 9.90E-01 | 3.30E+01 |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 1.27E+01 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 7.92E+01 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 1.50E-03 | 8.96E-05 | 4.96E+03 | 1.65E+05 |
| 117-84-0 | Di-n-octylphthalate | 7.72E-04 | 7.58E-05 | 5.87E+03 | 1.96E+05 |
| 118-74-1 | Hexachlorobenzene | 1.83E-02 | 4.38E-03 | 1.01E+02 | 3.38E+03 |
| 120-12-7 | Anthracene | 1.01E-01 | 7.26E-04 | 6.12E+02 | 2.04E+04 |
| 120-82-1 | 1,2,4-Trichlorobenzene | 1.79E-01 | 2.05E-02 | 2.15E+01 | 7.18E+02 |
| 121-14-2 | 2,4-Dinitrotoluene | 2.74E+00 | 4.02E-02 | 1.09E+01 | 3.64E+02 |
| 121-44-8 | Triethylamine | 5.55E+00 | 1.33E-01 | 3.22E+00 | 1.07E+02 |
| 122-39-4 | Diphenylamine | 3.59E-01 | 7.83E-03 | 5.66E+01 | 1.89E+03 |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | 5.52E+01 | 2.72E+00 | 3.00E-02 | 1.00E+00 |
| 126-73-8 | Tributyl Phosphate | 1.84E-01 | 7.83E-03 | 5.66E+01 | 1.89E+03 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 1.55E+01 | 8.58E-01 | 3.85E-01 | 1.28E+01 |
| 127-18-4 | Tetrachloroethylene | 4.11E-01 | 1.33E-01 | 3.20E+00 | 1.07E+02 |
| 129-00-0 | Pyrene | 5.69E-02 | 2.13E-04 | 2.08E+03 | 6.94E+04 |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 1.45E+01 | 1.40E+00 | 1.84E-01 | 6.13E+00 |
| 156-59-2 | cis-1,2-Dichloroethylene | 3.21E+00 | 3.07E-01 | 1.31E+00 | 4.38E+01 |
| 156-60-5 | trans-1,2-Dichloroethylene | 2.36E+00 | 3.07E-01 | 1.31E+00 | 4.38E+01 |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | 5.01E-03 | 5.54E-06 | 8.03E+04 | 2.68E+06 |
| 205-99-2 | Benzo[b]fluoranthene | 1.71E-02 | 1.84E-05 | 2.41E+04 | 8.03E+05 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 3.91E-02 | 2.09E-04 | 2.13E+03 | 7.09E+04 |
| 207-08-9 | Benzo[k]fluoranthene | 1.10E-02 | 1.88E-05 | 2.36E+04 | 7.87E+05 |
| 218-01-9 | Chrysene | 1.64E-02 | 6.27E-05 | 7.08E+03 | 2.36E+05 |
| 309-00-2 | Aldrin | 6.54E-03 | 1.40E-04 | 3.17E+03 | 1.06E+05 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 2.41E-01 | 4.38E-03 | 1.01E+02 | 3.38E+03 |

**Table A41. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.**

| CASRN | Chemical | Soil-to-Plant (dry) Transfer Factor | Leaching Factor (per year) | Soil-Water Partition Coefficient | Organic Carbon Partition Coefficient |
|---|---|---|---|---|---|
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 2.47E-01 | 4.38E-03 | 1.01E+02 | 3.38E+03 |
| 541-73-1 | 1,3-Dichlorobenzene | 3.45E-01 | 3.38E-02 | 1.30E+01 | 4.34E+02 |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 2.56E+00 | 1.74E-01 | 2.42E+00 | 8.08E+01 |
| 563-68-8 | Thallium Acetate | 5.75E-04 | 2.96E-04 | 1.50E+03 | 4.27E+00 |
| 621-64-7 | N-Nitrosodi-N-propylamine | 6.26E+00 | 3.03E-02 | 1.46E+01 | 4.85E+02 |
| 1314-62-1 | Vanadium pentoxide | 3.12E-03 | 4.44E-04 | 1.00E+03 | 1.93E+02 |
| 1330-20-7 | Xylenes (mixtures) | 5.97E-01 | 3.31E-02 | 1.33E+01 | 4.43E+02 |
| 1336-36-3 | Polychlorinated Biphenyls | 8.65E-03 | 3.31E-04 | 1.34E+03 | 4.48E+04 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | 8.65E-03 | 3.31E-04 | 1.34E+03 | 4.48E+04 |
| 6533-73-9 | Thallium carbonate | 5.75E-04 | 2.96E-04 | 1.50E+03 | 8.25E+00 |
| 7429-90-5 | Aluminum | 8.13E-04 | 2.96E-04 | 1.50E+03 | 1.43E+01 |
| 7439-89-6 | Iron | 4.00E-03 | 1.27E-04 | 3.50E+03 | 1.43E+01 |
| 7439-93-2 | Lithium | 5.02E-03 | 1.48E-03 | 3.00E+02 | 1.43E+01 |
| 7439-96-5 | Manganese | 2.73E-01 | 1.85E-04 | 2.40E+03 | 1.43E+01 |
| 7439-97-6 | Mercury metal vapor | 2.34E-01 | 4.39E-02 | 1.00E+01 | 1.43E+01 |
| 7439-98-7 | Molybdenum | 8.00E-01 | 5.90E-02 | 7.40E+00 | 1.43E+01 |
| 7440-02-0 | Nickel (soluble salts) | 6.00E-02 | 1.85E-04 | 2.40E+03 | 1.43E+01 |
| 7440-22-4 | Silver | 1.10E-03 | 4.93E-03 | 9.00E+01 | 1.43E+01 |
| 7440-24-6 | Strontium, Stable | 6.04E-01 | 2.47E-03 | 1.80E+02 | 1.43E+01 |
| 7440-28-0 | Thallium metal | 5.75E-04 | 2.96E-04 | 1.50E+03 | 1.43E+01 |
| 7440-31-5 | Tin | 7.17E-03 | 4.94E-04 | 9.00E+02 | 1.43E+01 |
| 7440-36-0 | Antimony | 1.90E-02 | 8.89E-05 | 5.00E+03 | 1.43E+01 |
| 7440-38-2 | Arsenic (inorganic) | 7.65E-03 | 2.22E-03 | 2.00E+02 | 1.43E+01 |
| 7440-39-3 | Barium | 3.58E-02 | 7.39E-03 | 6.00E+01 | 1.43E+01 |
| 7440-41-7 | Beryllium and compounds | 1.91E-03 | 1.85E-03 | 2.40E+02 | 1.43E+01 |
| 7440-42-8 | Boron and borates only | 2.10E+00 | 1.42E-01 | 3.00E+00 | 1.43E+01 |
| 7440-43-9 | Cadmium | 1.69E-01 | 6.00E-03 | 7.40E+01 | 1.43E+01 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | 3.00E-02 | 2.96E-04 | 1.50E+03 | 1.43E+01 |
| 7440-48-4 | Cobalt | 5.72E-02 | 7.39E-03 | 6.00E+01 | 1.43E+01 |
| 7440-50-8 | Copper | 8.00E-01 | 1.27E-02 | 3.50E+01 | 1.43E+01 |
| 7440-62-2 | Vanadium metal | 3.12E-03 | 4.44E-04 | 1.00E+03 | 1.43E+01 |
| 7440-66-6 | Zinc and compounds | 2.26E+01 | 2.22E-03 | 2.00E+02 | 1.43E+01 |
| 7446-18-6 | Thallium Sulfate | 5.75E-04 | 2.96E-04 | 1.50E+03 | 2.42E+01 |
| 7487-94-7 | Mercuric chloride | 2.34E-01 | 4.39E-02 | 1.00E+01 | 2.37E+01 |
| 7664-41-7 | Ammonia | 2.43E+02 | 7.90E-01 | 4.29E-01 | 1.43E+01 |
| 7723-14-0 | Phosphorus, white | 3.50E+00 | 4.87E-02 | 9.00E+00 | 1.43E+01 |
| 7782-41-4 | Fluorine (soluble fluoride) | 8.63E-03 | 2.96E-03 | 1.50E+02 | 1.43E+01 |
| 7782-49-2 | Selenium and compounds | 2.50E-02 | 2.08E-01 | 2.00E+00 | 1.43E+01 |
| 7791-12-0 | Thallium Chloride | 5.75E-04 | 2.96E-04 | 1.50E+03 | 1.43E+01 |
| 8001-35-2 | Toxaphene | 1.71E-02 | 1.49E-04 | 2.98E+03 | 9.93E+04 |
| 10102-45-1 | Thallium (I) Nitrate | 5.75E-04 | 2.96E-04 | 1.50E+03 | 1.43E+01 |
| 11096-82-5 | Aroclor 1260 | 6.15E-04 | 7.16E-05 | 6.20E+03 | 2.07E+05 |
| 11097-69-1 | Aroclor 1254 | 4.44E-03 | 1.96E-04 | 2.27E+03 | 7.56E+04 |

**Table A41. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.**

| CASRN | Chemical | Soil-to-Plant (dry) Transfer Factor | Leaching Factor (per year) | Soil-Water Partition Coefficient | Organic Carbon Partition Coefficient |
|---|---|---|---|---|---|
| 11104-28-2 | Aroclor 1221 | 9.08E-02 | 1.43E-03 | 3.10E+02 | 1.03E+04 |
| 11141-16-5 | Aroclor 1232 | 9.08E-02 | 1.43E-03 | 3.10E+02 | 1.03E+04 |
| 12672-29-6 | Aroclor 1248 | 8.10E-03 | 3.37E-04 | 1.32E+03 | 4.39E+04 |
| 12674-11-2 | Aroclor 1016 | 2.12E-02 | 5.46E-04 | 8.13E+02 | 2.71E+04 |
| 14797-55-8 | Nitrate | na | 5.33E-01 | 7.00E-01 | 1.43E+01 |
| 14797-65-0 | Nitrite | na | 5.33E-01 | 7.00E-01 | 2.37E+01 |
| 16065-83-1 | Chromium (III) (insoluble salts) | 1.00E-03 | 6.62E-03 | 6.70E+01 | na |
| 16984-48-8 | Fluorine anion | 8.63E-03 | 2.96E-03 | 1.50E+02 | 1.43E+01 |
| 18540-29-9 | Chromium (VI) (soluble salts) | 1.00E-03 | 5.33E-01 | 7.00E-01 | na |
| 22967-92-6 | Methyl Mercury | 2.34E-01 | 4.39E-02 | 1.00E+01 | 1.43E+01 |
| 53469-21-9 | Aroclor 1242 | 8.65E-03 | 3.31E-04 | 1.34E+03 | 4.48E+04 |
| na | Uranium (soluble salts) | 9.44E-03 | 6.23E-02 | 7.00E+00 | na |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The soil-to-plant transfer factors for organic chemicals are from EPI Suite version 3.20. Numbers for the inorganic chemicals are from Table A39.
- Soil-water partition coefficients for organic chemicals were calculated as the product of the organic carbon partition coefficient (from EPI Suite version 3.20) and the assumed carbon fraction in garden soil, 3%, discussed in Section A6.1. Numbers for inorganic chemicals are from Table A43. Numbers for Nitrate, Nitrite, and Chromium (VI) are the same as for tritium.
- Leaching factors are calculated from the Soil-Water Partition Coefficients as described in Section A6.0.
- Missing values are indicated with "na", which means "not available".

The Hanford Site is very dry and sandy, so that plant uptake factors would likely differ from the generic values listed in Tables A40 and A41. However, the preparation of the soil for a garden changes the properties of surface layer. The tilling, watering and addition of fertilizers and organic material produces soil that resembles the generic garden soil. It is therefore assumed that the concentration ratios in Tables A40 and A41 are adequate to describe plant uptakes in possible future gardens on the Hanford Site.

Groups of people gathering native vegetation for nourishment and other household needs may require special consideration. The soil-to-plant transfer factors for species not usually considered as garden plants growing without cultivation could differ considerably from the values shown on Tables A40 and A41. Soils deficient in some mineral may have much higher uptake factors for materials that are chemically similar to what is missing. The converse is also true. In addition, the distribution of the contaminant in the native vegetation during the growth of the plant is important. For example, Native American Indians use various parts of the cattail over its growth stages (CTUIR 1995). However, the tank waste PA exposure scenarios involve localized areas of contaminated soil resulting from intrusion or irrigation with contaminated ground water. In general, the transfer factors for native plant species are not needed because the contaminated portion would be an insignificant part of the overall diet.

## A5.2 RAIN SPLASH

The term "rain splash" refers to all the processes that cause soil to deposit on the surfaces of plants. It includes the transport of soil by the irrigation water, rain drops, and the wind. The standard model (NRC 1977) then includes a "translocation" factor, which is the fraction of activity deposited on plant surfaces that ends up in the edible portions of the plant. There are two basic approaches to estimating the concentration in plants due to resuspension of contaminated soil. The standard approach begins with an estimate of the average air concentration and then computes the activity deposition rate on the plant. The other approach (NUREG/CR-5512 1992) simply treats rain splash in a manner similar to root uptake.

In NUREG/CR-5512, Vol. 1, the amount of rain splash is characterized by a "mass loading" factor, which is the ratio of foliage contamination due to rain splash divided by the concentration in the soil nearby. It is similar to the root uptake concentration ratio described in the previous section. The value recommended in NUREG/CR-5512, Section 6.5.2 is 0.1 Ci/kg (dry produce) per Ci/kg soil for all plant types. In addition, this value "includes consideration of translocation of activity in soil from plant surfaces to edible parts of the plant." The only other parameter used to estimate the actual plant concentration from rain splash is the dry-to-wet ratio. Using a generic dry-to-wet ratio of 0.2 means that about (0.1)(0.2)=2% of the wet mass of the plant comes from attached soil. This large value applies to irrigation methods that involve large water drops and planting methods that leave considerable space between plants even at the time of harvest.

In IAEA Technical Report 364 (1994) the soil adhesion is given a range from 0.010 (short plants) to 0.25 for leafy vegetation. Using a representative dry-to-wet ratio of 0.1 for leafy vegetables means the mass loadings range from 0.1% to 2.5%. In NCRP Report Number 123 Section 5.1, the soil-to-plant concentration ratio has a minimum value of 0.001. In effect this is the soil adhesion term for the wet plant. Thus, the effective mass loading is 0.1%.

In the arid environment of southeastern Washington, irrigation methods that reduce evaporative loss are preferred. This has the effect of lowering the amount of soil transferred to plant surfaces during irrigation. The model used at Hanford and elsewhere (e.g., SAND2001-2977) begins with an average air concentration near the plants and computes a deposition rate onto plant surfaces. The RESRAD program (ANL/EAD/LD-2) has a default mass loading air concentration of 0.1 $mg/m^3$. The default value in GENII is 0.225 $mg/m^3$. Both of these use a deposition speed of 0.001 m/sec, which is suitable for respirable particles. The resulting deposition rate in RESRAD is 8.64 $mg/m^2$ per day, while in GENII Version 1.485 it is 19.44 $mg/m^2$ per day. However, these assumptions lead to rain splash transfers that are two or three orders of magnitude below the experimental data referenced in NUREG/CR-5512, Vol. 1.

For the tank waste PA the customary soil deposition model will be used rather than the effective mass loading approach of NUREG/CR-5512. However, the assumed average deposition rate will be taken to be 270 $mg/m^2$ per day, which is larger than used in GENII (19.44 $mg/m^2$ per day), but smaller than was used in the 2001 ILAW PA (864 $mg/m^2$ per day).

The decrease from the 2001 ILAW PA (DOE/ORP-2000-24) stems from the fact that irrigation is not continuous, but takes place for a relatively short period (less than 1 hour) every day or so. Thus the average involves large deposition rates during short periods with little

deposited between due to the moist conditions. For a small garden, much of the soil that adheres may come from sources of dust outside the garden. The average air concentration of 1 $mg/m^3$ with a deposition speed of 0.01 m/s used in the 2001 ILAW PA represents conditions during active irrigation. However, the average deposition rate will be some factor lower due to the intermittent nature of the irrigation process.

The increase from the deposition rate used in other performance assessments is based on the need to match the minimum value listed in the IAEA Technical Report Number 364 and NCRP Report Number 123. With a deposition rate of 270 $mg/m^2$ per day, the mass loading in leafy vegetables is about 0.1%. The calculation is shown below.

$$\frac{J_{SPLASH}\ F_{INT}\ F_{TRANS}\ T_W}{Y_V} = \frac{(2.7 \times 10^{-4}\ kg/m^2\ per\ day)(0.407)(1.0)(18\ d)}{2.0\ kg/m^2} = 9.89 \times 10^{-4}$$

where,

$F_{INT}$ = interception fraction for airborne dust on exposed surfaces of leafy vegetables, 0.407, from Table A42

$F_{TRANS}$ = translocation factor from exposed surfaces to the edible portion of leafy vegetables, 1.0, from Table A42

$J_{SPLASH}$ = average soil deposition rate due to rain splash, $2.7 \times 10^{-4}$ $kg/m^2$ per day

$T_W$ = effective exposure time for leafy vegetables, 18.0 days, from Table B1. This is derived from a 45-day growing period with a weathering half life of 14 days.

$Y_V$ = yield of leafy vegetables, from Table A42, 2.0 kg(wet)/$m^2$

In particular, the effective wet concentration ratios for leafy, other, fruit, and grains are calculated using the formula shown in Section 3.2 for the post-intrusion resident ingestion dose. The wet ratios are 0.099%, 0.022%, 0.015%, and 0.025% respectively. Since NUREG/CR-5512 recommended a number of about 2%, the model selected for the tank waste PA remains much lower, to some extent consistent with previous Hanford performance assessments.

Other parameters that are part of the standard model for foliar deposition, are the interception fraction, the crop yield (biomass), the translocation factor, the weathering half-life, and the growing period.

The interception fraction is the portion of the airborne contamination depositing in a unit area that initially attaches to vegetation. It includes the fraction of the ground surface that is covered by vegetation. Values for interception fraction for various crops are given in ORNL-5786. More recent publications described in PNNL-6584 (Section 4.7.4) will be used as the basis of the interception fractions for this performance assessment. The empirical relationship between interception fraction and standing biomass (dry weight) is shown below.

$$F_{INT,p} = 1.0 - \mathrm{Exp}(-P\ F_{DRY,p}\ Y_{V,p})$$

where,

$F_{DRY,p}$ = dry-to-wet ratio for garden produce type p from Table A42

$F_{INT,p}$ = interception fraction for airborne particulate on exposed surfaces of garden produce type p, see Table A42

P = parameter that depends on the type of vegetation. For "Other" and "Fruit" it is 3.6 $m^2$/kg. For all other types of produce it is 2.9 $m^2$/kg.

$Y_{V,p}$ = yield of garden produce type p, from Table A42, in kg(wet)/$m^2$

The parameter P depends on the type of vegetation, as discussed in PNL-6584 Volume 1. For leafy vegetables, grains, grass and hay the measured value for P is 2.9 $m^2$/kg dry weight, while for fruits (exposed) and other plants (protected) the measured value for P is 3.6 $m^2$/kg dry weight. The "Dry Yield" is the mass per unit area of the standing biomass at the time of harvest, adjusted for water content. The product of the dry-to-wet ratio and the crop yield (wet) is the effective dry yield. Values for interception fraction are shown on the Table A42.

**Table A42. Various Crop-Specific Parameters.**

| Type of Produce (p) | Dry-to-wet Ratio ($F_{DRY,p}$) | Crop Yield kg(wet)/$m^2$ ($Y_{V,p}$) | Interception Fraction ($F_{INT,p}$) | Direct Deposition ($F_{Direct,p}$) | Translocation Factor ($F_{TRANS,p}$) | Growing Period ($T_{GROW,p}$) |
|---|---|---|---|---|---|---|
| Generic Vegetables | 0.20 | 2.0 | 0.50 | 0.25 | 0.20 | 60 d |
| Leafy Vegetables | 0.09 | 2.0 | 0.407 | 0.104 | 1.0 | 45 d |
| Other (protected) | 0.25 | 2.0 | 0.835 | 0.288 | 0.1 | 90 d |
| Fruit (exposed) | 0.18 | 3.0 | 0.857 | 0.311 | 0.1 | 90 d |
| Grains | 0.20 | 0.8 | 0.371 | 0.092 | 0.1 | 90 d |
| Fresh Forage - Cow | 0.22 | 1.5 | 0.616 | 0.190 | 1.0 | 30 d |
| Stored Hay - Cow | 0.22 | 1.0 | 0.472 | 0.127 | 1.0 | 45 d |
| Stored Grain - Cow | 0.91 | 1.0 | 0.472 | 0.127 | 0.1 | 90 d |
| Forage - Poultry | 0.22 | 1.0 | 0.472 | 0.190 | 1.0 | 30 d |
| Grain - Poultry | 0.91 | 1.0 | 0.472 | 0.127 | 0.1 | 90 d |

Notes:
- The "Generic Vegetables" is used in the calculations for chemicals for all types of produce.
- The dry-to-wet ratio for leafy vegetables is from PNWD-2023. All other values are from NUREG/CR-5512 Section 6.5.7.
- Interception fraction for airborne particulate and direct deposition fraction for overhead irrigation are calculated using the formulas described in the text. The dry-to-wet ratio used for the calculations is the ratio for the standing biomass. Thus the value 0.22 is used to represent stored grain rather than 0.91.

The translocation factor is the fraction of what deposits on the foliage that reaches the edible parts of the plant. The values are shown on Table A42 are widely used in calculations of this type (NRC 1977; PNNL-6584 1988; NUREG/CR-5512 1992) and will be used in the tank waste PA. The value shown for "Generic Vegetables" is used in the calculations for chemicals. It is selected so that the consumption weighted mass of soil deposited on the foliage is the same as for the total leafy, protected, and exposed crops used with radionuclides in the all pathways exposure scenario.

The weathering half-life is the time required for half the contamination initially deposited on plant foliage to be removed by the action of wind, rain and irrigation. The value chosen for both chemicals and radionuclides is 14 days, based on the recommendations of NRC (1977) and the review given in ORNL-5786.

The growing period is the time that a plant is subject to the mechanical action of weathering prior to be harvested. The growing period varies with crop type. It is the time needed to produce one crop. During the irrigation season more than one crop may be harvested.

## A5.3 DIRECT DEPOSITION

The models for root uptake and rain splash contributions to growing plants depend only on the soil concentration at the time of harvest. Direct deposition is unique to overhead irrigation. It refers to the transfer of contamination from irrigation water to the foliage intercepting the water as it falls.

A key parameter to model the contamination of foliage by direct deposition is the interception fraction. The value 0.25 has been used for all plant types (NRC 1977, PNNL-6584 1988; NUREG/CR-5512 1992, HNF-SD-WM-TI-707 2004). Version 2 of the GENII software (Napier 2002) has adopted the model shown below for anions, such as iodide and sulfate. The formula will be used for all contaminants deposited on plant surfaces by overhead irrigation. Values for direct deposition fraction are listed in Table A42.

$$F_{Direct,p} = 2.3\ F_{DRY,p}\ Y_{V,p}\ R^{-0.92}$$

where,

$F_{DRY,p}$ = dry-to-wet ratio for garden produce type p from Table A42

$F_{Direct,p}$ = interception fraction for contaminants in irrigation water on exposed surfaces of garden produce type p, see Table A42

$R$ = Irrigation rate, 4.509 mm/d

$Y_{V,p}$ = yield of garden produce type p, from Table A42, in kg(wet)/$m^2$

The other parameters determining plant concentrations exposed to contaminated irrigation water are the translocation factors, the weathering half-life, and the growing periods. The same parameters used for describing rain splash will also be used for direct deposition. The translocation factors and growing periods are shown on Table A42, while the weathering half-life is 14 days.

If a special group of people were using overhead irrigation to increase growth density and crop yield, then the same parameters used for the standard group would apply to them also. No special modeling would be required unless the individuals were using the crop in some manner that could produce more dose than simply eating it.

## A6.0 SOIL PARAMETERS

The soil parameters of interest are those pertaining to the various exposure pathways and to retention of contaminants that have been introduced to the surface layer by spreading exhumed waste (intrusion scenarios), or irrigation with contaminated water (irrigation scenarios). The two main types of exposure are from external and internal sources. In addition, the internal exposure can be divided into intakes via inhalation, ingestion, and dermal absorption. Each of these routes of exposure will be discussed below.

External radiation exposure depends on surface soil characteristics such as density, chemical composition, and surface roughness. The density of the surface soil is assumed to be 1.5 g/cc. Higher density reduces the external dose through increased self-shielding. The contamination of interest is distributed through the top 15 cm, the tilling depth. The assumed composition of the surface layer is primarily silicon dioxide, with various organic additions and water. Over time the radioactive contaminants migrate into deeper layers of soil and the external dose rate decreases. Some inorganic contaminants, such as hydrogen (in water), technetium, and iodine are very soluble and leach from the surface layer in a few years. Other elements, such as cesium and plutonium hardly move at all.

Dose from contaminants absorbed through the skin accumulates because the person comes in contact with the soil. Some factors that affect the dermal absorption dose from contaminated soil are summarized here. First, some contaminants are absorbed more readily than others. The contaminant-specific parameters are presented later. Second, the particle size distribution of the soil contaminants affects dermal absorption. If the contaminants are found in (or attached to) smaller diameter particles, then the dermal absorption of contaminants is higher because the average concentration in the soil that adheres to the skin is greater than the bulk concentration in the surface soil. Third, the gradual leaching of radioactive contamination to deeper layers of soil reduces the dermal absorption by reducing the surface soil concentration.

Inhalation dose accumulates as contaminants in the soil become airborne. The presence of ground cover (i.e., vegetation) and moisture reduces the air concentration. Tilling the soil increases the air concentration. The gradual leaching of radioactive contamination to deeper layers of soil reduces the air concentration by reduction the average soil concentration. The particle size distribution of the soil contaminants affects the air concentration of contaminants. If the contaminants are found in (or attached to) smaller diameter particles, then the air concentration of contaminants is higher because the average concentration in the dust is higher than the average concentration in the surface soil.

Ingestion dose accumulates as contaminants in the soil become incorporated in plant and animal produce. Small amounts of soil are also ingested directly. It is assumed that the effects of tilling and fertilizers lead to soils that are similar to those for which the concentration ratios shown in Tables A40 and A41 were derived. The gradual leaching of contaminants into deeper layers of soil (below the root zone) reduces the concentration in plant and animal products as well.

## A6.1 LEACHING FROM THE SURFACE LAYER

Soil-specific parameters related to leaching are the soil composition (sand, clay, silt and organic), the distribution coefficients, the density, porosity, and the water content. The composition of the surface layer is assumed to be sandy, where sandy is defined to have greater than 70 percent sand-sized particles. With few exceptions this is what lies near the surface of the entire Hanford Site. The soil-to-plant concentration ratios and distribution coefficients depend on this assumption. However, the preparation of the soil for a garden changes the properties of surface layer. The tilling, watering and addition of fertilizers and organic material produces soil that tends to reduce the mobility of contaminants.

Leaching factors and distribution coefficients for chemicals are shown in Table A41. The value for the cyanide ion (CAS 57-12-5) is from Table C-4 in the EPA *Soil Screen Guidance User's Guide* (EPA/540/R-96/018). Values for other organic chemicals were calculated from the product of the organic carbon partition coefficient from Table A41 and the soil carbon fraction (3%) from Table A37. The formula used is shown below.

$$K_d = (0.03)\ K_{OC}$$

The organic carbon partition coefficients listed in Table A41 are from the EPI Suite Software Version 3.20. The program used for this purpose was PCKOCwin.

The carbon fraction in garden soil is taken from NUREG/CR-5512. Sandy soils typically have fractions less than 0.01. The larger number is due to the addition of organic matter to the garden or pasture soil. Larger carbon fractions lead to larger retardation factors in the surface soil, which leads to less leaching from the surface soil layer with time. Less leaching from the surface soil means the contaminant concentration decreases slowly with time, maximizing potential intakes. Thus, the assumed soil carbon fraction is chosen to be larger than it needs to be. When the transport of organic chemicals through the soil into ground water is evaluated (for example in EPA-540/R95/128), much smaller carbon fractions are assumed to decrease the retardation and maximize the amount reaching the ground water.

The distribution coefficients for inorganic chemicals were taken from Table A43. Because nitrate, nitrite, and chromium (VI) are very mobile, the Kd for tritium shown in Table A43 (0.7 ml/g) was assumed to apply. Thus, the leaching coefficients for nitrate, nitrite, and chromium (VI) are all 0.533.

Leaching factors and distribution coefficients for radionuclides are shown in Table A43. The hierarchy used for selecting values was first the Hanford-specific values for agricultural soils in PNNL-14041. For elements with no values in PNNL-14041, IAEA Technical Report Number 364 was used. Sandy soil was used to represent the Hanford area. The next report consulted was ORNL-5786. Last of all came NUREG/CR-5512. The values shown for iodine lie within the range of possible values given in PNWD-2023, so PNWD-2023 was not needed.

Leaching factors and distribution coefficients for berkelium (Bk) were assumed to be the same as those for americium (Am), because none of the references supplied any values for berkelium.

The thickness of the surface soil of interest in the dose calculations is the top 15 centimeters. This thickness represents typical cultivation depths for mechanical mixing of deposited activity. In addition, it represents typical root depths. This thickness has been used in all prior Hanford Site performance assessments.

**Table A43. Leaching Factors for Radionuclides in Garden Soil.**

| Element | Leach (per year) | Kd | Atomic Number | Element | Leach (per year) | Kd | Atomic Number |
|---|---|---|---|---|---|---|---|
| H | na | 0.70 a | 1 | In | 2.96E-04 | 1,500 c | 49 |
| Be | 1.85E-03 | 240 b | 4 | Sn | 4.94E-04 | 900 a | 50 |
| B | 1.42E-01 | 3.0 c | 5 | Sb | 8.89E-05 | 5,000 a | 51 |
| C | 6.23E-02 | 7.0 a | 6 | Te | 1.48E-03 | 300 c | 52 |
| F | 2.96E-03 | 150 c | 9 | I | 2.94E-02 | 15 a | 53 |
| Na | 4.44E-03 | 100 c | 11 | Cs | 2.22E-04 | 2,000 a | 55 |
| Al | 2.96E-04 | 1,500 c | 13 | Ba | 7.39E-03 | 60 c | 56 |
| Si | 1.34E-02 | 33 b | 14 | Ce | 2.96E-04 | 1,500 a | 58 |
| P | 4.87E-02 | 9.0 b | 15 | Pm | 6.84E-04 | 650 c | 61 |
| Cl | 3.92E-01 | 1.0 a | 17 | Sm | 1.85E-03 | 240 b | 62 |
| K | 4.39E-02 | 10 a | 19 | Eu | 6.84E-04 | 650 c | 63 |
| Ca | 4.87E-02 | 9.0 b | 20 | Gd | 6.84E-04 | 650 c | 64 |
| Ti | 4.44E-04 | 1,000 c | 22 | Ho | 1.85E-03 | 240 b | 67 |
| V | 4.44E-04 | 1,000 c | 23 | Re | 5.55E-03 | 80 a | 75 |
| Mn | 1.85E-04 | 2,400 a | 25 | Hg | 4.39E-02 | 10 c | 80 |
| Fe | 1.27E-04 | 3,500 a | 26 | Tl | 2.96E-04 | 1,500 c | 81 |
| Co | 7.39E-03 | 60 b | 27 | Pb | 5.56E-06 | 80,000 a | 82 |
| Ni | 1.85E-04 | 2,400 a | 28 | Bi | 4.94E-04 | 900 a | 83 |
| As | 2.22E-03 | 200 c | 33 | Po | 4.04E-04 | 1,100 a | 84 |
| Se | 2.08E-01 | 2.0 a | 34 | Ra | 8.89E-04 | 500 a | 88 |
| Rb | 8.06E-03 | 55 b | 37 | Ac | 2.96E-04 | 1,500 a | 89 |
| Sr | 2.47E-03 | 180 a | 38 | Th | 7.41E-07 | 600,000 a | 90 |
| Y | 2.96E-04 | 1,500 a | 39 | Pa | 1.23E-04 | 3,600 a | 91 |
| Zr | 7.41E-04 | 600 b | 40 | U | 6.23E-02 | 7.0 a | 92 |
| Nb | 2.78E-03 | 160 b | 41 | Np | 1.77E-02 | 25 a | 93 |
| Mo | 5.90E-02 | 7.4 b | 42 | Pu | 8.89E-05 | 5,000 a | 94 |
| Tc | 2.08E-01 | 2.0 a | 43 | Am | 2.96E-04 | 1,500 a | 95 |
| Ru | 8.89E-04 | 500 a | 44 | Cm | 2.96E-04 | 1,500 a | 96 |
| Pd | 8.06E-03 | 55 b | 46 | Bk | 2.96E-04 | 1,500 a | 97 |
| Ag | 4.93E-03 | 90 b | 47 | Cf | 8.71E-04 | 510 d | 98 |
| Cd | 6.00E-03 | 74 b | 48 | | | | |

Notes:

- These distribution coefficients were selected using the following hierarchy: (a) PNNL-14041, (b) IAEA Technical Report Number 364, (c) ORNL-5786, and (d) NUREG/CR-5512. The leaching coefficient for hydrogen is not used in the calculations (na).
- Note that the distribution coefficient for Bk is assumed to be the same as Am.

The density and thickness of the affected surface layer determine the external dose rate factors, as well as the leaching coefficients computed for the surface layer. Leaching is the

process by which contaminants migrate from the surface layer of soil into deeper layers below. The driving force behind the leaching process is the application of water to the soil. Leaching is treated as a removal rate constant giving the fraction of the material in the surface layer that is removed per unit of time. It is calculated using the equation shown below.

$$\lambda_S = \frac{P + I - E}{\theta d \left(1 + \rho K_d / \theta\right) T_{irr}}$$

where,

- $d$ = thickness of the surface soil layer from which nuclides migrate, 15 cm (5.9 inches).
- $E$ = total evapo-transpiration during the irrigation season, in cm. For the population scenario a value of 59.27 cm is assumed. For the other scenarios a value 78.06 cm is assumed. These assumptions lead to a total over-irrigation (P+I-E) of 10 cm. This over-irrigation assumption is consistent with PNWD-2023, which assumed that farmers over-irrigate by 10 percent.
- $I$ = total irrigation water applied during the irrigation season, in cm. For the population scenarios this is 63.5 cm (25 in.). For the other scenarios it is 82.3 cm (32.4 inches). Nearly all of this is deposited during the 6 month period from April to September. See Table A11.
- $K_d$ = distribution coefficient in surface soil for an element, in ml/g. Values for chemicals are shown on Table A41. Values for radionuclides are shown in Table A43.
- $P$ = total precipitation, in centimeters, during the irrigation period. Over the period 1971 to 2000, the precipitation during the 6 month irrigation season (April to September) has been 5.766 cm (PNNL-15160). See Table A11.
- $T_{irr}$ = irrigation period, 0.5 y
- $\lambda_S$ = average soil leaching coefficient, fraction removed from a soil layer of thickness "d" during the time that irrigation occurs, per year.
- $\rho$ = bulk density of the surface soil, 1.5 g/cc.
- $\theta$ = volumetric water content of the surface soil, milliliters of water per cubic centimeter of soil. A value of 0.2 ml/cc is assumed. Because the total soil porosity is about 0.4 ml/cc, the saturation ratio is about 50%.

The values assigned to the variables in the above equation were used in prior Hanford performance assessments. The annual irrigation total (82.3 cm/y) is based on the Specific Information on the Terrestrial Environment (SITE) database referenced ORNL-5786. The SITE database reports that a large percentage of the drier western states falls into the range from 70 to 85 cm/y. The values chosen in NUREG/CR-5512 is 76 cm/y, while the value more appropriate to Hanford is 82.3 cm/y (WHC-SD-WM-EE-004). The Hanford value is based on irrigation rates in the counties surrounding the site. Note that the amount of irrigation is assumed to be the same for all plant types including grains.

For the population living along the Columbia River, the annual irrigation amount is reduced to account for the greater precipitation closer to the ocean. In addition, the average irrigation rate along the river is 25 in/y (63.5 cm/y) (WHC-SD-WM-EE-004). This value was

obtained as an average in counties along the Columbia River, and thereby differs from the irrigation rate assumed for individuals living near the Hanford Site. Because this average is over a large population it will have an insignificant range.

Leaching coefficients computed from the above equation are listed in Table A43 along with the distribution coefficient. The numerator represents the excess water added each year. It is taken to be about 10 cm during the irrigation season based on the discussion in PNWD-2023.

The Hanford Environmental Dose Reconstruction Project (HEDR) found the irrigation rate in the counties surrounding the Hanford Site ranged from 61 cm/y to 98 cm/y (PNWD-2023, Rev 1). The excess watering term in the numerator (P+I-E) then ranges from 0 to 26 cm/y, and the leaching coefficients range from 0 to 2.5 times the chosen values. This range has little effect on the resulting doses for most nuclides because the leaching coefficients are generally small.

Because tritium is assumed to be in the form of water, the leaching factor for tritium must include both evaporation and percolation out of the surface layer. The evaporative losses are estimated assuming the soil gains no water. Thus, the amount deposited as irrigation or precipitation is the amount that leaves. The fractional removal rates for tritium were shown in Table A12.

## A6.2 GARDEN SOIL CONCENTRATION

A two-part removal rate from the soil has been adopted for use in the tank waste PA. It is assumed that significant irrigation occurs during 6 months of the year. The rest of the year has very little water infiltration. During the no-irrigation period there is no leaching from the surface layer. Tritium is an exception that is discussed below.

In the post-intrusion residential scenario, the irrigation water is free of contaminants and acts to reduce the surface soil concentration. The surface soil concentration decreases exponentially with time. The removal constant is the sum of the leaching coefficient and the decay coefficient. The equation below shows the factor that is applied to the initial garden soil concentration to calculate the concentration at the end of the year.

$$F_{NS} = \mathrm{Exp}(-\lambda T_{irr})\ \mathrm{Exp}(-\lambda_R T_{no})$$
$$\text{and} \quad \lambda = \lambda_S + \lambda_R \quad \text{and} \quad T_{irr} + T_{no} = 1\ \mathrm{y}$$

where,

$F_{NS}$ = fraction of the initial soil concentration that is left at the end of 1 year when the irrigation water adds no contaminants

$T_{irr}$ = irrigation period, 0.5 y

$T_{no}$ = no irrigation period, 1 y - $T_{irr}$ = 0.5 y

$\lambda$ = total removal constant, per year

$\lambda_R$ = radioactive decay or chemical decomposition constant, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_S$ = average soil leaching coefficient, fraction removed from a soil layer of thickness "d", per year

Each year the same factor is applied to calculate the soil concentration at the end of the year. Thus the soil concentration after N years is $F_{NS}$ raised to the Nth power.

The initial tritium concentration in soil decreases according to the above formula, with one exception. During the no-irrigation season, the removal constant (8.032 per year) is the decay constant (0.05622 per year for tritium) plus the evaporation constant (7.975 per year).

In the various irrigation scenarios, the irrigation water is contaminated and adds to the surface soil concentration. The surface soil concentration increases during the irrigation season, and decreases during the no-irrigation season. The equation below shows the factor that is applied to the irrigated soil total concentration (amount deposited per unit area during the year divided by the area density of the soil) to calculate the concentration at the end of the year.

$$F_{IS} = \frac{1 - \mathrm{Exp}(-\lambda T_{irr})}{\lambda T_{irr}} \mathrm{Exp}(-\lambda_R T_{no})$$

$$\text{and} \quad \lambda = \lambda_S + \lambda_R \quad \text{and} \quad T_{irr} + T_{no} = 1\ \mathrm{y}$$

where,

$F_{IS}$ = fraction of the total soil concentration (amount deposited per unit area during the year divided by the area density of the soil) that is present at the end of 1 year when the irrigation water is adding contaminants to the soil

$T_{irr}$ = irrigation period, 0.5 y

$T_{no}$ = no irrigation period, 1 y - $T_{irr}$ = 0.5 y

$\lambda$ = total removal constant, per year

$\lambda_R$ = radioactive decay or chemical decomposition constant, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

$\lambda_S$ = average soil leaching coefficient, fraction removed from a soil layer of thickness "d", per year

Each year the same amount is added to the soil by ongoing irrigation, and the amounts deposited in prior years decrease by the factor $F_{NS}$ each year. After N years of irrigation, the soil concentration is the total soil concentration (amount deposited per unit area during one year divided by the area density of the soil) times the factor shown below.

$$F_{IS} \frac{1 - (F_{NS})^N}{1 - F_{NS}}$$

Natural precipitation acts to dilute contaminated irrigation water slightly. It adds water that is not contaminated. The formula below shows the dilution factors [Dilution = I/(I+P)] used in these calculations where appropriate.

Dilution Adjustment (individual) = (82.3 cm)/(82.3 + 5.77 cm) = 0.9345

Dilution Adjustment (population) = (63.5 cm)/(63.5 + 5.77 cm) = 0.9168

The tritium concentration in irrigated soil is calculated using an equilibrium model. The tritium is chemically bound in a water molecule and thus goes with the water. The concentration of tritium in irrigation water, is similar to the concentration in the water in the soil. The soil hydrogen fraction is 0.0149 kg hydrogen per kg soil, as shown in Table A37. Thus the effective moisture content of the soil is calculated as shown below. The density of water is 1.0 kg/L.

$$(8.94 \text{ g } H_2O/\text{g } H_2)(0.0149 \text{ kg } H_2/\text{kg soil})/(1.0 \text{ kg/L}) = 0.133 \text{ L } H_2O/\text{kg soil}$$

This value may also be calculated from the assumed value for the volumetric water content of soil (0.2 ml/cc) and its density (1.5 kg/L). Note that the value reported in NUREG/CR-5512 is 0.1 L/kg. A somewhat higher value is being used in the tank waste PA, which leads to higher tritium concentrations in soil during the irrigation season.

The tritium concentration in irrigated soils during the irrigation season is this soil water concentration times the concentration of tritium in the irrigation water times the natural precipitation dilution fraction. During the non-irrigation season the tritium concentration decreases exponentially using the evaporation plus decay removal constant (8.032 per year) discussed above. By the end of the year, the tritium concentration is essentially zero. Thus, there is no accumulation of tritiated water in soil in the present model.

## A6.3 SHORELINE SEDIMENT CONCENTRATION

Shoreline sediments accumulate contaminants present in river water much the same as garden soil. A simple model to represent this accumulation is based on models from BNWL-1754 and NCRP Report No. 76. In the former, the accumulated sediment concentration depends on the water concentration, a deposition factor, and the radioactive half life. In the latter, the accumulation depends only on the water concentration and the distribution coefficient for sediment. The model chosen for these calculations is a combination of the two and is shown below.

$$C_D = \frac{C_W V_S}{\rho d \lambda}\left[1 - \text{Exp}(-\lambda T)\right] \quad \text{and} \quad \lambda = \lambda_S + \lambda_R$$

where,

- $C_D$ = concentration of the contaminant in shoreline sediment, in Ci/kg
- $C_W$ = concentration of the contaminant in the river water, in Ci/L
- $d$ = thickness of the shoreline sediment layer that holds the contaminants, 15 cm (5.9 inches) assumed
- $T$ = time at which the sediment concentration is calculated, in years
- $V_S$ = effective river to sediment deposition rate, 25,300 L/m$^2$ per year (BNWL-1754 and PNNL-6584)
- $\lambda$ = total removal constant, per year
- $\lambda_R$ = decay or decomposition constant, per year
- $\lambda_S$ = average soil leaching coefficient, fraction removed from a soil layer of thickness "d", per year
- $\rho$ = bulk density of the shoreline sediment layer, 1.5 g/cc assumed

If the product ($\lambda T$) is small, the sediment concentration grows linearly with time. If this product is large, the sediment concentration is proportional to the inverse of the total removal constant ($\lambda$), which depends on both the decay half life and the distribution coefficient. In general, sediment concentrations are much larger than garden soil concentrations. For an irrigation rate of 82.3 cm/y, there is 823 L/m$^2$ applied by irrigation each year. The shoreline sediment increases by 25,300 L/m$^2$ each year, a factor of 30 greater.

## A6.4 VOLATILE EMISSIONS FROM THE SOIL SURFACE

Chemicals dissolved in water that is applied to the soil for irrigation purposes will evaporate much like the water does. A simple model to represent this process was developed by Jury, et al. (1983, 1984, and 1990). EPA has adopted a simplified version for estimating inhalation dose from volatile chemical emissions from the soil surface (EPA/540/R95/128). The simple model represents the time dependence of a layer of surface soil that is initially contaminated at some uniform concentration ($C_0$). The formula for the fractional loss rate from the surface layer as a function of time is shown below.

$$\lambda_V = \frac{J_S}{\rho\, d\, C_0} = \frac{1}{d}\sqrt{\frac{D_E}{\pi T}}\left[1 - \mathrm{Exp}\left(\frac{-d^2}{4 D_E T}\right)\right]\mathrm{Exp}(-\lambda_R T)$$

$$D_E = \frac{\theta^{10/3} D_W + (\theta_A)^{10/3} D_A H'}{(\rho K_d + \theta + \theta_A H')\varphi^2}$$

where,

- $C_0$ = initial soil concentration, in g/kg
- $d$ = thickness of the surface layer that holds the contaminants, 15 cm (5.9 inches) assumed
- $D_A$ = diffusion coefficient for the chemical vapor in air from Table A44, cm$^2$/s
- $D_E$ = effective diffusion coefficient for contaminant motion from the soil and soil water into the soil air, cm$^2$/y
- $D_W$ = diffusion coefficient for the chemical dissolved in water from Table A44, cm$^2$/s
- $T$ = time at which the chemical loss rate is calculated, in years
- $H'$ = unitless Henry's Law Constant for the chemical from Table A3
- $J_S$ = mass flux of the chemical out of the soil surface, in g/cm$^2$ per year
- $K_d$ = distribution coefficient, or soil-water partition coefficient, for the chemical in surface soil, in ml/g. Values for chemicals are shown on Table A41.
- $\varphi$ = total soil porosity, in ml/cm$^3$. $\varphi = 1 - \rho/\rho_p =$ 0.40 ml/cm$^3$
- $\lambda_V$ = volatile emanation constant for the chemical, or fractional loss rate from the surface soil layer into the air above the soil, per year
- $\lambda_R$ = decomposition constant for the chemical, per year (assumed zero)
- $\rho$ = bulk density of the surface soil layer, 1.5 g/cm$^3$ assumed
- $\rho_p$ = particle density of the surface soil layer, 2.5 g/cm$^3$ assumed
- $\theta$ = volumetric water content of the surface soil, milliliters of water per cubic centimeter of soil. A value of 0.2 ml/cm$^3$ is assumed.

$\theta_A$ = volumetric air content of the surface soil, milliliters of air per cubic centimeter of soil. $\theta_A = \varphi - \theta$

The loss rate decreases with time. Thus, an average loss rate is calculated by performing the time integral of the above formula divided by the averaging time ($T_{AVE}$). The average loss rate (or emanation constant) assuming no decomposition ($\lambda_R$=0) is shown in the equation below.

$$\lambda_V = \frac{2}{d}\sqrt{\frac{D_E}{\pi T_{AVE}}}\left[1 - \mathrm{Exp}\left(\frac{-d^2}{4 D_E T_{AVE}}\right)\right] + \frac{1}{T_{AVE}}\mathrm{ERFC}\left(\frac{d}{2\sqrt{D_A T_{AVE}}}\right)$$

Values for the diffusion coefficients ($D_A$ and $D_W$) are from the ORNL RAIS data base. Several chemicals did not have numbers, so values were imputed from a fit to the diffusivity versus molecular weight (MW) data. The diffusion coefficients ($D_A$ and $D_W$) are shown in Table A44, while the molecular weights are listed in Table A3. The fitting functions for the air and water diffusion coefficients are shown below. The data and fitting functions are graphed in Figures A1 and A2. The points on the curve are the imputed numbers.

$$D_A = \frac{0.4\,\mathrm{cm}^2/\mathrm{s}}{1 + 0.04 * \mathrm{MW}} \quad \text{and} \quad D_W = \frac{2.1 \times 10^{-5}\,\mathrm{cm}^2/\mathrm{s}}{1 + 0.01 * \mathrm{MW}}$$

Numbers for diffusion coefficients are shown in Table A44 along with the emanation constants ($\lambda_V$). Irrigated fields are represented as a series of contamination events. Active watering of the soil lasts less than an hour. The averaging period is taken to be the time between irrigation additions to the soil. Because the emanation constant decreases with time, the longest averaging time possible was used, namely, 168 hours (1 week). During the non-irrigation period, the emanation constants are calculated using an averaging period of 0.5 year.

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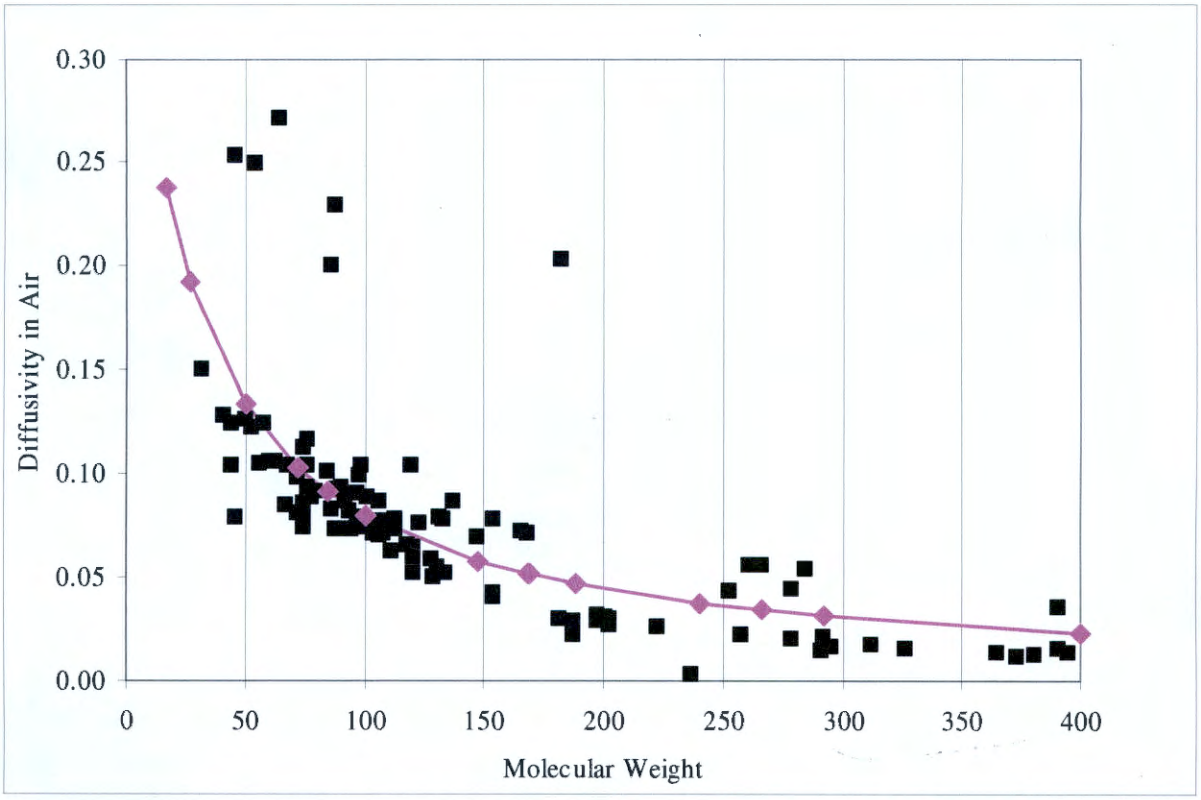


**Figure A1. Diffusivity in Air as a Function of Molecular Weight**

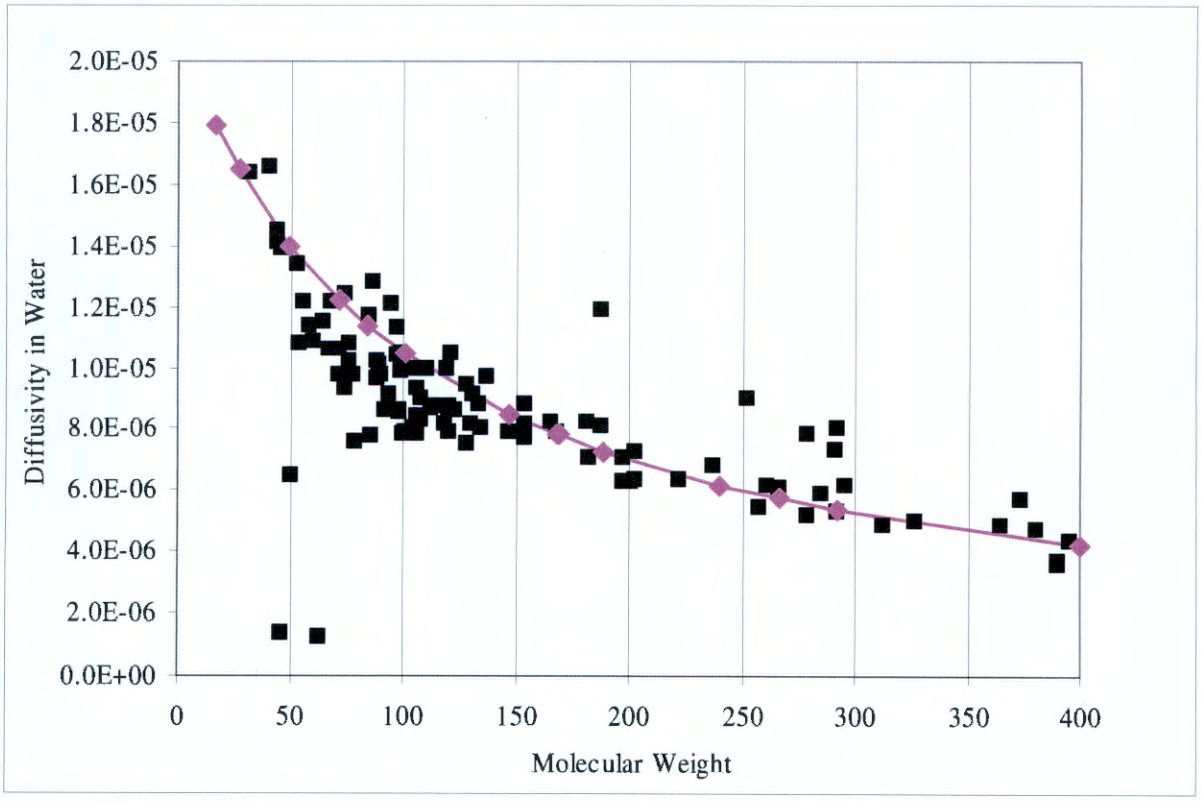


**Figure A2. Diffusivity in Water as a Function of Molecular Weight**

**Table A44. Diffusion Coefficients and Emanation Constants**

| CASRN | Chemical | Diffusion Coefficients ($cm^2$/sec) | | Emanation Constants (per year) | |
|---|---|---|---|---|---|
| | | Air | Water | Active Irrigation | No Irrigation |
| 50-32-8 | Benzo[a]pyrene | 4.30E-02 | 9.00E-06 | 8.68E-03 | 1.70E-03 |
| 53-70-3 | Dibenz[a,h]anthracene | 2.02E-02 | 5.18E-06 | 3.49E-03 | 6.83E-04 |
| 56-23-5 | Carbon tetrachloride | 7.80E-02 | 8.80E-06 | 4.32E+01 | 1.93E+00 |
| 56-55-3 | Benz[a]anthracene | 5.10E-02 | 9.00E-06 | 2.98E-02 | 5.84E-03 |
| 57-12-5 | Cyanide, free | 1.92E-01 | 1.65E-05 | 4.38E+00 | 8.32E-01 |
| 57-14-7 | 1,1-Dimethylhydrazine | 1.06E-01 | 1.09E-05 | 1.67E+00 | 3.27E-01 |
| 57-55-6 | Propylene glycol (1,2-Propanediol) | 9.30E-02 | 1.02E-05 | 3.37E+00 | 6.55E-01 |
| 58-89-9 | gamma-Benzene hexachloride (gamma-Lindane) | 1.42E-02 | 7.34E-06 | 1.36E-01 | 2.66E-02 |
| 60-29-7 | Ethyl ether (Diethyl ether) | 7.40E-02 | 9.30E-06 | 3.57E+01 | 1.87E+00 |
| 60-34-4 | Methylhydrazine | 2.53E-01 | 1.39E-05 | 1.96E+00 | 3.85E-01 |
| 60-57-1 | Dieldrin | 1.25E-02 | 4.74E-06 | 7.49E-02 | 1.47E-02 |
| 62-75-9 | N-Nitrosodimethylamine | 1.13E-01 | 1.24E-05 | 1.72E+00 | 3.36E-01 |
| 64-18-6 | Formic acid | 7.90E-02 | 1.37E-06 | 1.46E+00 | 2.85E-01 |
| 67-56-1 | Methanol (Methyl alcohol) | 1.50E-01 | 1.64E-05 | 7.01E+00 | 1.16E+00 |
| 67-64-1 | Acetone (2-Propanone) | 1.24E-01 | 1.14E-05 | 1.41E+01 | 1.55E+00 |
| 67-66-3 | Chloroform | 1.04E-01 | 1.00E-05 | 3.53E+01 | 1.87E+00 |
| 67-72-1 | Hexachloroethane | 2.50E-03 | 6.80E-06 | 3.26E+00 | 6.35E-01 |
| 71-36-3 | n-Butyl alcohol (n-Butanol) | 8.00E-02 | 9.30E-06 | 5.78E+00 | 1.03E+00 |
| 71-43-2 | Benzene | 8.80E-02 | 9.80E-06 | 2.49E+01 | 1.76E+00 |
| 71-55-6 | 1,1,1-Trichloroethane (Methyl chloroform) | 7.80E-02 | 8.80E-06 | 4.11E+01 | 1.92E+00 |
| 72-20-8 | Endrin | 1.25E-02 | 4.74E-06 | 6.75E-02 | 1.32E-02 |
| 74-83-9 | Bromomethane | 7.28E-02 | 1.21E-05 | 4.09E+01 | 1.91E+00 |
| 74-87-3 | Methyl chloride (Chloromethane) | 1.26E-01 | 6.50E-06 | 4.48E+01 | 1.94E+00 |
| 75-00-3 | Ethyl Chloride | 2.71E-01 | 1.15E-05 | 4.67E+01 | 1.96E+00 |
| 75-01-4 | Vinyl chloride (Chloroethene) | 1.06E-01 | 1.23E-06 | 4.63E+01 | 1.96E+00 |
| 75-05-8 | Acetonitrile | 1.28E-01 | 1.66E-05 | 1.15E+01 | 1.46E+00 |
| 75-07-0 | Acetaldehyde | 1.24E-01 | 1.41E-05 | 1.87E+01 | 1.66E+00 |
| 75-09-2 | Dichloromethane (Methylene chloride) | 1.01E-01 | 1.17E-05 | 3.66E+01 | 1.88E+00 |
| 75-15-0 | Carbon disulfide | 1.04E-01 | 1.00E-05 | 4.81E+01 | 1.97E+00 |
| 75-21-8 | Ethylene Oxide (Oxirane) | 1.04E-01 | 1.45E-05 | 2.42E+01 | 1.75E+00 |
| 75-34-3 | 1,1-Dichloroethane (Ethylidene chloride) | 7.42E-02 | 1.05E-05 | 3.59E+01 | 1.87E+00 |
| 75-35-4 | 1,1-Dichloroethylene | 9.00E-02 | 1.04E-05 | 4.47E+01 | 1.94E+00 |
| 75-45-6 | Chlorodifluoromethane | 8.30E-02 | 1.28E-05 | 4.57E+01 | 1.95E+00 |
| 75-68-3 | Chloro-1,1-difluoroethane, 1- | 7.97E-02 | 1.05E-05 | 4.58E+01 | 1.95E+00 |
| 75-69-4 | Trichlorofluoromethane | 8.70E-02 | 9.70E-06 | 4.71E+01 | 1.96E+00 |
| 75-71-8 | Dichlorodifluoromethane | 5.20E-02 | 1.05E-05 | 4.77E+01 | 1.97E+00 |
| 76-13-1 | 1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113) | 2.88E-02 | 8.07E-06 | 4.42E+01 | 1.94E+00 |
| 76-44-8 | Heptachlor | 1.12E-02 | 5.69E-06 | 1.27E-01 | 2.49E-02 |
| 78-83-1 | Isobutanol | 8.60E-02 | 9.30E-06 | 6.38E+00 | 1.10E+00 |
| 78-87-5 | 1,2-Dichloropropane | 7.82E-02 | 8.73E-06 | 2.55E+01 | 1.76E+00 |
| 78-93-3 | Methyl ethyl ketone (2-Butanone) | 8.08E-02 | 9.80E-06 | 1.20E+01 | 1.48E+00 |

**Table A44. Diffusion Coefficients and Emanation Constants**

| CASRN | Chemical | Diffusion Coefficients ($cm^2/sec$) | | Emanation Constants (per year) | |
|---|---|---|---|---|---|
| | | Air | Water | Active Irrigation | No Irrigation |
| 79-00-5 | 1,1,2-Trichloroethane | 7.80E-02 | 8.80E-06 | 1.48E+01 | 1.57E+00 |
| 79-01-6 | Trichloroethylene | 7.90E-02 | 9.10E-06 | 3.61E+01 | 1.87E+00 |
| 79-10-7 | 2-Propenoic acid (Acrylic acid) | 9.80E-02 | 1.06E-05 | 3.60E+00 | 6.97E-01 |
| 79-34-5 | 1,1,2,2-Tetrachloroethane (Acetylene tetrachloride) | 7.10E-02 | 7.90E-06 | 7.63E+00 | 1.22E+00 |
| 79-46-9 | 2-Nitropropane | 9.23E-02 | 1.01E-05 | 9.71E+00 | 1.37E+00 |
| 82-68-8 | Pentachloronitrobenzene (PCNB) | 1.59E-02 | 6.14E-06 | 2.96E-01 | 5.79E-02 |
| 83-32-9 | Acenaphthene | 4.21E-02 | 7.69E-06 | 5.63E-01 | 1.10E-01 |
| 84-66-2 | Diethyl phthalate | 2.56E-02 | 6.35E-06 | 5.69E-01 | 1.11E-01 |
| 84-74-2 | Dibutyl phthalate | 4.38E-02 | 7.86E-06 | 2.14E-01 | 4.19E-02 |
| 85-68-7 | Butyl benzyl phthalate | 1.74E-02 | 4.83E-06 | 6.08E-02 | 1.19E-02 |
| 86-73-7 | Fluorene | 3.63E-02 | 7.88E-06 | 2.84E-01 | 5.56E-02 |
| 86-74-8 | Carbazole | 3.90E-02 | 7.03E-06 | 6.48E-02 | 1.27E-02 |
| 87-68-3 | Hexachlorobutadiene | 5.61E-02 | 6.16E-06 | 1.20E+01 | 1.48E+00 |
| 87-86-5 | Pentachlorophenol | 5.60E-02 | 6.10E-06 | 1.05E-01 | 2.05E-02 |
| 88-06-2 | 2,4,6-Trichlorophenol | 3.18E-02 | 6.25E-06 | 2.21E-01 | 4.33E-02 |
| 88-85-7 | 2-sec-Butyl-4,6-dinitrophenol (Dinoseb) | 3.77E-02 | 6.17E-06 | 1.08E-01 | 2.12E-02 |
| 91-20-3 | Naphthalene | 5.90E-02 | 7.50E-06 | 1.87E+00 | 3.67E-01 |
| 92-52-4 | 1,1'-Biphenyl | 4.04E-02 | 8.15E-06 | 7.07E-01 | 1.38E-01 |
| 95-47-6 | o-Xylene | 8.70E-02 | 1.00E-05 | 1.57E+01 | 1.60E+00 |
| 95-48-7 | 2-Methylphenol (o-Cresol) | 7.40E-02 | 8.30E-06 | 4.01E-01 | 7.86E-02 |
| 95-50-1 | 1,2-Dichlorobenzene (ortho-) | 6.90E-02 | 7.90E-06 | 8.56E+00 | 1.29E+00 |
| 95-57-8 | 2-Chlorophenol | 5.01E-02 | 9.46E-06 | 6.62E-01 | 1.30E-01 |
| 95-63-6 | 1,2,4-Trimethylbenzene | 6.44E-02 | 7.92E-06 | 1.16E+01 | 1.46E+00 |
| 95-95-4 | 2,4,5-Trichlorophenol | 2.91E-02 | 7.03E-06 | 2.13E-01 | 4.18E-02 |
| 98-86-2 | Acetophenone | 6.00E-02 | 8.73E-06 | 2.02E+00 | 3.96E-01 |
| 98-95-3 | Nitrobenzene | 7.60E-02 | 8.60E-06 | 1.60E+00 | 3.14E-01 |
| 100-00-5 | p-Chloronitrobenzene | 3.49E-02 | 9.42E-06 | 5.62E-01 | 1.10E-01 |
| 100-02-7 | 4-Nitrophenol | 4.30E-02 | 9.61E-06 | 4.31E-01 | 8.43E-02 |
| 100-25-4 | 1,4-Dinitrobenzene (para-) | 5.18E-02 | 7.83E-06 | 4.82E-01 | 9.43E-02 |
| 100-41-4 | Ethyl benzene | 7.50E-02 | 7.80E-06 | 1.66E+01 | 1.62E+00 |
| 100-42-5 | Styrene | 7.10E-02 | 8.00E-06 | 9.61E+00 | 1.36E+00 |
| 100-51-6 | Benzyl alcohol | 7.12E-02 | 8.97E-06 | 1.73E+00 | 3.39E-01 |
| 106-42-3 | p-Xylene | 7.69E-02 | 8.44E-06 | 1.72E+01 | 1.63E+00 |
| 106-44-5 | 4-Methylphenol (p-Cresol) | 7.40E-02 | 1.00E-05 | 4.24E-01 | 8.30E-02 |
| 106-46-7 | 1,4-Dichlorobenzene (para-) | 6.90E-02 | 7.90E-06 | 9.68E+00 | 1.37E+00 |
| 106-93-4 | 1,2-Dibromoethane (Ethylene dibromide) | 2.17E-02 | 1.19E-05 | 8.69E+00 | 1.30E+00 |
| 106-99-0 | 1,3-Butadiene | 2.49E-01 | 1.08E-05 | 4.90E+01 | 1.98E+00 |
| 107-02-8 | 2-Propenal (Acrolein) | 1.05E-01 | 1.22E-05 | 2.07E+01 | 1.70E+00 |
| 107-05-1 | 3-Chloropropene (Allyl chloride) | 1.17E-01 | 1.08E-05 | 4.15E+01 | 1.92E+00 |
| 107-06-2 | 1,2-Dichloroethane (Ethylene chloride) | 1.04E-01 | 9.90E-06 | 2.38E+01 | 1.74E+00 |
| 107-13-1 | Acrylonitrile | 1.22E-01 | 1.34E-05 | 1.81E+01 | 1.65E+00 |

**Table A44. Diffusion Coefficients and Emanation Constants**

| CASRN | Chemical | Diffusion Coefficients ($cm^2$/sec) | | Emanation Constants (per year) | |
|---|---|---|---|---|---|
| | | Air | Water | Active Irrigation | No Irrigation |
| 108-10-1 | Methyl isobutyl ketone (4-Methyl-2-pentanone) | 7.50E-02 | 7.80E-06 | 1.30E+01 | 1.52E+00 |
| 108-38-3 | m-Xylene | 7.00E-02 | 7.80E-06 | 1.67E+01 | 1.62E+00 |
| 108-39-4 | 3-Methylphenol (m-Cresol) | 7.40E-02 | 1.00E-05 | 4.17E-01 | 8.16E-02 |
| 108-67-8 | 1,3,5-Trimethylbenzene | 6.02E-02 | 8.67E-06 | 1.36E+01 | 1.53E+00 |
| 108-87-2 | Methyl cyclohexane | 9.86E-02 | 8.52E-06 | 4.72E+01 | 1.96E+00 |
| 108-88-3 | Toluene (Methyl benzene) | 8.70E-02 | 8.60E-06 | 2.21E+01 | 1.72E+00 |
| 108-90-7 | Chlorobenzene | 7.30E-02 | 8.70E-06 | 1.43E+01 | 1.56E+00 |
| 108-94-1 | Cyclohexanone | 7.84E-02 | 8.62E-06 | 3.40E+00 | 6.61E-01 |
| 108-95-2 | Phenol (Carbolic acid) | 8.20E-02 | 9.10E-06 | 4.76E-01 | 9.33E-02 |
| 109-99-9 | Tetrahydrofuran | 9.80E-02 | 1.10E-05 | 1.92E+01 | 1.67E+00 |
| 110-00-9 | Furan (Oxacyclopentadiene) | 1.04E-01 | 1.22E-05 | 3.15E+01 | 1.83E+00 |
| 110-54-3 | n-Hexane | 2.00E-01 | 7.77E-06 | 5.01E+01 | 1.98E+00 |
| 110-80-5 | 2-Ethoxyethanol | 9.32E-02 | 9.76E-06 | 3.58E+00 | 6.95E-01 |
| 110-82-7 | Cyclohexane | 9.16E-02 | 1.14E-05 | 4.56E+01 | 1.95E+00 |
| 110-86-1 | Pyridine | 9.10E-02 | 7.60E-06 | 2.80E+00 | 5.47E-01 |
| 111-76-2 | 2-Butoxyethanol (Ethylene Glycol Monobutyl Ether) | 6.51E-02 | 8.15E-06 | 3.71E+00 | 7.18E-01 |
| 111-90-0 | 2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether) | 5.24E-02 | 8.02E-06 | 2.98E+00 | 5.83E-01 |
| 117-81-7 | Di (2-ethylhexyl) phthalate (DEHP) | 3.51E-02 | 3.66E-06 | 1.22E-02 | 2.38E-03 |
| 117-84-0 | Di-n-octylphthalate | 1.51E-02 | 3.58E-06 | 1.26E-02 | 2.48E-03 |
| 118-74-1 | Hexachlorobenzene | 5.42E-02 | 5.91E-06 | 2.60E+00 | 5.08E-01 |
| 120-12-7 | Anthracene | 3.24E-02 | 7.74E-06 | 1.55E-01 | 3.04E-02 |
| 120-82-1 | 1,2,4-Trichlorobenzene | 3.00E-02 | 8.23E-06 | 3.83E+00 | 7.38E-01 |
| 121-14-2 | 2,4-Dinitrotoluene | 2.03E-01 | 7.06E-06 | 3.51E-01 | 6.88E-02 |
| 121-44-8 | Triethylamine | 8.81E-02 | 7.88E-06 | 5.43E+00 | 9.85E-01 |
| 122-39-4 | Diphenylamine | 5.15E-02 | 7.80E-06 | 2.18E-01 | 4.28E-02 |
| 123-91-1 | 1,4-Dioxane (Diethylene oxide) | 2.29E-01 | 1.02E-05 | 7.82E+00 | 1.24E+00 |
| 126-73-8 | Tributyl Phosphate | 3.43E-02 | 5.73E-06 | 1.38E-01 | 2.70E-02 |
| 126-98-7 | 2-Methyl-2-propenenitrile (Methacrylonitrile) | 8.45E-02 | 1.06E-05 | 1.72E+01 | 1.63E+00 |
| 127-18-4 | Tetrachloroethylene | 7.20E-02 | 8.20E-06 | 3.65E+01 | 1.88E+00 |
| 129-00-0 | Pyrene | 2.72E-02 | 7.24E-06 | 4.22E-02 | 8.27E-03 |
| 141-78-6 | Ethyl acetate (Acetic acid, ethyl ester) | 7.32E-02 | 9.66E-06 | 1.53E+01 | 1.58E+00 |
| 156-59-2 | cis-1,2-Dichloroethylene | 7.36E-02 | 1.13E-05 | 3.18E+01 | 1.83E+00 |
| 156-60-5 | trans-1,2-Dichloroethylene | 7.07E-02 | 1.19E-05 | 3.77E+01 | 1.89E+00 |
| 193-39-5 | Indeno[1,2,3-cd]pyrene | 1.90E-02 | 5.66E-06 | 3.66E-03 | 7.17E-04 |
| 205-99-2 | Benzo[b]fluoranthene | 2.26E-02 | 5.56E-06 | 6.81E-03 | 1.33E-03 |
| 206-44-0 | Fluoranthene (1,2-Benzacenaphthene) | 3.02E-02 | 6.35E-06 | 3.84E-02 | 7.52E-03 |
| 207-08-9 | Benzo[k]fluoranthene | 2.26E-02 | 5.56E-06 | 6.85E-03 | 1.34E-03 |
| 218-01-9 | Chrysene | 2.48E-02 | 6.21E-06 | 1.72E-02 | 3.36E-03 |
| 309-00-2 | Aldrin | 1.32E-02 | 4.86E-06 | 4.05E-02 | 7.93E-03 |
| 319-84-6 | alpha-Benzene hexachloride (alpha-Lindane) | 1.42E-02 | 7.34E-06 | 1.61E-01 | 3.14E-02 |

**Table A44. Diffusion Coefficients and Emanation Constants**

| CASRN | Chemical | Diffusion Coefficients ($cm^2/sec$) | | Emanation Constants (per year) | |
|---|---|---|---|---|---|
| | | Air | Water | Active Irrigation | No Irrigation |
| 319-85-7 | beta-Benzene hexachloride (beta-Lindane) | 1.42E-02 | 7.34E-06 | 1.16E-01 | 2.28E-02 |
| 541-73-1 | 1,3-Dichlorobenzene | 5.81E-02 | 8.50E-06 | 9.29E+00 | 1.34E+00 |
| 542-75-6 | 1,3-Dichloropropene (cis & trans) | 6.26E-02 | 1.00E-05 | 2.40E+01 | 1.75E+00 |
| 563-68-8 | Thallium Acetate | na | na | 0.0 | 0.0 |
| 621-64-7 | N-Nitrosodi-N-propylamine | 5.45E-02 | 8.17E-06 | 4.99E-01 | 9.77E-02 |
| 1314-62-1 | Vanadium pentoxide | na | na | 0.0 | 0.0 |
| 1330-20-7 | Xylenes (mixtures) | 7.14E-02 | 9.34E-06 | 1.61E+01 | 1.61E+00 |
| 1336-36-3 | Polychlorinated Biphenyls | 1.75E-02 | 8.00E-06 | 1.85E-01 | 3.62E-02 |
| 1336-36-3 | Polychlorinated Biphenyls (lowest risk) | 1.75E-02 | 8.00E-06 | 1.85E-01 | 3.62E-02 |
| 6533-73-9 | Thallium carbonate | na | na | 0.0 | 0.0 |
| 7429-90-5 | Aluminum | na | na | 0.0 | 0.0 |
| 7439-89-6 | Iron | na | na | 0.0 | 0.0 |
| 7439-93-2 | Lithium | na | na | 0.0 | 0.0 |
| 7439-96-5 | Manganese | na | na | 0.0 | 0.0 |
| 7439-97-6 | Mercury metal vapor | 3.07E-02 | 6.30E-06 | 3.36E-01 | 6.58E-02 |
| 7439-98-7 | Molybdenum | na | na | 0.0 | 0.0 |
| 7440-02-0 | Nickel (soluble salts) | na | na | 0.0 | 0.0 |
| 7440-22-4 | Silver | na | na | 0.0 | 0.0 |
| 7440-24-6 | Strontium, Stable | na | na | 0.0 | 0.0 |
| 7440-28-0 | Thallium metal | na | na | 0.0 | 0.0 |
| 7440-31-5 | Tin | na | na | 0.0 | 0.0 |
| 7440-36-0 | Antimony | na | na | 0.0 | 0.0 |
| 7440-38-2 | Arsenic (inorganic) | na | na | 0.0 | 0.0 |
| 7440-39-3 | Barium | na | na | 0.0 | 0.0 |
| 7440-41-7 | Beryllium and compounds | na | na | 0.0 | 0.0 |
| 7440-42-8 | Boron and borates only | na | na | 0.0 | 0.0 |
| 7440-43-9 | Cadmium | na | na | 0.0 | 0.0 |
| 7440-45-1 | Cerium (Ceric oxide 1306-38-3) | na | na | 0.0 | 0.0 |
| 7440-48-4 | Cobalt | na | na | 0.0 | 0.0 |
| 7440-50-8 | Copper | na | na | 0.0 | 0.0 |
| 7440-62-2 | Vanadium metal | na | na | 0.0 | 0.0 |
| 7440-66-6 | Zinc and compounds | na | na | 0.0 | 0.0 |
| 7446-18-6 | Thallium Sulfate | na | na | 0.0 | 0.0 |
| 7487-94-7 | Mercuric chloride | na | na | 0.0 | 0.0 |
| 7664-41-7 | Ammonia | 2.38E-01 | 1.79E-05 | 4.08E+00 | 7.81E-01 |
| 7723-14-0 | Phosphorus, white | na | na | 0.0 | 0.0 |
| 7782-41-4 | Fluorine (soluble fluoride) | na | na | 0.0 | 0.0 |
| 7782-49-2 | Selenium and compounds | na | na | 0.0 | 0.0 |
| 7791-12-0 | Thallium Chloride | na | na | 0.0 | 0.0 |
| 8001-35-2 | Toxaphene | 1.16E-02 | 4.34E-06 | 2.09E-02 | 4.10E-03 |
| 10102-45-1 | Thallium (I) Nitrate | na | na | 0.0 | 0.0 |
| 11096-82-5 | Aroclor 1260 | 1.38E-02 | 4.32E-06 | 7.53E-02 | 1.47E-02 |
| 11097-69-1 | Aroclor 1254 | 1.56E-02 | 5.00E-06 | 1.22E-01 | 2.38E-02 |
| 11104-28-2 | Aroclor 1221 | 4.68E-02 | 7.27E-06 | 5.09E-01 | 9.98E-02 |

**Table A44. Diffusion Coefficients and Emanation Constants**

| CASRN | Chemical | Diffusion Coefficients ($cm^2/sec$) | | Emanation Constants (per year) | |
|---|---|---|---|---|---|
| | | Air | Water | Active Irrigation | No Irrigation |
| 11141-16-5 | Aroclor 1232 | 4.68E-02 | 7.27E-06 | 5.09E-01 | 9.98E-02 |
| 12672-29-6 | Aroclor 1248 | 3.15E-02 | 5.36E-06 | 2.81E-01 | 5.50E-02 |
| 12674-11-2 | Aroclor 1016 | 2.22E-02 | 5.42E-06 | 2.04E-01 | 4.00E-02 |
| 14797-55-8 | Nitrate | na | na | 0.0 | 0.0 |
| 14797-65-0 | Nitrite | na | na | 0.0 | 0.0 |
| 16065-83-1 | Chromium (III) (insoluble salts) | na | na | 0.0 | 0.0 |
| 16984-48-8 | Fluorine anion | na | na | 0.0 | 0.0 |
| 18540-29-9 | Chromium (VI) (soluble salts) | na | na | 0.0 | 0.0 |
| 22967-92-6 | Methyl Mercury | na | na | 0.0 | 0.0 |
| 53469-21-9 | Aroclor 1242 | 2.14E-02 | 5.31E-06 | 2.03E-01 | 3.97E-02 |
| na | Uranium (soluble salts) | na | na | 0.0 | 0.0 |

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The averaging times for the "Active" and "No" irrigation cases are 1 week (168 hours) and 0.5 year.
- Diffusion Coefficients marked with an asterisk were estimated from a fit to the Diffusivity versus Molecular Weight data. Missing values are indicated with "na", which means "not available".

## A7.0 DIAMETER OF TYPICAL WATER WELLS

The State of Washington Department of Ecology, Water Resources has placed a database of well reports on their web site. The address is "http://apps.ecy.wa.gov/welllog/". These reports summarize the location, dimensions, and geologic information collected at each well. The well report viewer enables one to retrieve and examine individual well reports.

To obtain a picture of the typical water well in the area surrounding the Hanford Site, well records for Adams, Benton, Franklin, and Grant County were obtained for well depths ranging from 200 ft to 400 ft. These were then sorted by well diameter and totaled. The results are shown in Table A45.

**Table A45. Number of Wells of Each Diameter**

| Diameter | Number | % of Total |
|---|---|---|
| 1 in | 1 | 0.033% |
| 3 in | 1 | 0.033% |
| 4 in | 51 | 1.689% |
| 5 in | 10 | 0.331% |
| 6 in | 1952 | 64.636% |
| 8 in | 529 | 17.517% |
| 9 in | 2 | 0.066% |
| 10 in | 105 | 3.477% |
| 11 in | 2 | 0.066% |
| 12 in | 123 | 4.073% |
| 12.25 in | 1 | 0.033% |
| 14 in | 13 | 0.430% |
| 15 in | 18 | 0.596% |
| 16 in | 129 | 4.272% |
| 17 in | 1 | 0.033% |
| 18 in | 11 | 0.364% |
| 20 in | 12 | 0.397% |
| 22 in | 2 | 0.066% |
| 26 in | 4 | 0.132% |
| 30 in | 3 | 0.099% |
| blank | 50 | 1.656% |
| Totals | 3020 | 99.999% |

The database does not distinguish between domestic and industrial or irrigation use for the well. Hence, a second list of wells was created whose owner name was an individual's name. This removed government entities, farms, ranches, orchards and various businesses.

In addition, the Water Well Reports for the larger diameters (10 inches and above) were examined to obtain any well use information. For the past 25 years, the form submitted to the

Department of Ecology has a "Proposed Use" check box. It was found that none of the wells greater than 16 inches had the "Domestic" box checked. Most were listed as "Irrigation". Wells with the "Domestic" use were retained along with wells for which no proposed use was stated. The large number of wells with diameters less than 10 inches was not examined in detail. Samples of the Water Well Reports show that most of the smaller diameters are domestic use wells. The subtotals for the second list are shown in Table A46.

**Table A46. Number of Individual Wells of Each Diameter**

| Diameter | Number | % of Total |
|---|---|---|
| 1 in | 1 | 0.042% |
| 4 in | 1 | 0.042% |
| 5 in | 10 | 0.424% |
| 6 in | 1792 | 75.964% |
| 8 in | 405 | 17.168% |
| 9 in | 2 | 0.085% |
| 10 in | 55 | 2.331% |
| 11 in | 1 | 0.042% |
| 12 in | 56 | 2.374% |
| 14 in | 2 | 0.085% |
| 15 in | 2 | 0.085% |
| blank | 32 | 1.357% |
| Totals | 2359 | 99.999% |

The list of all wells summarized in Table A45 shows that 64% have a diameter of 6 inches. The modified list summarized in Table A46 shows that 76% have a diameter of 6 inches. Since the 6 and 8 inch well counts in Table A46 were not adjusted for proposed use, their percentage is exaggerated. Nevertheless, it is apparent that the typical well drilled for domestic use is 6 inches in diameter. Comparing the two tables, the most likely large diameter commercial irrigation well is 16 inches.

The diameter of a well that might be used in the rural pasture scenario ranges from 6 to 16 inches. A diameter of 10 inches is recommended as an intermediate size suitable for the larger water flow rate needed to supply irrigation water for a cow pasture.

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## Attachment A1. ISCST3 Input Files for the 100 $m^2$ Source

## FIRST CASE -- ZERO ELEVATION RECEPTORS

```
CO STARTING
   TITLEONE  Area Sources --- 100 sq.m
   MODELOPT  MSGPRO  CONC  RURAL
   AVERTIME  ANNUAL
   TERRHGTS  ELEV
   FLAGPOLE  0.0
   POLLUTID  OTHER
   RUNORNOT  RUN
   ERRORFIL  ERRORS.LST
CO FINISHED

SO STARTING
**           SRCID  SRCTYP    XS       YS        ZS
**           -----  ------   -----    -----     -----
   LOCATION  A100    AREA    -5.0     -5.0     .0000

**           SRCID    QS       HS     XINIT   YINIT
**           -----   ----     ----    -----   -----
   SRCPARAM  A100     1.0      0.0      10.     10.

   EMISUNIT     1.00  (GRAMS/(SEC-M**2))          grams/cubic-meter

   SRCGROUP    AREA1   A100
SO FINISHED

RE STARTING
   GRIDPOLR POL1 STA
                 DIST  1.  1.5  2.  2.5  3.  5.  10.  15.  20.
                 GDIR  36   0.0   10.0
   GRIDPOLR POL1 END
   DISCCART      0.     0.     0.     0.
   DISCCART      0.     0.     0.     1.
   DISCCART      0.    10.     0.     0.
   DISCCART      0.    10.     0.     1.
   DISCCART     10.    10.     0.     0.
   DISCCART     10.    10.     0.     1.
   DISCCART     10.     0.     0.     0.
   DISCCART     10.     0.     0.     1.
   DISCCART     10.   -10.     0.     0.
   DISCCART     10.   -10.     0.     1.
   DISCCART      0.   -10.     0.     0.
   DISCCART      0.   -10.     0.     1.
   DISCCART    -10.   -10.     0.     0.
   DISCCART    -10.   -10.     0.     1.
   DISCCART    -10.     0.     0.     0.
   DISCCART    -10.     0.     0.     1.
   DISCCART    -10.    10.     0.     0.
   DISCCART    -10.    10.     0.     1.
RE FINISHED
```

```
ME STARTING
   INPUTFIL  MET\EPA92-96.2E
   ANEMHGHT  10.0
   SURFDATA  67656  1992   Hanford-200
   UAIRDATA  67656  1992   Hanford-200
ME FINISHED

OU STARTING
   RECTABLE ALLAVE FIRST  SECOND
   MAXTABLE ALLAVE  50
OU FINISHED
```

## SECOND CASE -- 0.5 M ELEVATION RECEPTORS

```
CO STARTING
   TITLEONE  Area Sources --- 100 sq.m
   MODELOPT  MSGPRO  CONC  RURAL
   AVERTIME  ANNUAL
   TERRHGTS  ELEV
   FLAGPOLE  0.5
   POLLUTID  OTHER
   RUNORNOT  RUN
   ERRORFIL  ERRORS.LST
CO FINISHED

SO STARTING
**            SRCID  SRCTYP    XS       YS        ZS
**            -----  ------   -----    -----     -----
   LOCATION   A100    AREA    -5.0     -5.0     .0000

**            SRCID    QS       HS     XINIT   YINIT
**            -----   ----     ----    -----   -----
   SRCPARAM   A100     1.0      0.0      10.     10.

   EMISUNIT     1.00  (GRAMS/(SEC-M**2))          grams/cubic-meter

   SRCGROUP    AREA1   A100
SO FINISHED

RE STARTING
   GRIDPOLR POL1 STA
                DIST  3.  5.  6.  7.  8.  9.  10.  12.  15.
                GDIR  36   0.0   10.0
   GRIDPOLR POL1 END
RE FINISHED

ME STARTING
   INPUTFIL  MET\EPA92-96.2E
   ANEMHGHT  10.0
   SURFDATA  67656  1992   Hanford-200
   UAIRDATA  67656  1992   Hanford-200
ME FINISHED

OU STARTING
```

```
   RECTABLE ALLAVE FIRST  SECOND
   MAXTABLE ALLAVE  50
OU FINISHED
```

## THIRD CASE -- 1 M ELEVATION RECEPTORS

```
CO STARTING
   TITLEONE  Area Sources --- 100 sq.m
   MODELOPT  MSGPRO  CONC  RURAL
   AVERTIME  ANNUAL
   TERRHGTS  ELEV
   FLAGPOLE  1.0
   POLLUTID  OTHER
   RUNORNOT  RUN
   ERRORFIL  ERRORS.LST
CO FINISHED

SO STARTING
**           SRCID  SRCTYP    XS       YS        ZS
**           -----  ------   -----    -----     -----
   LOCATION  A100    AREA    -5.0     -5.0     .0000

**           SRCID    QS       HS     XINIT   YINIT
**           -----   ----     ----    -----   -----
   SRCPARAM  A100     1.0      0.0      10.     10.

   EMISUNIT     1.00  (GRAMS/(SEC-M**2))           grams/cubic-meter

   SRCGROUP    AREA1   A100
SO FINISHED

RE STARTING
   GRIDPOLR POL1 STA
                DIST  8.  12.  13.  14.  15.  16.  17.  20.  25.
                GDIR  36   0.0   10.0
   GRIDPOLR POL1 END
RE FINISHED

ME STARTING
   INPUTFIL  MET\EPA92-96.2E
   ANEMHGHT  10.0
   SURFDATA  67656  1992   Hanford-200
   UAIRDATA  67656  1992   Hanford-200
ME FINISHED

OU STARTING
   RECTABLE ALLAVE FIRST  SECOND
   MAXTABLE ALLAVE  50
OU FINISHED
```

# APPENDIX B

# DECAY PROGENY INGROWTH

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# DECAY PROGENY INGROWTH

## B1.0 INTRODUCTION

The mathematical models incorporating radioactive decay are described in this section. The various pathway parameters discussed in Appendix A are put to use in the formulas. The presence of radioactive decay chains complicates this discussion, and the subsequent calculations. But the use of decay chains is necessary because some progeny nuclides are more significant than the parent nuclide.

To facilitate calculations with the large number of nuclides that may be found at the Hanford Site, the hand calculations were automated using commercial spreadsheet software. Spreadsheet calculations have been verified by hand calculations presented in the attachments to this appendix.

Doses to humans exposed to exhumed contamination or irrigation water include both internal and external radiation exposures. The internal dose comes from the inhalation of resuspended dust and the ingestion of contaminated water, soil, and foodstuffs. The external dose comes primarily from being near the contaminated soil. The sections below describe how the human dose is computed from the parameters of Appendix A together with standard models for estimating this dose. First, the time dependence of soil concentrations are presented. Second, the external and inhalation doses received from contaminated soil are described. Third, the concentrations and doses for various plant types are described. Finally, the concentrations and doses for animal products are described. The role of radioactive decay and daughter in-growth is discussed in each section.

## B2.0 TIME DEPENDENCE OF SOIL CONCENTRATIONS

The soil concentrations are of two types. The first type of soil contamination results from drilling a hole through the waste site and spreading the contamination in a garden. In this case there is some initial concentration of a nuclide in the surface layer that decreases with time due to radioactive decay and leaching from the surface layer. The second type of soil concentration results from irrigating with contaminated water. In this case the contamination increases with time due to the added radioactivity. However, this increase is offset by radioactive decay and leaching from the surface layer.

In the description of progeny in-growth, it will be assumed that only the parent nuclide along with any of its short-lived progeny shown in Table A1 is present initially. Each nuclide in the decay chains listed in Table A2 must be treated independently. This enables the calculation of unit dose factors for each of the principal nuclides in a decay chain. In the case of irrigation water, it is also assumed that the decay chain progeny are not accumulating in the water prior to irrigation. Only the parent nuclide is coming from the well and being deposited on the soil. In addition, it is assumed that the water concentration is constant during the year of irrigation. As before, this enables the calculation of unit dose factors for each of the principal nuclides in a decay chain.

The discussion below is divided into three parts. The first describes the decay of a nuclide and progeny in-growth with time due to nuclear decay alone, i.e., without leaching or additions from contaminated irrigation water. The second part adds decay in the presence of leaching from the surface layer. The third includes irrigation with contaminated water. In all cases, the decay chains shown in Table A2 are used. The longest decay chain has just four members because decay times less than 1000 years are assumed for generation of the unit dose factors. Additional discussion is provided to show how decay chains are incorporated into the calculations.

## B2.1 DECAY WITHOUT LEACHING OR IRRIGATION DEPOSITION

The radioactive decay constants will be represented as $\lambda_{1r}$, $\lambda_{2r}$, $\lambda_{3r}$, $\lambda_{4r}$, and so forth until $\lambda_{nr}$, which is the last member of the chain. The leaching coefficients describing removal from the surface layer by water infiltration will be represented as $\lambda_{1s}$, $\lambda_{2s}$, $\lambda_{3s}$, $\lambda_{4s}$, and so forth. The sum of these the radioactive and leaching constants for a given nuclide will be represented as $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$, and so forth. In other words, $\lambda_2$ is defined by the equation $\lambda_2 = \lambda_{2r} + \lambda_{2s}$. Radioactive decay constants are computed by dividing the half life of the nuclide (Table A1) into the logarithm of 2 (Ln 2 = 0.69314718). Leaching coefficients for radionuclides are listed in Table A43.

The following demonstrates the general form of the customary decay chain formula to describe the in-growth of the "nth" progeny from the first member of the chain. In other words, the only member of the chain with any activity to begin with is the first nuclide. The equations below describe the in-growth of a specific progeny nuclide, the "nth" member of the chain in the absence of leaching and irrigation with contaminated water. These equations also describe the activity in contaminated vegetables or animal products after they are harvested.

$$C_{sn} = C_{s1}^{0}\left(\prod_{k=1}^{n-1} B_{k,k+1}\right)\left(\prod_{k=2}^{n} \lambda_{kr}\right) DR_{1n} \qquad (1)$$

$$DR_{1n} = \sum_{k=1}^{n} \frac{e^{-\lambda_{kr} t}}{PD_{1,kr,n}} \qquad (2)$$

$$PD_{1,kr,n} = \prod_{\substack{i=1 \\ i \neq k}}^{n} \left(\lambda_{ir} - \lambda_{kr}\right) \qquad (3)$$

$C_{s1}^{0}$ is the initial soil concentration of the first member of the chain. $C_{sn}$ is the concentration of the "nth" member of the chain after the time "t" has elapsed. $C_{sn}$ is assumed to be zero initially, and to increase with time. Both concentrations have units of Ci/kg.

The term $B_{k,k+1}$ is the fraction of decays of nuclide number "k" which produce nuclide number "k+1". $B_{k,k+1}$ is also known as the branching ratio for nuclear transition from k to k+1. Most branching ratios are simply 1.0. Non-unit branching ratios are given in Table A2.

The term $DR_{1n}$ contains the time dependent functions for each nuclide in the chain from nuclide "1" down to nuclide "n". For convenience in writing the denominator, the product of decay constant differences is defined as shown in Equation (3). Note that when n=1, $PD_{1,1,1}=1$.

The decay equations are presented as Equation (4) for the first four nuclides. In a four-step decay chain, nuclide 1 (the parent) decays to nuclide 2, which then decays to nuclide 3, which then decays to nuclide 4.

$$
\begin{aligned}
C_{s1} &= C_{s1}^{0}\, e^{-\lambda_1 t} = C_{s1}^{0}\, E_1 \\
C_{s2} &= C_{s1}^{0}\, B_{12}\, \lambda_2 \left[\frac{E_1}{\lambda_{21}} + \frac{E_2}{\lambda_{12}}\right] = C_{s1}^{0}\, \frac{B_{12}\, \lambda_2}{\lambda_2 - \lambda_1}\left[E_1 - E_2\right] \\
C_{s3} &= C_{s1}^{0}\, B_{12}\, B_{23}\, \lambda_2\, \lambda_3 \left[\frac{E_1}{\lambda_{21}\, \lambda_{31}} + \frac{E_2}{\lambda_{12}\, \lambda_{32}} + \frac{E_3}{\lambda_{13}\, \lambda_{23}}\right] \\
C_{s4} &= C_{s1}^{0}\, B_{12}\, B_{23}\, B_{34}\, \lambda_2\, \lambda_3\, \lambda_4 \left[\frac{E_1}{\lambda_{21}\lambda_{31}\lambda_{41}} + \frac{E_2}{\lambda_{12}\lambda_{32}\lambda_{42}} + \frac{E_3}{\lambda_{13}\lambda_{23}\lambda_{43}} + \frac{E_4}{\lambda_{14}\lambda_{24}\lambda_{34}}\right]
\end{aligned}
\tag{4}
$$

note that $E_K = e^{-\lambda_K t}$ and $\lambda_{KL} = \lambda_K - \lambda_L$ where $K, L = 1, 2, 3, 4$

where,

$C_{s1}^{0}$ = initial concentration of nuclide 1 (T=0), in Ci/kg. The initial concentrations of all other members of the chain are assumed to be zero.

$C_{s1}, C_{s2}, C_{s3}, C_{s4}$ = concentration of nuclides 1, 2, 3, and 4 at time T, in Ci/kg.

$B_{12}, B_{23}, B_{34}$ = branching ratios for nuclides 1, 2, and 3.

$\lambda_{1r}, \lambda_{2r}, \lambda_{3r}, \lambda_{4r}$ = radioactive decay constants for nuclides 1, 2, 3, and 4. Note that the decay constant is the natural logarithm of 2 divided by the half-life of the nuclide. Note also that the decay constants in a decay chain are all different so the differences will never be zero.

## B2.2 DECAY WITH LEACHING BUT WITHOUT IRRIGATION DEPOSITION

The situation with an initial soil contamination that decreases due to irrigation and radioactive decay is described next. When leaching from the surface layer takes place, there is an additional removal mechanism that increases the size of the removal terms. Leaching coefficients were discussed in Section A6.0 and are listed in Tables A41 and A43. Multiple years of leaching and decay will be described using a two-part irrigation model. The first half of the year has significant leaching due to the irrigation. The second half of the year has no leaching.

### B2.2.1. Initial Soil Concentration During the Irrigation Season

The addition of leaching only changes Equations (2) and (3) by replacing the radioactive decay constants ($\lambda_{kr}$) with the combined leaching and decay coefficients ($\lambda_k = \lambda_{ks} + \lambda_{kr}$). In effect, the radioactive decay constant increases. The new equations for decay with leaching are shown below as Equations (5), (6), and (7). Note that the product of radioactive decay constants in Equation (5) is unchanged from Equation (1).

$$C_{sn} = C_{s1}^{0}\left(\prod_{k=1}^{n-1} B_{k,k+1}\right)\left(\prod_{k=2}^{n} \lambda_{kr}\right) DS_{1n} \tag{5}$$

$$DS_{1n} = \sum_{k=1}^{n} \frac{e^{-\lambda_k t}}{PD_{1,k,n}} \tag{6}$$

$$PD_{1,k,n} = \prod_{\substack{i=1 \\ i \neq k}}^{n} (\lambda_i - \lambda_k) \tag{7}$$

The term $C_{s1}^{0}$ is the same as in Equation (1). It is the initial soil concentration of the parent nuclide in the chain. The $B_{k,k+1}$ terms are also the same as in Equation (1). The change in the definition of the time-dependent function $DS_{1n}$ increases the exponents, so the decline in soil concentration is faster. Note that when n=1, $PD_{1,1,1}=1$. Note also that the subtractions in the $PD_{1,k,n}$ term do not eliminate the leaching factor unless they are all the same for that decay chain. Therefore Equations (3) and (7) are normally not the same.

### B2.2.2. Initial Soil Concentration at the End of the First Year

To describe the concentration of a nuclide in the soil at the end of the first year, one must combine the equations of the previous section into the physically allowable sequences. During the first 6 months of the year irrigation takes place. During the second 6 months of the year irrigation ceases and the precipitation rate is assumed to match the evapo-transpiration rate, so that the leaching factors are all zero. The second half of the year has only radioactive decay.

In the post-intrusion garden scenario, for the first member of a decay chain, the soil concentration at the end of the year is the initial concentration multiplied by factors for decay and leaching during the irrigation season followed by simple decay during the remainder of the year. This is shown in Equation (8) below. The $W_{11}$ term is introduced to simplify later equations.

$$\begin{aligned} C_{s1}(1) &= C_{s1}^{0}\, DS_{11}\, DR_{11} = C_{s1}^{0}\, W_{11} \\ W_{11} &= \mathrm{Exp}(-\lambda_1 T_{irr})\, \mathrm{Exp}(-\lambda_{1r} T_{no}) \\ \text{and} \quad \lambda_1 &= \lambda_{1s} + \lambda_{1r} \quad \text{and} \quad T_{irr} + T_{no} = 1\,\mathrm{y} \end{aligned} \tag{8}$$

where,

$C_{s1}(1)$ = soil concentration of the first member of the decay chain at the end of the first year, in Ci/kg

$C_{s1}^0$ = initial soil concentration of the first member of the decay chain, in Ci/kg
$T_{irr}$ = irrigation period, 0.5 y
$T_{no}$ = no irrigation period, $T_{no} = 1\ y - T_{irr} = 0.5\ y$
$W_{11}$ = fraction of the initial soil concentration of the first member of the decay chain that is left at the end of 1 year when the irrigation water adds no contaminants
$\lambda_1$ = total removal constant for the first member of the chain, per year
$\lambda_{1r}$ = radioactive decay constant for the first member of the chain, per year
$\lambda_{1s}$ = average soil leaching coefficient for the first member of the chain, per year

The first daughter of nuclide "1" is produced during the irrigation period and then decays during the rest of the year. It also is produced from the decay of the parent nuclide that is present at the end of the irrigation season. This is shown in Equation (9). The term $B_{12}^C$ is introduced to simplify later equations.

$$C_{s2}(1) = C_{s1}^0 B_{12}^C (DS_{12} DR_{22} + DS_{11} DR_{12}) = C_{s1}^0 B_{12}^C W_{12} \qquad (9)$$
$$\text{where} \quad B_{12}^C = B_{12} \lambda_2$$

The concentration of the third and fourth nuclides in the chain at the end of the first year is calculated using Equations (10). Longer chains are computed in a similar fashion. Note that all possible decay paths must be considered. This leads to as many terms as there are members in the decay chain.

$$C_{s3}(1) = C_{s1}^0 B_{13}^C (DS_{13} DR_{33} + DS_{12} DR_{23} + DS_{11} DR_{13}) = C_{s1}^0 B_{13}^C W_{13}$$
$$C_{s4}(1) = C_{s1}^0 B_{14}^C (DS_{14} DR_{44} + DS_{13} DR_{34} + DS_{12} DR_{24} + DS_{11} DR_{14}) \qquad (10)$$
$$= C_{s1}^0 B_{14}^C W_{14}$$
$$\text{where} \quad B_{13}^C = B_{12} B_{23} \lambda_2 \lambda_3 \quad \text{and} \quad B_{14}^C = B_{12} B_{23} B_{34} \lambda_2 \lambda_3 \lambda_4$$

### B2.2.3. Initial Soil Concentration after Several Years

To describe the concentration of a nuclide in the soil after several years, the decay factors are multiplied by the soil concentration at the start of each year. This is demonstrated for the first member of the decay chain in Equation (11). The concentration is at the end of N years when the amount at the start of the first year was $C_{s1}^0$. Each year the concentration decreases by the factor $W_{11}$.

$$C_{s1}(N) = C_{s1}(N-1) W_{11} = C_{s1}^0 (W_{11})^N \qquad (11)$$

For the 2nd member of the decay chain, there are two sources. The first source is the 1st member of the decay chain. The 1st member's activity is multiplied by $B_{12}^C W_{12}$. The second source is the presence of the 2nd member in the soil after the first year. The activity of the 2nd

member is multiplied by $W_{22}$, which is similar to $W_{11}$ except that the decay factors use the decay and leaching parameters for the 2nd nuclide. The X-notation is introduced in Equation (12) to simplify the calculation. The exponent (N-1) does not refer to the exponentiation process, but rather is another index. When N=1 the $X_{12}$ term is 1.

$$C_{s2}(N) = C_{s2}(N-1)W_{22} + C_{s1}(N-1)B_{12}^{C}\,W_{12} = C_{s1}^{0}\,B_{12}^{C}\,X_{12}^{N-1}$$
$$\text{where}\quad X_{12}^{N-1} = \frac{(W_{11})^N - (W_{22})^N}{W_{11} - W_{22}} = \sum_{K=0}^{N-1}(W_{11})^K\,(W_{22})^{N-1-K} \tag{12}$$

For the 3rd member of the decay chain, there are three sources. The first source is the 1st member of the decay chain. The 1st member's activity is multiplied by $B_{13}W_{13}$. The second source is the presence of the 2nd member in the soil after the first year. The activity of the 2nd member is multiplied by $B_{23}W_{23}$. The third source is the presence of the 3rd member in the soil after the first year. The activity of the 3rd member is multiplied by $W_{33}$. The X-notation is used in Equation (13) to simplify the calculation. The exponents of X are indices rather than exponentiation. When N=1 the $X_{13}$ term is 1 but the $X_{123}$ term is 0.

$$C_{s3}(N) = C_{s3}(N-1)W_{33} + C_{s2}(N-1)B_{23}^{C}\,W_{23} + C_{s1}(N-1)B_{13}^{C}\,W_{13}$$
$$C_{s3}(N) = C_{s1}^{0}\,B_{13}^{C}\left(W_{13}\,X_{13}^{N-1} + W_{12}\,W_{23}\,X_{123}^{N-2}\right)$$
$$\text{where}\quad X_{13}^{N-1} = \frac{(W_{11})^N - (W_{33})^N}{W_{11} - W_{33}} \quad\text{and}\quad X_{123}^{N-2} = \frac{(W_{11})^N}{(W_{11} - W_{22})(W_{11} - W_{33})} \tag{13}$$
$$+ \frac{(W_{22})^N}{(W_{22} - W_{11})(W_{22} - W_{33})} + \frac{(W_{33})^N}{(W_{33} - W_{11})(W_{33} - W_{22})}$$

For the 4th member of the decay chain, there are four sources corresponding to the four members of the decay chain. The X-notation is used in Equation (14) to simplify the calculation. This notation also indicates the technique for modeling longer decay chains. When N=1 the $X_{14}$ term is 1 but the $X_{134}$, $X_{124}$, and $X_{1234}$ terms are all 0. When N=2 the $X_{134}$ and $X_{124}$ terms are 1 but the $X_{1234}$ term is 0.

$$C_{s4}(N) = C_{s4}(N-1)W_{44} + C_{s3}(N-1)B_{34}^{C}\,W_{34} + C_{s2}(N-1)B_{24}^{C}\,W_{24} + C_{s1}(N-1)B_{14}^{C}\,W_{14}$$
$$C_{s4}(N) = C_{s1}^{0}\,B_{14}^{C}\left(W_{14}\,X_{14}^{N-1} + W_{13}\,W_{34}\,X_{134}^{N-2} + W_{12}\,W_{24}\,X_{124}^{N-2} + W_{12}\,W_{23}\,W_{34}\,X_{1234}^{N-3}\right)$$
$$\text{where}\quad X_{1234}^{N-3} = \frac{(W_{11})^N}{(W_{11} - W_{22})(W_{11} - W_{33})(W_{11} - W_{44})} + \frac{(W_{22})^N}{(W_{22} - W_{11})(W_{22} - W_{33})(W_{22} - W_{44})} \tag{14}$$
$$+ \frac{(W_{33})^N}{(W_{33} - W_{11})(W_{33} - W_{22})(W_{33} - W_{44})} + \frac{(W_{44})^N}{(W_{44} - W_{11})(W_{44} - W_{22})(W_{44} - W_{33})}$$

### B2.2.4. Initial Soil Concentration Cumulative Dose

The doses that result from continuous intakes, or exposures, during the years of interest can be calculated from the above equations for soil concentration assuming the instantaneous

dose rate (i.e., dose per day) is proportional to the soil concentration. The dose during one year is the time-integral of the soil concentration times a conversion factor (CF). This time integral of the soil concentration during the irrigation period is shown in Equations (15) and (16). Note that Equation (7), which defines $PD_{1,k,n}$, is not changed by the integration. Also note that the integrated soil concentration term (IDS) is unitless.

$$H_{sn} = \int C_{sn} CF_n \, dt = CF_n \, t \, C_{s1}^0 \left( \prod_{k=1}^{n-1} B_{k,k+1} \right) \left( \prod_{k=2}^{n} \lambda_{kr} \right) IDS_{1n} \tag{15}$$

$$\text{where} \quad IDS_{1n} = \sum_{k=1}^{n} \frac{1 - e^{-\lambda_k t}}{\lambda_k t \; PD_{1,k,n}} \tag{16}$$

A similar function results from the time integral of DR over the latter half of the year. The total dose that accumulates during the first year is shown in the equations below (17). The year must be divided into the irrigation and non-irrigation parts to complete the integration. The T term is introduced to simplify the notation.

$$\begin{aligned}
H_{s1}(1) &= CF_1 \, C_{s1}^0 \left( IDS_{11} \, T_{irr} + DS_{11} \, IDR_{11} \, T_{no} \right) = CF_1 \, C_{s1}^0 \, T_{11} \\
&= CF_1 \, C_{s1}^0 \left[ \left( \frac{1 - Exp(-\lambda_1 \, T_{irr})}{\lambda_1 \, T_{irr}} \right) T_{irr} + Exp(-\lambda_1 \, T_{irr}) \left( \frac{1 - Exp(-\lambda_{1r} T_{no})}{\lambda_{1r} T_{no}} \right) T_{no} \right] \\
H_{s2}(1) &= CF_2 \, C_{s1}^0 \, B_{12}^C \left( IDS_{12} \, T_{irr} + \left( DS_{12} \, IDR_{22} + DS_{11} \, IDR_{12} \right) T_{no} \right) = CF_2 \, C_{s1}^0 \, B_{12}^C \, T_{12} \\
H_{s3}(1) &= CF_3 \, C_{s1}^0 \, B_{13}^C \left( IDS_{13} \, T_{irr} + \left( DS_{13} \, IDR_{33} + DS_{12} \, IDR_{23} + DS_{11} \, IDR_{13} \right) T_{no} \right) \\
H_{s3}(1) &= CF_3 \, C_{s1}^0 \, B_{13}^C \, T_{13} \\
H_{s4}(1) &= CF_4 \, C_{s1}^0 \, B_{14}^C \left( IDS_{14} \, T_{irr} + \left( DS_{14} \, IDR_{44} + DS_{13} \, IDR_{34} + DS_{12} \, IDR_{24} + DS_{11} \, IDR_{14} \right) T_{no} \right) \\
H_{s4}(1) &= CF_4 \, C_{s1}^0 \, B_{14}^C \, T_{14}
\end{aligned} \tag{17}$$

The cumulative dose after N years is the sum of the doses received in the previous (N-1) years plus the dose that accumulates during the Nth year. For the 1st isotope in the decay chain, it is the sum of N terms, as shown in Equation (18). The Y term is introduced to simplify later equations. Note that the upper index of the Y term is not an exponent, unlike the upper index of the $W_{11}$ term.

$$H_{s1}(N) = \sum_{K=1}^{N} H_{s1}(K) = \sum_{K=1}^{N} H_{s1}(1)(W_{11})^{K-1} = H_{s1}(1) \frac{1 - (W_{11})^N}{1 - W_{11}} = H_{s1}(1) \, Y_1^{N-1} \tag{18}$$

For decay fractions that are close to 1, a small decay approximation has been derived to improve numeric accuracy. This approximation is shown in Equation (19).

For $W = e^{-\varepsilon}$ and $\varepsilon < 0.001$

$$\frac{W^{N_1} - W^{N_2}}{1 - W} \cong 1 - \frac{\varepsilon}{2}(M-1) + \frac{\varepsilon^2}{12}\left(2M^2 - 3M + 1\right)$$
$$- \frac{\varepsilon^3}{24}\left(M^3 - 2M^2 + M\right) + \frac{\varepsilon^4}{720}\left(6M^4 - 15M^3 + 10M^2 - 1\right) \qquad (19)$$

where $M = N_1 + N_2$ and $M^2 = (N_1)^2 + N_1 N_2 + (N_2)^2$

and $M^K = \dfrac{(N_1)^{K+1} - (N_2)^{K+1}}{N_1 - N_2}$

For the 2nd member of the decay chain the cumulative dose has two components. The first is the contribution from the 1st member of the decay chain each year. The second comes from the 2nd member of the decay chain as it accumulates after the first year. These are shown in Equation (20). The Y term simplifies later equations. It also illustrates the technique for modeling longer decay chains. Equation (20) is largely the same as Equation (12) except that $W^N$ has been replaced with $(1-W^N)/(1-W)$. Note that when N=1, the $Y_1$ term is 1 while the $Y_{12}$ term is zero. This indicates that all the dose calculated from the 2nd member during the first year comes directly from the 1st member of the decay chain. Not until the second year does the 2nd member become a separate source of dose.

$$H_{s2}(N) = \sum_{K=1}^{N} H_{s2}(1)(W_{11})^{K-1} + \sum_{K=2}^{N} CF_2\, C_{s1}^0\, B_{12}^C\, X_{12}^{K-2}\, T_{22}$$
$$H_{s2}(N) = CF_2\, C_{s1}^0\, B_{12}^C \left(Y_1^{N-1} T_{12} + W_{12} Y_{12}^{N-2} T_{22}\right) \qquad (20)$$
$$\text{where} \quad Y_{12}^{N-2} = \frac{\left(\dfrac{1-(W_{11})^N}{1-W_{11}}\right) - \left(\dfrac{1-(W_{22})^N}{1-W_{22}}\right)}{W_{11} - W_{22}} = \frac{Y_1^{N-1} - Y_2^{N-1}}{W_{11} - W_{22}}$$

For the 3rd member of the decay chain the cumulative dose has three components. The first is the contribution from the 1st member of the decay chain each year. The second and third come from the 2nd and 3rd members of the decay chain as they accumulate after the first year. These are shown in Equation (21). The Y term illustrates the technique for modeling longer decay chains. Equation (21) is largely the same as Equation (13) except that $W^N$ has been replaced with $(1-W^N)/(1-W)$. Note that the $Y_{123}$ term is zero until N=3.

$$H_{s3}(N) = \sum_{K=1}^{N} H_{s3}(1)(W_{11})^{K-1} + \sum_{K=2}^{N} CF_3\, C_{s1}^{0}\, B_{13}^{C}\left[W_{12}X_{12}^{K-2}T_{23} + \left(W_{13}X_{13}^{K-2} + W_{12}W_{23}X_{123}^{K-3}\right)T_{33}\right]$$

$$H_{s3}(N) = CF_3\, C_{s1}^{0}\, B_{13}^{C}\left[Y_1^{N-1}T_{13} + W_{12}Y_{12}^{N-2}T_{23} + \left(W_{13}Y_{13}^{N-2} + W_{12}W_{23}Y_{123}^{N-3}\right)T_{33}\right]$$

$$\text{where} \quad Y_{13}^{N-2} = \frac{\left(\dfrac{1-(W_{11})^N}{1-W_{11}}\right) - \left(\dfrac{1-(W_{33})^N}{1-W_{33}}\right)}{W_{11} - W_{33}} = \frac{Y_1^{N-1} - Y_3^{N-1}}{W_{11} - W_{33}} \tag{21}$$

$$Y_{123}^{N-3} = \frac{Y_1^{N-1}}{(W_{11} - W_{22})(W_{11} - W_{33})} + \frac{Y_2^{N-1}}{(W_{22} - W_{11})(W_{22} - W_{33})} + \frac{Y_3^{N-1}}{(W_{33} - W_{11})(W_{33} - W_{22})}$$

For the 4th member of the decay chain the cumulative dose has four components. The first is the contribution from the 1st member of the decay chain each year. The others are from the 2nd, 3rd, and 4th members of the decay chain as they accumulate after the first year. These are shown in Equation (22). The Y term illustrates the technique for modeling longer decay chains. Equation (22) is largely the same as Equation (14) except that $W^N$ has been replaced with $(1-W^N)/(1-W)$. Note that the $Y_{1234}$ term is zero until N=4.

$$\begin{aligned} H_{s4}(N) = \sum_{K=1}^{N} H_{s4}(1)(W_{11})^{K-1} + \sum_{K=2}^{N} CF_4\, C_{s1}^{0}\, B_{14}^{C}\Big[&W_{12}X_{12}^{K-1}T_{24} + \left(W_{13}X_{13}^{K-1} + W_{12}W_{23}X_{123}^{K-2}\right)T_{34} \\ &+ \left(W_{14}X_{14}^{K-1} + W_{13}W_{34}X_{134}^{K-2} + W_{12}W_{24}X_{124}^{K-2} + W_{12}W_{23}W_{34}X_{1234}^{K-3}\right)T_{44}\Big] \\ H_{s4}(N) = CF_4\, C_{s1}^{0}\, B_{14}^{C}\Big[&Y_1^{N-1}T_{14} + W_{12}Y_{12}^{N-2}T_{24} + \left(W_{13}Y_{13}^{N-2} + W_{12}W_{23}Y_{123}^{N-3}\right)T_{34} \\ &+ \left(W_{14}Y_{14}^{N-2} + W_{13}W_{34}Y_{134}^{N-3} + W_{12}W_{24}Y_{124}^{N-3} + W_{12}W_{23}W_{34}Y_{1234}^{N-4}\right)T_{44}\Big] \end{aligned} \tag{22}$$

$$\text{where} \quad Y_{1234}^{N-4} = \frac{Y_1^{N-1}}{(W_{11} - W_{22})(W_{11} - W_{33})(W_{11} - W_{44})} + \frac{Y_2^{N-1}}{(W_{22} - W_{11})(W_{22} - W_{33})(W_{22} - W_{44})}$$
$$+ \frac{Y_3^{N-1}}{(W_{33} - W_{11})(W_{33} - W_{22})(W_{33} - W_{44})} + \frac{Y_4^{N-1}}{(W_{44} - W_{11})(W_{44} - W_{22})(W_{44} - W_{33})}$$

## B2.3 DECAY WITH LEACHING AND IRRIGATION DEPOSITION

The sources of contaminated irrigation water are either groundwater or Columbia River water. The instantaneous rate of addition of contamination to the soil is shown as the first equation in Equation (23). The conversion factor (10 L $m^{-2}$ $cm^{-1}$) changes centimeters of water applied to the soil to liters applied per square meter. The instantaneous rate of increase in the in the soil concentration is computed as shown in the second equation below.

$$\begin{aligned} ID_p &= \frac{C_w\, I}{T_{irr}}\left(10\,\frac{L}{m^2\,cm}\right) \\ ID_{s1}^{0} &= \frac{ID_p}{\rho\, d} \end{aligned} \tag{23}$$

Where

$C_w$ = irrigation water concentration, in curies per liter (Ci/L). This concentration is assumed to be constant (no decay) during the 6 month application period.

d = thickness of the surface layer of soil from which nuclides migrate downward, 15 cm (5.9 inches).

I = irrigation water applied to plants during the irrigation period. For the maximum individual cases, this value is 82.3 cm. For the population dose, this value was lowered to 63.5 cm due to less irrigation in areas farther down the Columbia River (WHC-SD-WM-EE-004).

$ID_p$ = instantaneous activity deposition rate during the irrigation of areas growing plant type p, in curies per square meter per year (Ci $y^{-1}$ $m^{-2}$).

$ID^0_{s1}$ = instantaneous rate of increase in the soil concentration during the irrigation season, in curies per kilogram per year.

$T_{irr}$ = irrigation period in years. The value 0.5 yr is used since the irrigation is assumed to take place 6 months per year (April through September).

$\rho$ = bulk density of the surface soil, in grams per cubic centimeter. The value normally used in Hanford Site PA work is 1.5 g/cc.

The instantaneous deposition rate is twice the average deposition rate for the year because the deposition only occurs during the irrigation season. Additional formulas for soil concentration are presented in the sections that follow.

### B2.3.1. Irrigated Soil Concentration During the Irrigation Season

Using contaminated irrigation water, the concentration of radioactivity in the surface layer of soil increases with time. The equations to represent this turn out to be the time integral of Equations (5), (6), and (7). This activity accumulation is shown in Equations (24) and (25), below. Equation (7), which defines $PD_{1,k,n}$, is not affected by the integration. The term $ID^0_{s1}$ is the rate at which the concentration of the parent nuclide increases due to irrigation deposition. Note the addition of the irrigation time (t) to the equation to make the DI decay term a unitless fraction representing accumulation in the soil of contaminants that decay or are leached from the surface layer. At the end of the irrigation period, $t=T_{irr}$. The DI term is mathematically identical to the IDS term shown in Equation (16).

$$C_{sn} = t\left(ID^0_{s1}\right)\left(\prod_{k=1}^{n-1} B_{k,k+1}\right)\left(\prod_{k=2}^{n} \lambda_{kr}\right)\left(DI_{1n}\right) \tag{24}$$

$$DI_{1n} = \sum_{k=1}^{n} \frac{1 - e^{-\lambda_k t}}{\lambda_k \, t \, PD_{1,k,n}} \tag{25}$$

Equations (1), (2), and (3) apply to soil with no leaching at all. Whatever water falls on the soil evaporates without forcing contamination through the surface layer into deeper layers. The key to represent this ordinary decay is the term $DR_{1n}$. Equations (5), (6), and (7) apply to soil with some leaching taking place. This might be due to excess natural precipitation or

irrigation with uncontaminated water. The key to represent this decay with leaching is the term $DS_{1n}$. Equations (24) and (25) apply to soil being irrigated with contaminated water. Leaching from the surface layer is also occurring. The key to represent this combination of decay, leaching, and accumulation is the term $DI_{1n}$. These key terms will be used in the next section to describe the soil concentration after many years of irrigation with contaminated water.

One exception to the above is for tritium in the irrigation water applied to the soil. An equilibrium approach is used. The tritium concentration in the soil moisture is assumed to equal the tritium concentration in the applied irrigation water, adjusted for natural precipitation. This is calculated using the formula below. Note the absence of time dependence. The tritium concentration is constant during the irrigation season.

$$C_{s,H3} = 8.94\ F_{Hs}\ C_{w,H3}\left(\frac{I}{I+P}\right) \tag{26}$$

Where

$C_{s,H3}$ = concentration of tritium in the surface soil during the irrigation season, in curies per kilogram.

8.94 = factor to convert the hydrogen weight fraction into a water fraction. It comes from the ratio of molecular weights for hydrogen (2.0159 g/gmole) and water (18.0153 g/gmole).

$F_{Hs}$ = fraction of hydrogen in garden soil, 0.0149 g hydrogen per gram of soil (from Table A37).

$C_{w,H3}$ = concentration of tritium in the irrigation water, in pCi/L.

I = total irrigation water applied to the soil during the irrigation season, 82.3 cm/y (63.5 cm/y for the population).

P = total natural precipitation water reaching the soil during the irrigation period, 5.77 cm/y (PNNL-15160).

The ratio I/(I+P) incorporates the dilution of contaminated irrigation water with natural precipitation. This soil concentration is constant during the irrigation season, but decreases exponentially during the non-irrigation season due to continuing precipitation and evaporation.

### B2.3.2. Irrigated Soil Concentration at the End of the First Year

In the irrigation scenarios, for the first member of the chain, the concentration at the end of the year is the product of the accumulated activity at the end of the irrigation season and the decay factor resulting from decay without irrigation or leaching for the remainder of the year. This is shown in Equation (27). Note the similarity between Equations (8) and (27). This will be seen again in the next few equations.

$$C_{s1}(1) = T_{irr}\, ID_{s1}^{0}\, DI_{11}\, DR_{11}$$
$$DI_{11}\, DR_{11} = \left(\frac{1-\mathrm{Exp}(-\lambda_1 T_{irr})}{\lambda_1 T_{irr}}\right) \mathrm{Exp}(-\lambda_{1r} T_{no}) \tag{27}$$

where,

$C_{s1}(1)$ = soil concentration of the first member of the decay chain at the end of the first year, in Ci/kg

$ID_{s1}^{0}$ = instantaneous soil deposition rate from irrigation for the first member of the decay chain, in Ci/kg per year

$T_{irr}$ = irrigation period, 0.5 y

$T_{no}$ = no irrigation period, $T_{no} = 1\ y - T_{irr} = 0.5\ y$

$W_{11}$ = fraction of the initial soil concentration of the first member of the decay chain that is left at the end of 1 year when the irrigation water adds no contaminants

$\lambda_1$ = total removal constant for the first member of the chain, per year

$\lambda_{1r}$ = radioactive decay constant for the first member of the chain, per year

$\lambda_{1s}$ = average soil leaching coefficient for the first member of the chain, per year

The first daughter of nuclide "1" is produced during the irrigation period and then decays during the rest of the year. It also is produced from the decay of the parent nuclide that is present at the end of the irrigation season. This is shown in Equation (28). Note that the assumed amount of the daughter in the irrigation water is always zero. The term $B_{12}^{C}$ is introduced to simplify later equations and is the same as before. Equation (28) is similar to Equation (9).

$$C_{s2}(1) = T_{irr}\, ID_{s1}^{0}\, B_{12}^{C}\, (DI_{12}\, DR_{22} + DI_{11}\, DR_{12})$$
$$\text{where} \quad B_{12}^{C} = B_{12}\, \lambda_2 \tag{28}$$

The concentration of the third and fourth nuclides in the chain at the end of the first year is calculated using Equation (29). Longer chains are computed in a similar fashion. Note that all possible decay paths must be considered. This leads to as many terms as there are members in the decay chain. Equation (29) is similar to Equation (10).

$$C_{s3}(1) = T_{irr}\, ID_{s1}^{0}\, B_{13}^{C}\, (DI_{13}\, DR_{33} + DI_{12}\, DR_{23} + DI_{11}\, DR_{13})$$
$$C_{s4}(1) = T_{irr}\, ID_{s1}^{0}\, B_{14}^{C}\, (DI_{14}\, DR_{44} + DI_{13}\, DR_{34} + DI_{12}\, DR_{24} + DI_{11}\, DR_{14}) \tag{29}$$
$$\text{where} \quad B_{13}^{C} = B_{12}\, B_{23}\, \lambda_2\, \lambda_3 \quad \text{and} \quad B_{14}^{C} = B_{12}\, B_{23}\, B_{34}\, \lambda_2\, \lambda_3\, \lambda_4$$

In practice, it is better to calculate the decay factors for each nuclide, since these are unitless fractions whose value is near 1.0 for nuclides with long half lives. The calculation of media concentrations and dose can be carried out ignoring decay. A decay factor can then be added.

### B2.3.3. Irrigated Soil Concentration after Several Years

After the first year of irrigation, there is residual contamination, which must be taken into account when computing the total activity at the end of the year under consideration. The

activity after N years is the sum of the activity after (N-1) years decaying for 1 year, plus the activity that normally accumulates during the year. The added activity is independent of the amount of residual contamination. The residual contamination from prior years irrigation is modeled as an initial soil concentration, described in Section B2.2.

For the 1st member of the decay chain (the parent nuclide) after several years of irrigation, the total soil concentration is the sum of N years of deposition each adjusted for decay. This is demonstrated in Equation (30). The concentration is at the end of N years when the amount added every year is $C_{s1}$. Each year the concentration added in any year decreases by the factor $W_{11}$. The Y-notation is used in Equation (30) to simplify the calculation. These are the same W's and Y's that were used in Equation (18). The exponent (N-1) does not refer to the exponentiation process, but rather is another index. When N=1 the $Y_1$ term is 1.

$$C_{s1}(N) = \sum_{K=1}^{N} C_{s1}(1)(W_{11})^{K-1} = C_{s1}(1)\frac{1-(W_{11})^N}{1-W_{11}} = C_{s1}(1)Y_1^{N-1} \tag{30}$$

For the 2nd member of the decay chain, there are two sources for the residual contamination. The first source is the activity of the 1st member of the decay chain at the end of (N-1) years. The 1st member's activity is multiplied by $B_{12}^{C}W_{12}$. The second source is the presence of the 2nd member in the soil after the first year. The activity of the 2nd member of the decay chain after (N-1) years is multiplied by $W_{22}$. The W's and Y's are the same as used in Equation (20). Equation (31) summarizes this discussion.

$$\begin{aligned}
C_{s2}(N) &= C_{s2}(1) + C_{s2}(N-1)W_{22} + C_{s1}(N-1)B_{12}^{C}\,W_{12} \\
C_{s2}(N) &= \sum_{K=1}^{N} C_{s2}(1)(W_{22})^{K-1} + \sum_{K=2}^{N} C_{s1}(1)B_{12}^{C}\,W_{12}\,X_{12}^{K-2} \\
C_{s2}(N) &= C_{s2}(1)Y_2^{N-1} + C_{s1}(1)B_{12}^{C}\,W_{12}\,Y_{12}^{N-2} \\
\text{where}\quad Y_2^{N-1} &= \frac{1-(W_{22})^N}{1-W_{22}} \quad \text{and} \quad Y_{12}^{N-2} = \frac{Y_1^{N-1}-Y_2^{N-1}}{W_{11}-W_{22}}
\end{aligned} \tag{31}$$

For the 3rd member of the decay chain, there are three sources of residual contamination. The first source is the activity of the 1st member of the decay chain at the end of (N-1) years of irrigation. The 1st member's activity is multiplied by $B_{13}^{C}W_{13}$ and $B_{13}^{C}W_{12}W_{23}$. The second source is the presence of the 2nd and 3rd members of the decay chain at the end of (N-1) years. The activity of the 2nd member is multiplied by $B_{23}^{C}W_{23}$. The activity of the 3rd member is multiplied by $W_{33}$. The Y-notation used in Equation (32) is the same as used in Equation (21). The exponents of Y are indices rather than exponentiation. When N=1 the $Y_{13}$ term is 1 but the $Y_{123}$ term is 0. This indicates that during the first year, all the activity of the 3rd member comes directly from the 1st member of the chain.

$$C_{s3}(N) = \sum_{K=1}^{N} C_{s3}(1)(W_{33})^{K-1} + \sum_{K=2}^{N} C_{s2}(1) B_{23}^{C} W_{23} X_{23}^{K-2}$$

$$+ \sum_{K=2}^{N} C_{s1}(1) B_{13}^{C}\left(W_{13} X_{13}^{K-2} + W_{12} W_{23} X_{123}^{K-3}\right)$$

$$C_{s3}(N) = C_{s3}(1) Y_3^{N-1} + C_{s2}(1) B_{23}^{C} W_{23} Y_{23}^{N-2} + C_{s1}(1) B_{13}^{C}\left(W_{13} Y_{13}^{N-2} + W_{12} W_{23} Y_{123}^{N-3}\right) \qquad (32)$$

where $Y_3^{N-1} = \dfrac{1-(W_{33})^N}{1-W_{33}}$ and $Y_{13}^{N-2} = \dfrac{Y_1^{N-1} - Y_3^{N-1}}{W_{11} - W_{33}}$

$$Y_{123}^{N-3} = \frac{Y_1^{N-1}}{(W_{11} - W_{22})(W_{11} - W_{33})} + \frac{Y_2^{N-1}}{(W_{22} - W_{11})(W_{22} - W_{33})} + \frac{Y_3^{N-1}}{(W_{33} - W_{11})(W_{33} - W_{22})}$$

For the 4th member of the decay chain, there are four sources of residual activity corresponding to the four members of the decay chain. These are shown in Equation (33). The Y term illustrates the technique for modeling longer decay chains. It is the same Y shown in Equation (22).

$$C_{s4}(N) = \sum_{K=1}^{N} C_{s4}(1)(W_{44})^{K-1} + \sum_{K=2}^{N} C_{s3}(1) B_{34}^{C} W_{34} X_{34}^{K-2}$$

$$+ \sum_{K=2}^{N} C_{s2}(1) B_{24}^{C}\left(W_{24} X_{24}^{K-2} + W_{23} W_{34} X_{234}^{K-3}\right)$$

$$+ \sum_{K=2}^{N} C_{s1}(1) B_{14}^{C}\left(W_{14} X_{14}^{K-2} + W_{13} W_{34} X_{134}^{K-3} + W_{12} W_{24} X_{124}^{K-3} + W_{12} W_{23} W_{34} X_{1234}^{K-4}\right)$$

$$C_{s4}(N) = C_{s4}(1) Y_4^{N-1} + C_{s3}(1) B_{34}^{C} W_{34} Y_{34}^{N-2} + C_{s2}(1) B_{24}^{C}\left(W_{24} Y_{24}^{N-2} + W_{23} W_{34} Y_{234}^{N-3}\right) \qquad (33)$$

$$+ B_{14}^{C}\left(W_{14} Y_{14}^{N-2} + W_{13} W_{34} Y_{134}^{N-3} + W_{12} W_{24} Y_{124}^{N-3} + W_{12} W_{23} W_{34} Y_{1234}^{N-4}\right)$$

$$Y_{1234}^{N-4} = \frac{Y_1^{N-1}}{(W_{11} - W_{22})(W_{11} - W_{33})(W_{11} - W_{44})} + \frac{Y_2^{N-1}}{(W_{22} - W_{11})(W_{22} - W_{33})(W_{22} - W_{44})}$$

$$+ \frac{Y_3^{N-1}}{(W_{33} - W_{11})(W_{33} - W_{22})(W_{33} - W_{44})} + \frac{Y_4^{N-1}}{(W_{44} - W_{11})(W_{44} - W_{22})(W_{44} - W_{33})}$$

### B2.3.4. Irrigated Soil Concentration Cumulative Dose

Dose calculations involving several years' irrigation with contaminated water are calculated as the sum of an initial soil concentration case and an irrigation case. The dose from irrigation water used during the year of interest is the same every year. This dose has a component that depends on the soil concentration. The other components are direct intakes of irrigation water and shoreline sediment exposures.

The dose from the irrigated soil can be calculated from the above equations for irrigated soil concentration assuming the instantaneous dose rate (i.e., dose per day) is proportional to the soil concentration. The dose during one year is the time-integral of the soil concentration times a

conversion factor. This time integral of the soil concentration during the irrigation period is shown in the equations below. Note that Equation (7), which defines $PD_{1,k,n}$, is not changed by the integration. Also note that the integrated soil concentration term (IDI) is unitless.

$$\int C_{sn} dt = t^2 \left(ID_{s1}^0\right)\left(\prod_{k=1}^{n-1} B_{k,k+1}\right)\left(\prod_{k=2}^{n} \lambda_{kr}\right)\left(IDI_{1n}\right) \tag{34}$$

$$IDI_{1n} = \sum_{k=1}^{n} \frac{\lambda_k t - 1 + e^{-\lambda_k t}}{(\lambda_k t)^2 \, PD_{1,k,n}} \tag{35}$$

The total dose that accumulates during the first year is shown in the Equation (36). As before, the general conversion factor for each nuclide in the chain is represented by term CF. The year must be divided into the irrigation and non-irrigation portions to complete the integration.

$$\begin{aligned}
H_{s1}(1) &= CF_1 \, T_{irr} \, DI_{s1}^0 \left(IDI_{11} \, T_{irr} + DI_{11} \, IDR_{11} \, T_{no}\right) \\
&= CF_1 \, T_{irr} \, DI_{s1}^0 \left[\left(\frac{\lambda_1 T_{irr} - 1 + Exp(-\lambda_1 T_{irr})}{(\lambda_1 \, T_{irr})^2}\right) T_{irr} + \left(\frac{1 - Exp(-\lambda_1 T_{irr})}{\lambda_1 \, T_{irr}}\right)\left(\frac{1 - Exp(-\lambda_{1r} T_{no})}{\lambda_{1r} T_{no}}\right) T_{no}\right] \\
H_{s2}(1) &= CF_2 \, T_{irr} \, ID_{s1}^0 \, B_{12}^C \left(IDI_{12} \, T_{irr} + \left(DI_{12} \, IDR_{22} + DI_{11} \, IDR_{12}\right) T_{no}\right) \\
H_{s3}(1) &= CF_3 \, T_{irr} \, ID_{s1}^0 \, B_{13}^C \left(IDI_{13} \, T_{irr} + \left(DI_{13} \, IDR_{33} + DI_{12} \, IDR_{23} + DI_{11} \, IDR_{13}\right) T_{no}\right) \\
H_{s4}(1) &= CF_4 \, T_{irr} \, ID_{s1}^0 \, B_{14}^C \left(IDI_{14} \, T_{irr} + \left(DI_{14} \, IDR_{44} + DI_{13} \, IDR_{34} + DI_{12} \, IDR_{24} + DI_{11} \, IDR_{14}\right) T_{no}\right)
\end{aligned} \tag{36}$$

The cumulative dose after N years is the sum of the doses received in the previous (N-1) years plus the dose that accumulates during the Nth year. The dose in the Nth year is the dose from irrigation (the same every year) plus the dose from the soil contamination that is present after (N-a) years of irrigation. For the first member of the decay chain, the cumulative total dose at the end of N years is shown in Equation (37). $C_{s1}(1)$ is the soil concentration at the end of the first year of irrigation as defined in Equation (27). $T_{11}$ is the same as defined in Equation (17). The Z term is introduced to simplify later equations. The Z terms are sums of the Y terms.

$$\begin{aligned}
H_{s1}(N) &= \sum_{K=1}^{N}\left(H_{s1}(1) + \sum_{J=2}^{K} CF_1 \, C_{s1}(1) (W_{11})^{J-2} T_{11}\right) = N \, H_{s1}(1) + \sum_{K=1}^{N} CF_1 \, C_{s1}(1)\left(\frac{1-(W_{11})^{K-1}}{1-W_{11}}\right) T_{11} \\
H_{s1}(N) &= N \, H_{s1}(1) + \left(\frac{CF_1 \, C_{s1}(1)}{1-W_{11}}\right)\left(N - \frac{1-(W_{11})^N}{1-W_{11}}\right) T_{11} = N \, H_{s1}(1) + CF_1 \, C_{s1}(1) Z_1^{N-2} \, T_{11}
\end{aligned} \tag{37}$$

For decay fractions that are close to 1, a small decay approximation has been derived to improve numeric accuracy. This approximation is shown in Equation (38).

For $W = e^{-\varepsilon}$ and $\varepsilon < 0.001$

$$\frac{1 - \left[\dfrac{W^{N_1} - W^{N_2}}{(N_2 - N_1)(1 - W)}\right]}{1 - W} \cong \frac{(M-1)}{2} + \frac{\varepsilon}{6}\left(M^2 - 3M + 2\right)$$
$$- \frac{\varepsilon^2}{24}\left(M^3 - 4M^2 + 5M - 2\right) + \frac{\varepsilon^3}{360}\left(3M^4 - 15M^3 + 25M^2 - 15M + 2\right) \qquad (38)$$

where $M = N_1 + N_2$ and $M^2 = (N_1)^2 + N_1 N_2 + (N_2)^2$

and $M^K = \dfrac{(N_1)^{K+1} - (N_2)^{K+1}}{N_1 - N_2}$

For the second member of the decay chain, the cumulative total dose at the end of N years is shown in Equation (39). $C_{s2}(1)$ is the soil concentration of the 2nd member at the end of the first year of irrigation as defined in Equation (27). $T_{12}$ is the same as defined in Equation (17). $T_{22}$ is similar to $T_{11}$ except that the decay and leaching parameters belong to the 2nd member of the chain.

$$H_{s2}(N) = \sum_{K=1}^{N}\left[H_{s2}(1) + CF_2\, C_{s1}(1)\, Y_1^{K-2} B_{12}^C T_{12} + CF_2\left(C_{s2}(1)\, Y_2^{K-2} + C_{s1}(1)\, B_{12}^C W_{12} Y_{12}^{K-3}\right) T_{22}\right]$$
$$H_{s2}(N) = N\, H_{s2}(1) + CF_2\left[C_{s1}(1)\, Z_1^{N-2} B_{12}^C T_{12} + \left(C_{s2}(1)\, Z_2^{N-2} + C_{s1}(1)\, B_{12}^C W_{12} Z_{12}^{N-3}\right) T_{22}\right] \qquad (39)$$
$$Z_{12}^{N-3} = \frac{\left(\dfrac{1}{1 - W_{11}}\right)\left(N - \dfrac{1 - W_{11}^N}{1 - W_{11}}\right) - \left(\dfrac{1}{1 - W_{22}}\right)\left(N - \dfrac{1 - W_{22}^N}{1 - W_{22}}\right)}{W_{11} - W_{22}} = \frac{Z_1^{N-2} - Z_2^{N-2}}{W_{11} - W_{22}}$$

For the third member of the decay chain, the cumulative total dose at the end of N years is shown in Equation (40). $C_{s3}(1)$ is the soil concentration of the 3rd member at the end of the first year of irrigation as defined in Equation (27). $T_{13}$ is the same as defined in Equation (17).

$$H_{s3}(N) = \sum_{K=1}^{N}\Big\{H_{s3}(1) + CF_3\, C_{s1}(1)\, Y_1^{K-2}\, B_{13}^C\, T_{13}$$
$$+ CF_3\left(C_{s2}(1)\, Y_2^{K-2} + C_{s1}(1)\, B_{12}^C\, W_{12}\, Y_{12}^{K-3}\right) B_{23}^C\, T_{23}$$
$$+ CF_3\left[C_{s3}(1)\, Y_3^{K-2} + C_{s2}(1)\, B_{23}^C\, W_{23}\, Y_{23}^{K-3} + C_{s1}(1)\, B_{13}^C\left(W_{13}\, Y_{13}^{K-3} + W_{12}\, W_{23}\, Y_{123}^{K-4}\right)\right] T_{33}\Big\}$$
$$H_{s3}(N) = N\, H_{s3}(1) + CF_3\Big\{C_{s1}(1)\, Z_1^{N-2}\, B_{13}^C\, T_{13} + \left(C_{s2}(1)\, Z_2^{N-2} + C_{s1}(1)\, B_{12}^C\, W_{12}\, Z_{12}^{N-3}\right) B_{23}^C\, T_{23}$$
$$+ \left[C_{s3}(1)\, Z_3^{N-2} + C_{s2}(1)\, B_{23}^C\, W_{23}\, Z_{23}^{N-3} + C_{s1}(1)\, B_{13}^C\left(W_{13}\, Z_{13}^{N-3} + W_{12}\, W_{23}\, Z_{123}^{N-4}\right)\right] T_{33}\Big\} \qquad (40)$$

where $Z_{123}^{N-4} = \dfrac{Z_1^{N-2}}{(W_{11} - W_{22})(W_{11} - W_{33})} + \dfrac{Z_2^{N-2}}{(W_{22} - W_{11})(W_{22} - W_{33})} + \dfrac{Z_3^{N-2}}{(W_{33} - W_{11})(W_{33} - W_{22})}$

For the fourth member of the decay chain, the cumulative total dose at the end of N years is shown in Equation (41). $C_{s4}(1)$ is the soil concentration of the 4th member at the end of the first year of irrigation as defined in Equation (27). $T_{14}$ is the same as defined in Equation (17).

$$
\begin{aligned}
H_{s4}(N) = \sum_{K=1}^{N} \Big\{ & H_{s4}(1) + CF_4\, C_{s1}(1)\, Y_1^{K-2}\, B_{14}^{C}\, T_{14} \\
& + CF_4 \left( C_{s2}(1)\, Y_2^{K-2} + C_{s1}(1)\, B_{12}^{C}\, W_{12}\, Y_{12}^{K-3} \right) B_{24}^{C}\, T_{24} \\
& + CF_4 \left[ C_{s3}(1)\, Y_3^{K-2} + C_{s2}(1)\, B_{23}^{C}\, W_{23}\, Y_{23}^{K-3} + C_{s1}(1)\, B_{13}^{C} \left( W_{13}\, Y_{13}^{K-3} + W_{12}\, W_{23}\, Y_{123}^{K-4} \right) \right] B_{34}^{C}\, T_{34} \\
& + CF_4 \Big[ C_{s4}(1)\, Y_4^{K-2} + C_{s3}(1)\, B_{34}^{C}\, W_{34}\, Y_{34}^{K-3} + C_{s2}(1)\, B_{24}^{C} \left( W_{24}\, Y_{24}^{K-3} + W_{23}\, W_{34}\, Y_{234}^{K-4} \right) \\
& \qquad + C_{s1}(1)\, B_{14}^{C} \left( W_{14}\, Y_{14}^{K-3} + W_{13}\, W_{34}\, Y_{134}^{K-4} + W_{12}\, W_{24}\, Y_{124}^{K-4} + W_{12} W_{23} W_{34}\, Y_{1234}^{K-5} \right) \Big] T_{44} \Big\} \\
H_{s4}(N) = N\, & H_{s4}(1) + CF_4 \Big\{ C_{s1}(1)\, Z_1^{N-2}\, B_{14}^{C}\, T_{14} + \left( C_{s2}(1)\, Z_2^{N-2} + C_{s1}(1)\, B_{12}^{C}\, W_{12}\, Z_{12}^{N-3} \right) B_{24}^{C}\, T_{24} \\
& + \left[ C_{s3}(1)\, Z_3^{N-2} + C_{s2}(1)\, B_{23}^{C}\, W_{23}\, Z_{23}^{N-3} + C_{s1}(1)\, B_{13}^{C} \left( W_{13}\, Z_{13}^{N-3} + W_{12}\, W_{23}\, Z_{123}^{N-4} \right) \right] B_{34}^{C}\, T_{34} \\
& + \Big[ C_{s4}(1)\, Z_4^{N-2} + C_{s3}(1)\, B_{34}^{C}\, W_{34}\, Z_{34}^{N-3} + C_{s2}(1)\, B_{24}^{C} \left( W_{24}\, Z_{24}^{N-3} + W_{23}\, W_{34}\, Z_{234}^{N-4} \right) \\
& \qquad + C_{s1}(1)\, B_{14}^{C} \left( W_{14}\, Z_{14}^{N-3} + W_{13}\, W_{34}\, Z_{134}^{N-4} + W_{12}\, W_{24}\, Z_{124}^{N-4} + W_{12} W_{23} W_{34}\, Z_{1234}^{N-5} \right) \Big] T_{44} \Big\} \qquad (41)
\end{aligned}
$$

where $Y_{1234}^{N-5} = \dfrac{Z_1^{N-2}}{(W_{11} - W_{22})(W_{11} - W_{33})(W_{11} - W_{44})} + \dfrac{Z_2^{N-2}}{(W_{22} - W_{11})(W_{22} - W_{33})(W_{22} - W_{44})}$

$$
+ \frac{Z_3^{N-2}}{(W_{33} - W_{11})(W_{33} - W_{22})(W_{33} - W_{44})} + \frac{Z_4^{N-2}}{(W_{44} - W_{11})(W_{44} - W_{22})(W_{44} - W_{33})}
$$

## B3.0 EXTERNAL AND INHALATION DOSE

The inhalation dose that is received by exposure to airborne water during showering or a sauna or under ambient conditions is simply the product of the volume of water inhaled during the year, the water concentration, and the inhalation dose factor as shown in Equation (42). No consideration of radioactive decay or progeny in-growth is needed, because the water concentration is assumed to be constant during the year, and no progeny are allowed to accumulate in the water.

$$H_{bw} = Q_{wb}\, C_w\, D_{inh}\, T_{inh} \tag{42}$$

Where

$H_{bw}$ = inhalation dose from airborne moisture during one year, in mrem.

$Q_{wb}$ = quantity of contaminated water inhaled by the person while in the shower or sauna, in L/y. Values are given in Table A16.

$C_w$ = concentration of a nuclide in the contaminated water, in pCi/L.

$D_{inh}$ = inhalation dose factor for a nuclide, in mrem per pCi inhaled. Values are given in Table A25.

$T_{inh}$ = inhalation exposure time of the individual, 1 y.

The external and inhalation dose due to exposure to contaminated soil are accumulated over the course of a year for all exposure scenarios except the waste intruder (driller). The amount accumulated per day depends on the soil concentration on that day. The external dose rate and the inhalation dose rate are proportional to the soil concentration. The total accumulated over the year is proportional to the time integral of the soil concentration. The external dose and inhalation doses are shown in equation (43). To obtain the total dose from the parent nuclide it is necessary to include the contributions from each progeny nuclide. Hence the sum over nuclides in a decay chain is shown. Note that radioactive decay is not considered for the well drilling scenario because the exposure time is so brief (5 days) compared to the half lives of the nuclides selected for analysis.

$$\begin{aligned} H_{xs} &= \sum_{i=1}^{n} \int_0^{1y} \rho\, d\, C_{si}\, D_{ext,i}\, dT \\ H_{bs} &= \sum_{i=1}^{n} \int_0^{1y} M_{sb}\, C_{si}\, D_{inh,i}\, dT \end{aligned} \tag{43}$$

Where

$C_{si}$ = time-dependent soil concentration of the ith nuclide during the year, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil.

d = thickness of the surface layer of soil from which nuclides migrate downward, 15 cm (5.9 inches).

$D_{ext,i}$ = external dose rate factor for exposure to radiation from nuclide "I" in contaminated soil, in mrem/h per Ci/m$^2$. Values are given in Table A28.

$D_{inh,i}$ = inhalation dose factor for nuclide "I", in mrem per pCi inhaled. Values are given in Table A25.

$H_{xs}$ = external dose accumulated during the year from one radionuclide and its progeny due to radioactivity in the soil, mrem

$H_{bs}$ = inhalation dose accumulated during the year from one radionuclide and its progeny due to radioactivity in the soil, mrem

I = index over the decay chain. I=1 refers to the first member, or parent nuclide; I=2 refers to the second member of the decay chain; I=3 refers to the third member; I=4 refers to the fourth member.

$M_{sb}$ = mass of soil inhaled annually by the individual, in mg/y. Values are discussed in Section A3.2.1. The intake occurs at a relatively constant rate during the year.

$\rho$ = bulk density of the surface soil, in grams per cubic centimeter. The value normally used in Hanford Site PA work is 1.5 g/cc.

The only term in the integrals with any time dependence is the soil concentration. Thus the accumulated dose at time T is the time integral of the activity equations. These integrations are simply the integral of each exponential. Each of the exponential terms in the decay Equations (2) and (6) are replaced with the time integral shown in Equation (44). Note that the integral of the DS term in Equation (16) is the same as the DI term in Equation (25).

$$\text{Time Integral} = \int_0^T \text{Exp}(-\lambda t)\,dt = \frac{1}{\lambda}[1 - \text{Exp}(-\lambda T)] \qquad (44)$$

If the product $\lambda T$ is less than 0.0002, there is a loss of numeric accuracy when calculating the time integral in Equation (44). To overcome this, the integration result in Equation (44) is replaced with the equivalent polynomial to improve the numeric precision of the calculation. The polynomial used is shown in Equation (45).

$$\frac{1}{\lambda}[1 - \text{Exp}(-\lambda T)] \cong T\left[1 - \frac{\lambda T}{2} + \frac{(\lambda T)^2}{6} - \frac{(\lambda T)^3}{24}\right] \qquad (45)$$

Notice that if the product $\lambda T$ is very small, the time integral approaches the decay period, T. For this reason, the time integral of the decay equation will be referred to as an effective time period. In effect, it is a particular time interval (T) adjusted for radioactive decay. To consistently work with unitless decay periods, all time integrals are divided by the integration period. Thus the integration period must be made a factor in the calculation. A thorough discussion of small time approximations in radioactive decay calculations is found in WHC-SA-1282-FP.

For the irrigated farm scenario, the concentration of nuclides in the soil increases with time due to the irrigation of the soil as shown in Section B2.3. The soil concentration follows the time

integral formula of Equations (44) and (45). The accumulated intake or dose at time T is the time integral of these equations. In other words, each exponential term in the decay equation, is replaced with its second integral, shown in Equation (46).

$$\text{Second Integral} = \int_0^T \frac{1}{\lambda}\left[1 - \text{Exp}(-\lambda t)\right] dt = \frac{1}{\lambda^2}\left[\lambda T - 1 + \text{Exp}(-\lambda T)\right] \quad (46)$$

If the product $\lambda T$ is less than 0.001, there is a loss of numeric accuracy when calculating the time integral in Equation (46). To overcome this, the integration result in Equation (46) is replaced with the equivalent polynomial to improve the numeric precision of the calculation. The polynomial used is shown in Equation (47).

$$\frac{1}{\lambda^2}\left[\lambda T - 1 + \text{Exp}(-\lambda T)\right] \cong \frac{T^2}{2}\left[1 - \frac{\lambda T}{3} + \frac{(\lambda T)^2}{12} - \frac{(\lambda T)^3}{60}\right] \quad (47)$$

Notice that if the product $\lambda T$ is very small, the time integral in Equations (46) and (47) approaches the decay period squared. Again, to only work with unitless decay factors, the second integral is divided by the integration period squared. This time must then be made a factor in the dose equation.

Using the two-part irrigation model, the dose accumulated during the first 6 months depends only on the DS or DI integration. The dose during the second 6 months (without irrigation) depends only on the DR integration. This was described in Section B2.2.4 for an initial soil concentration, and B2.3.4 for irrigation deposition.

## B4.0 INGESTION DOSE

Human ingestion dose comes from the pathways discussed earlier, such as contaminated drinking water, trace intakes of soil, vegetables grown on contaminated soil, and animal products. Each of these is discussed below. The basic dose calculation is the product of three factors, (1) the quantity consumed, (2) the radionuclide concentration in what is consumed, and (3) the ingestion dose factor. The addition of radioactive decay and progeny in-growth is discussed with each pathway.

### B4.1 SOIL AND WATER INGESTION

The ingestion dose from drinking water is shown in Equation (48). The drinking water has no progeny. The concentration of each nuclide in a chain is treated separately.

$$H_{ew} = Q_{we} C_w D_{ing} T_{ing} \tag{48}$$

where

$C_w$ = concentration of a nuclide in the contaminated water, in pCi/L.

$D_{ing}$ = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table A24.

$H_{ew}$ = ingestion dose from drinking water, in mrem.

$Q_{we}$ = quantity of contaminated drinking water ingested by the person, in L/y. See Table A5 for values.

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

The ingestion dose from the intake of trace amounts of soil is shown in Equation (49). The soil concentration does include leaching, decay and progeny in-growth. Because the soil is consumed in small amounts during the year, the total dose is represented as the time integral of the daily intake. As before, the time integral must accommodate the change in infiltration rates during the year, just as was done for the inhalation and external doses.

$$H_{es} = \sum_{i=1}^{n} \int_{0}^{1y} M_{se} C_{si} D_{ing,i} \, dT \tag{49}$$

where

$C_{si}$ = time-dependent soil concentration of the ith nuclide during the year, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil.

$D_{ing,i}$ = ingestion dose factor for nuclide "I", in mrem per pCi ingested. Values are given in Table A24.

$H_{es}$ = ingestion dose accumulated during the year from one radionuclide and its progeny due to radioactivity in the soil, mrem

I = index over the decay chain. I=1 refers to the first member, or parent nuclide; I=2 refers to the second member of the decay chain; I=3 refers to the third member; I=4 refers to the fourth member.

$M_{se}$ = mass of soil ingested annually by the individual, in mg/y. The intake occurs at a relatively constant rate during the year.

## B4.2 GARDEN PRODUCE

The ingestion dose from garden produce grown in contaminated soil is the product of the quantity of vegetables eaten, the concentration of radioactivity in the vegetables, and the ingestion dose factor. The ingestion dose factors from Federal Guidance Report Number 11 are given in Table A24. Quantities eaten are given in Table A5. The calculation of radionuclide concentrations in living plants uses three main routes, (1) root uptake, (2) resuspension to leaves (also called "rain splash"), and (3) direct deposition of irrigation water on foliage. Each of these will be considered separately below. The three uptake routes are then combined to obtain the total ingestion dose from the garden produce.

The equations presented below apply to both garden produce and cattle feed in the sense that the quantity eaten and the ingestion dose factor can be removed to give the nuclide concentration in the cattle feed. These concentrations are needed to calculate dose from ingestion of contaminated animal products.

The garden produce intakes are based on the two situations. The first applies to leafy vegetables. It is assumed that leafy vegetables are produced more-or-less continuously during the growing season. They are consumed shortly after being collected. Thus the continuous model uses a time integral to represent the accumulated dose from leafy vegetables during the growing season. It is further assumed that leafy vegetables are not raised after the growing season has ended. Any leafy vegetables consumed after the growing seasons ends are assumed to have been imported from uncontaminated areas. The 25% of a person's diet that comes from contaminated sources is then assumed to be 50% during the irrigation period and 0% during the remainder of the year.

The second garden produce model applies to the other types of garden produce. These foods are assumed to be grown and harvested twice during the growing season. The plant concentration depends on the soil concentration at the time of harvest. Hence the initial soil contamination is harvested earlier than the irrigation deposition case. For an initial soil contamination (e.g., post-intrusion garden or prior irrigation) this time is taken to be midway through the irrigation season. For the irrigation scenarios harvest is assumed to occur at the end of the irrigation season.

Because these foods may be stored and eaten over a period of time, radioactive decay during the storage and consumption periods needs to be taken into account. The amount of radioactive contamination eaten during the consumption period is the time integral of the ordinary decay Equations (1), (2), and (3) because there is no leaching. This leads to a factor of $IDR(T_{veg})$, where $T_{veg}$ is the consumption period. The average consumption period for non-leafy vegetables is taken to be 90 days. Some products do not keep well, and have shorter

consumption periods. Others keep very well and have longer consumption periods. The value selected for the tank waste PA (90 days) simplifies the calculations in that all non-leafy vegetables have the same period. Note that for long half life nuclides the actual value has no effect on the final doses.

Root Uptake:

Root uptake is calculated using concentration ratios. These ratios are listed in Table A40. The ingestion dose from garden produce due to root uptake into the various types of vegetation is described with Equation (50). The first equation shows the continuous model for leafy vegetables. Note that the integral is over half the year so the assumed annual intake from garden must be adjusted upward to compensate. Hence the ratio (1 y)/($T_{irr}$). The second equation shows the harvest model for the other vegetables. In both equations the sum over radionuclides in a decay chain is needed to obtain the total dose from the parent nuclide.

$$H_{epr}(\text{leafy}) = \sum_{i=1}^{n} \frac{1\,y}{T_{irr}} \int_{0}^{T_{irr}} R_p\, B_{pi}\, Q_{vp}\, C_{si}\, D_{ing,i}\, dT$$

$$H_{epr}(\text{other}) = \sum_{i=1}^{n} R_p\, B_{pi}\, Q_{vp}\, C_{si}\, IDR_i(T_{veg})\, D_{ing,i}\, T_{ing} \qquad (50)$$

Where

$B_{pi}$ = soil to plant concentration ratio, as Ci/kg dry weight of vegetables to Ci/kg of soil. See Table A40 for values.

$C_{si}$ = soil concentration of the ith nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season. In the second equation it is the soil concentration at the time of harvest.

$D_{ing,i}$ = ingestion dose factor for nuclide "I", in mrem per pCi ingested. Values are given in Table A24.

$H_{epr}$ = ingestion dose from plant type p due to root uptake, in mrem.

$IDR_i$ = decay factor that accounts for radioactive decay of the ith nuclide during the consumption of garden produce

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

$Q_{vp}$ = quantity of plant type p eaten by the person, in kg/y. See Table A5 for values.

$R_p$ = dry to wet ratio for plant type p. See Table A39 for values.

$T_{irr}$ = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site.

$T_{veg}$ = consumption period for all garden produce, 90 days

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

Rain Splash:

The resuspension of dust by wind, or water drops splashing soil onto the foliage leads to some contamination of the edible portion of the plant. The ingestion dose from this source of contamination is calculated using Equation (51). The first equation shows the continuous model for leafy vegetables. Note that the integral is over half the year so the assumed annual intake from garden must be adjusted upward to compensate. Hence the ratio (1 y)/($T_{irr}$). The second equation shows the harvest model for the other vegetables. Note that the sum is over radionuclides in a decay chain to obtain the total dose from the parent nuclide.

$$H_{epf}\,(\text{leafy}) = \sum_{i=1}^{n} \frac{1\,y}{T_{irr}} \int_{0}^{T_{irr}} J_d \frac{F_{fp}\,F_{tp}\,T_w}{Y_p} Q_{vp}\,C_{si}\,D_{ing,i}\,dT$$

$$H_{epf}\,(\text{others}) = \sum_{i=1}^{n} R^a\,V_d \frac{F_{fp}\,F_{tp}\,T_w}{Y_p} Q_{vp}\,C_{si}\,IDR_i\left(T_{veg}\right) D_{ing,i}\,T_{ing} \qquad (51)$$

where

$C_{si}$ = time-dependent soil concentration of the ith nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season. In the second equation it is the soil concentration at the time of harvest.

$D_{ing,I}$ = ingestion dose factor for nuclide "I", in mrem per pCi ingested. Values are given in Table A24.

$F_{fp}$ = interception fraction for plant type p. The fraction of what falls to the earth that lands on the plant. Computed as shown in Section A5.2. Values are listed in Table A42.

$F_{tp}$ = translocation factor, i.e., the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table A42.

$H_{epf}$ = ingestion dose from plant type p due to resuspension of contaminated soil onto plant surfaces (rain splash), in mrem.

$IDR_i$ = decay factor that accounts for radioactive decay of the ith nuclide during the consumption of garden produce

$J_d$ = average soil deposition rate on plant surfaces due to rain splash, $2.7 \times 10^{-4}$ kg/m$^2$ per day. See Section A5.2 for further discussion.

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

$Q_{vp}$ = quantity of plant type p eaten by the person during the year, in kg/y. See Table A5 for values.

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

$T_{irr}$ = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site.

$T_{veg}$ = consumption period for garden produce, assumed to be 90 days

$T_w$ = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table B1.

$Y_p$ = harvest yield of crop type p, in kg/m$^2$ (wet weight). Also called the standing biomass. Values are listed in Table A42.

One effect of wind, rain, and irrigation is to remove deposited contamination from plant surfaces. This effect is included using a weathering term shown in Equation (52). Values for the effective growing period are only slightly affected by the radioactive half life of the isotope for the long half lives shown in Table A1. Therefore, the decay effeets were not considered ($\lambda_r$=0). Values for $T_w$ are given in Table B1 for the growing periods shown in Table A42.

$$T_w = \frac{1}{(\lambda_w + \lambda_r)}\left\{1 - \mathrm{Exp}\left[-(\lambda_w + \lambda_r)T_p^f\right]\right\} \tag{52}$$

Where

$T_p^f$ = exposure time of the plant type p to the airborne contamination depositing on the foliage, in days (also called growing period). Values are shown in Table A42.

$T_w$ = effective exposure period for foliar deposition, in days. Values are shown in Table B1.

$\lambda_w$ = weathering removal coefficient, 0.0495105 per day, or 18.0713 per year, which corresponds to a 14 day half time.

$\lambda_r$ = radioactive decay constant, namely, the natural logarithm of 2 divided by the radioactive decay half life in days. Values are listed in Table A1.

**Table B1. Effective Exposure Times for Foliar Deposition**

| Growing Period | $T_w$ |
|---|---|
| 30 days | 15.6 days |
| 45 days | 18.0 days |
| 90 days | 20.0 days |

The effective exposure times are computed assuming radioactive decay is negligible for the nuclides of Table A1.

Direct Deposition:

Direct deposition of the contaminants in irrigation water onto the foliage occurs only during the irrigation season. The ingestion dose due to radioactivity in the edible portion of the plants due to direct deposition on foliage is given in equation (53).

$$\begin{aligned} H_{epd}(\text{leafy}) &= ID_p \frac{F_{dp}\, F_{tp}\, T_w}{Y_p} Q_{vp}\, D_{ing}\, T_{ing} \\ H_{epd}(\text{other}) &= \sum_{i=1}^{n} ID_p \frac{F_{dp}\, F_{tp}\, T_w}{Y_p} Q_{vp}\, IDR_i(T_{veg})\, D_{ing,i}\, T_{ing} \end{aligned} \tag{53}$$

Where

$D_{ing,i}$ = ingestion dose factor for the ith nuclide, in mrem per pCi ingested. Values are given in Table A24.

$F_{dp}$ = interception fraction for contaminants in irrigation water. The fraction of what falls to the earth that lands on the plant. Computed as shown in Section A5.3. Values are listed in Table A42.

$F_{tp}$ = translocation factor, i.e., the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table A42.

$H_{epd}$ = ingestion dose from plant type p due to deposition of a nuclide in contaminated irrigation water onto plant surfaces, in mrem.

$ID_p$ = instantaneous activity deposition rate due to irrigation of soils growing plant type p, in Ci/yr/m$^2$. Only the parent nuclide is present. Any progeny nuclides are assumed to be absent.

$IDR_i$ = decay factor that accounts for radioactive decay during the consumption of garden produce

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

$Q_{vp}$ = quantity of plant type p eaten by the person during the year, in kg/y. See Table A5 for values.

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

$T_{veg}$ = consumption period for garden produce, assumed to be 90 days

$T_w$ = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table B1.

$Y_p$ = harvest yield of crop type p, in kg/m$^2$ (wet weight). Also called the standing biomass. Values are listed in Table A42.

The ingestion dose from garden produce due to direct deposition depends on the rate at which water is applied. In the previous two pathways, root uptake and rain splash, the determining factor is the total amount of water (and thus activity) applied to the soil. A summary of the essential calculation and the decay corrections is presented in Table B2.

**Table B2. Summary of Ingestion Dose from Garden Produce**

| | |
|---|---|
| **Essential Dose Calculation for an Initial Soil Contamination** | |
| Root Uptake: | $R_p B_p C_s Q_{vp} D_{ing} T_{ing}$ |
| Rain Splash: | $J_d F_{fp} (F_{tp} T_w / Y_p) C_s Q_{vp} D_{ing} T_{ing}$ |
| Correction for Radioactive Decay and Progeny In-growth | |
| Leafy Vegetables: | $IDS(T_{irr})$ |
| Other Vegetables, Fruit, and Grain: | $DS(T_h) \cong IDR(T_{veg})$ |
| **Essential Dose Calculation for Irrigation with Contaminated Water** | |
| Root Uptake: | $R_p B_p C_s Q_{vp} D_{ing} T_{ing}$ |
| Rain Splash: | $J_d F_{fp} (F_{tp} T_w / Y_p) C_s Q_{vp} D_{ing} T_{ing}$ |
| Direct Deposition: | $ID_p F_{dp} (F_{tp} T_w / Y_p) Q_{vp} D_{ing} T_{ing}$ |
| Correction for Radioactive Decay and Progeny In-growth | |
| Leafy Vegetables: | Root Uptake & Splash: $IDI(T_{irr})$<br>Direct Deposition: no decay |
| Other Vegetables, Fruit, and Grain: | Root Uptake & Splash: $DI(T_{irr}) \cong IDR(T_{veg})$<br>Direct Deposition: $IDR(T_{veg})$ |

Notes: Leafy vegetables are consumed continuously during growing season ($T_{irr}$) only. Other produce is harvested and consumed over a period of time ($T_{veg}$). The decay factors are unitless fractions. Progeny in-growth is computed using the method shown in Section B2.

Explanation of Symbols Used in Table B2.

$B_p$ = soil to plant concentration ratio, as Ci/kg dry weight of vegetables to Ci/kg of soil. See Table A40 for values.

$C_s$ = soil concentration of a nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season.

$D_{ing}$ = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table A24.

$F_{dp}$ = interception fraction for contaminants in irrigation water. The fraction of what falls to the earth that lands on the plant. Computed as shown in Section A5.3. Values are listed in Table A42.

$F_{fp}$ = interception fraction for plant type p. The fraction of what falls to the earth that lands on the plant. Computed as shown in Section A5.2. Values are listed in Table A42.

$F_{tp}$ = translocation factor, i.e., the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table A42.

$ID_p$ = instantaneous activity deposition rate due to irrigation of soils growing plant type p, in Ci/yr/m$^2$.

$J_d$ = average soil deposition rate on plant surfaces due to rain splash, $2.7 \times 10^{-4}$ kg/m$^2$ per day. See Section A5.2 for further discussion.

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

$Q_{vp}$ = quantity of plant type p eaten by the person during the year, in kg/y. See Table A5 for values.

$R_p$ = dry to wet ratio for plant type p. See Table A42 for values.

$T_h$ = time at which harvest occurs. For initial soil contaminations, harvest is assumed to occur halfway through the growing season, $T_h=T_{irr}/2$. For irrigation with contaminated water, the harvest occurs at the end of the irrigation season to maximize the soil contamination.

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

$T_{irr}$ = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site.

$T_{veg}$ = consumption period for garden produce, assumed to be 90 days

$T_w$ = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table B1.

$Y_p$ = harvest yield of crop type p, in kg/m$^2$ (wet weight). Also called the standing biomass. Values are listed in Table A42.

The equilibrium model used for tritium in the post-intrusion residential garden is summarized in Section 3.2. The radioactive decay and leaching terms are shown in Table B2. Tritium in irrigation water leads to an equilibrium situation in which the concentration of tritium in the water is reproduced throughout the plant. Since the equilibrium is established rather quickly, the decay corrections are simpler than for other nuclides. The calculation of dose from tritium in irrigation water is shown in Equation (54) below.

$$\begin{aligned} H_{epH}(\text{leafy}) &= \frac{I\,C_{w,H3}}{I+P}\left(8.94\,F_{Hp}\right)Q_{vp}\,D_{ing,H3}\,T_{ing} \\ H_{epH}(\text{other}) &= \frac{I\,C_{w,H3}}{I+P}\left(8.94\,F_{Hp}\right)Q_{vp}\,IDR\left(T_{veg}\right)\,D_{ing,H3}\,T_{ing} \end{aligned} \qquad (54)$$

Where

$H_{epH}$ = ingestion dose from plant type p due to tritium (H-3) in the irrigation water, in

mrem.

p = type of plant. There are 4 types of garden produce. The first equation covers leafy vegetables (p=1). The second equation covers other vegetables, fruit, and grain (p=2,3,4).

I = total irrigation water applied to the soil during the irrigation season, 82.3 cm/y (63.5 cm/y for populations).

$C_{w,H3}$ = concentration of tritium in the irrigation water, in pCi/L.

P = total natural precipitation water applied to the soil during the irrigation period, 5.77 cm/y (PNNL-15160).

$F_{Hp}$ = fraction of hydrogen in plant type p. Values are listed in Table A37. The factor of 8.94 converts the hydrogen fraction to an effective water fraction that includes organically bound hydrogen.

$Q_{vp}$ = quantity of plant type p eaten by the person during the year, in kg/y. See Table A5 for values.

IDR = decay factor that accounts for radioactive decay during the consumption of garden produce

$T_{veg}$ = consumption period for garden produce, assumed to be 90 days

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

$D_{ing,H3}$ = ingestion dose factor for tritium, in mrem per pCi ingested. Value is given in Table A24.

## B4.3 ANIMAL PRODUCTS EATEN

The simplest animal product to evaluate is fish. The dose from fish consumption is shown in Equation (55). It is the product of the quantity of fish consumed during the year, the concentration in the fish, and the ingestion dose factor. The fish harvested is consumed over the next few days, so there is no need to correct for radioactive decay and progeny in-growth.

$$H_{ef} = Q_{fe}\, C_w\, B_f\, D_{ing}\, T_{ing} \qquad (55)$$

where

$B_f$ = bioaccumulation factor in fish from Table A36, in L/kg. It is the ratio of the contamination in the edible parts of the fish to the concentration in the water.

$C_w$ = concentration of a nuclide in the contaminated water, in pCi/L.

$D_{ing}$ = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table A24.

$H_{ef}$ = ingestion dose from contaminated fish, in mrem.

$Q_{fe}$ = quantity of contaminated fish consumed by the person during the year, in kg/y. See Table A5 for values.

$T_{ing}$ = ingestion exposure time of the individual, 1 y

The ingestion dose from foods obtained from land animals is computed using equilibrium transfer factors shown in Table A36. These relate the total radioactive material ingested by the animal each day to the concentration in the animal product consumed by a person. The total diet of the animal must be taken into account. The animal may drink contaminated water, ingest contaminated soil, graze on contaminated grass and be fed stored material that is also contaminated. Each of these will be presented in turn. The total ingestion dose from animal products is the sum of these.

Just as with garden produce there is a continuous production model for milk, and a harvest model in which the animal is slaughtered for later consumption. The beef cattle model illustrates the latter, while the milk cow illustrates the former. The chicken (meat) and egg are treated as continuous because these are produced at regular intervals during the year and then consumed shortly thereafter.

The ingestion dose that results from contaminated water consumed by the animal is shown in Equation (56). Because the progeny nuclides are not allowed to form in the water supply, the dose from each nuclide in a chain will be calculated separately. When the beef cattle is slaughtered (i.e., harvested), there is a large quantity of beef available. This food is then consumed over a period of time during which radioactive decay and progeny in-growth occurs. The quantity of contaminated beef consumed during the year is from Table A5. These values have already been adjusted for the fraction of the year that contaminated beef is consumed. Hence, the factor ($T_{ing}/T_{beef}$) is included.

$$H_{eqr}(\text{beef}) = \sum_{i=1}^{n} \frac{T_{veg}}{T_{beef}} \int_{0}^{T_{beef}} Q_{wq}\, C_w\, F_{qi}\, Q_{aq}\, D_{ing,i}\, DR_i\, dT \qquad (56)$$

$$H_{eqr}(\text{other}) = Q_{wq}\, C_w\, F_q\, Q_{aq}\, D_{ing}\, T_{ing}$$

where

$C_w$ = concentration of the parent nuclide in a decay chain in the contaminated water, in pCi/L. The progeny nuclide concentrations are assumed to be zero in the water.

$D_{ing,i}$ = ingestion dose factor for the ith nuclide in a decay chain, in mrem per pCi ingested. Values are given in Table A24. $D_{ing}$ is the ingestion dose factor of the first nuclide in the chain.

$F_{qi}$ = equilibrium transfer factor for animal product q for the ith nuclide in a decay chain, in d/kg (or d/L for milk). Values are given in Table A36. $F_q$ is the transfer factor of the first nuclide.

$H_{eqw}$ = ingestion dose from animal product q due to contaminated drinking water, in mrem.

q = index for animal products. There are 4 types of animal products, beef, milk, poultry, and eggs.

$Q_{wq}$ = quantity of contaminated drinking water ingested by the animal associated with animal product q each day, in L/d. See Table A35 for values.

$Q_{aq}$ = quantity of animal product q consumed by the person during the year, in kg/y (or L/y for milk). See Table A5 for values.

$T_{beef}$ = consumption period for beef cattle, assumed to be 120 days

$T_{ing}$ = ingestion exposure time of the individual, 1 y

The other contributors to the overall contamination of an animal product are summarized in Table B3. For the case of an initial soil contamination, the two components are vegetable foods consumed by the animal and the soil ingestion shown in Table A35. The animal foods are contaminated by root uptake and rain splash. There are three main kinds of food: fresh fodder (grass), stored hay (grass that is harvested and stored), and stored feed (grain that is harvested and stored). For the case of irrigation with contaminated water, additional components are direct deposition on the animal foods, and direct ingestion of the irrigation water.

**Table B3. Summary of Ingestion Dose from Animal Products**

| **Essential Dose Calculation for an Initial Soil Contamination.**<br>The activity intake rates are computed using the formulas below.<br>These are converted to annual dose equivalent by means of the factor,<br>$F_q Q_{aq} D_{ing} T_{ing}$. | |
|---|---|
| Trace Soil Ingestion: | $C_s Q_{sq}$ |
| Fodder -- Root Uptake: | $R_p B_p C_s Q_{pq}$ |
| Fodder -- Rain Splash: | $J_d F_{fp} (F_{tp} T_w / Y_p) C_s Q_{pq}$ |
| Correction for Radioactive Decay and Progeny In-growth -- Beef | |
| Soil Ingestion and Fresh Grass: | $DS(T_h) \cong IDR(T_{beef})$ |
| Stored Hay (grass) and Stored Grain: | $DS(T_h) \cong DR(T_s) \cong IDR(T_{beef})$ |
| Correction for Radioactive Decay and Progeny In-growth -- Milk, Poultry, Eggs | |
| Soil Ingestion and Fresh Grass: | $[T_{irr} \cong IDS(T_{irr}) + T_{no} \cong DS(T_{irr}) \cong IDR(T_{no})]/T_{ing}$ |
| Stored Hay (grass) and Stored Grain: | $DS(T_h) \cong DR(T_s) \cong IDR(T_{an})$ |

| **Essential Dose Calculation for Irrigation with Contaminated Water.**<br>The activity intake rates are computed using the formulas below.<br>These are converted to annual dose equivalent by means of the factor,<br>$F_q Q_{aq} D_{ing} T_{ing}$. | |
|---|---|
| Trace Soil Ingestion: | $C_s Q_{sq}$ |
| Fodder -- Root Uptake: | $R_p B_p C_s Q_{pq}$ |
| Fodder -- Rain Splash: | $R^a V_d F_{fp} (F_{tp} T_w / Y_p) C_s Q_{pq}$ |
| Fodder -- Direct Deposition: | $ID_p F_{dp} (F_{tp} T_w / Y_p) Q_{pq}$ |
| Drinking Water Ingestion: | $C_w Q_{wq}$ |
| Correction for Radioactive Decay and Progeny In-growth -- Beef | |
| Trace Soil Ingestion: | $DI(T_{irr}) \cong IDR(T_{beef})$ |
| Fresh Grass: | Root & Splash: $DI(T_{irr}) \cong IDR(T_{beef})$<br>Direct Deposition: $IDR(T_{beef})$ |
| Stored Hay and Grain: | Root & Splash: $DI(T_{irr}) \cong DR(T_s) \cong IDR(T_{beef})$<br>Direct Deposition: $DR(T_s) \cong IDR(T_{beef})$ |
| Drinking Water: | $IDR(T_{beef})$ |
| Correction for Radioactive Decay and Progeny In-growth -- Milk, Poultry, Eggs | |
| Trace Soil Ingestion: | $[T_{irr} \cong IDI(T_{irr}) + T_{no} \cong DI(T_{irr}) \cong IDR(T_{no})]/T_{ing}$ |
| Fresh Grass: | Root Uptake & Rain Splash:<br>$[T_{irr} \cong IDI(T_{irr}) + T_{no} \cong DI(T_{irr}) \cong IDR(T_{no})]/T_{ing}$<br>Direct Deposition: no decay |
| Stored Hay and Grain: | Root & Splash: $DI(T_{irr}) \cong DR(T_s) \cong IDR(T_{an})$<br>Direct Deposition: $DR(T_s) \cong IDR(T_{an})$ |
| Drinking Water: | no decay |

Notes: Beef is harvested and consumed over a period of time. Milk, poultry, and eggs are consumed continuously during the year. The decay factors are unitless fractions shown in Equation (50). Progeny in-growth is computed using the method shown in Section B2.

Explanation of Symbols Used in Table B3.

$B_p$ = soil to plant concentration ratio, as Ci/kg dry weight of vegetables to Ci/kg of soil. See Table A40 for values.

$C_s$ = soil concentration of a nuclide, in Ci/kg. It is affected by radioactive decay and leaching from the surface layer of soil during the irrigation season.

$C_w$ = concentration of a nuclide in the contaminated water, in pCi/L. Any progeny nuclide concentrations are assumed to be zero.

$D_{ing}$ = ingestion dose factor for a nuclide, in mrem per pCi ingested. Values are given in Table A24.

$F_q$ = equilibrium transfer factor for animal product q for a nuclide, in d/kg (or d/L for milk). Values are given in Table A36.

$F_{dp}$ = interception fraction for contaminants in irrigation water. The fraction of what falls to the earth that lands on the plant. Computed as shown in Section A5.3. Values are listed in Table A42.

$F_{fp}$ = interception fraction for plant type p. The fraction of what falls to the earth that lands on the plant. Computed as shown in Section A5.2. Values are listed in Table A42.

$F_{tp}$ = translocation factor, i.e., the fraction of what deposits on the foliage that ends up in the edible portions of the plant. Values are listed in Table A42.

$ID_p$ = instantaneous activity deposition rate due to irrigation of soils growing plant type p, in Ci/yr/m$^2$.

$J_d$ = average soil deposition rate on plant surfaces due to rain splash, $2.7 \times 10^{-4}$ kg/m$^2$ per day. See Section A5.2 for further discussion.

p = index for animal fodder. There are 3 types of animal fodder, fresh grass, stored hay, and stored grain.

q = index for animal products. There are 4 types of animal products, beef, milk, poultry, and eggs.

$Q_{aq}$ = quantity of animal product q eaten by the person during the year, in kg/y (or L/y for milk). See Table A5 for values.

$Q_{pq}$ = quantity of fodder type p eaten by the animal during the year, in kg/y. See Table A35 for values.

$Q_{sq}$ = quantity of contaminated soil ingested by the animal associated with animal product q each day, in kg/d. See Table A35 for values.

$Q_{wq}$ = quantity of contaminated drinking water ingested by the animal associated with animal product q each day, in L/d. See Table A35 for values.

$R_p$ = dry to wet ratio for plant type p. See Table A42 for values.

$T_{an}$ = time period over which stored hay and grain are consumed by the milk cow and chickens. Assumed to be the same as $T_{veg}$, 90 d.

$T_{beef}$ = consumption period for beef cattle, assumed to be 120 days.

$T_h$ = time at which harvest occurs. For initial soil contaminations, harvest is assumed to occur halfway through the growing season, $T_h = T_{irr}/2$. For irrigation with contaminated water, the harvest occurs at the end of the irrigation season to maximize the soil contamination.

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

$T_{irr}$ = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site. $T_{no} = 1y - T_{irr}$

$T_s$ = storage time for the stored feed (hay and grain), 90 d.

$T_w$ = effective exposure period for foliar deposition, in days. The values are computed using a foliage weathering time of 14 days. Values are shown in Table B1.

$Y_p$ = harvest yield of crop type p, in kg/m$^2$ (wet weight). Also called the standing biomass. Values are listed in Table A42.

The one special case nuclide is tritium in contaminated irrigation water. Tritium present in an initial soil contamination is handled using the same method as any other nuclide. The equilibrium transfer factors shown in Table A36 are used. Tritium in irrigation water leads to an equilibrium situation in which the concentration of tritium in the water is reproduced throughout the animal product. Since the equilibrium is established rather quickly, the decay corrections are simpler than for other nuclides. The calculation of dose from tritium in irrigation water is shown in Table B4 below. Note that the tritium model assumes that loss of tritium by evaporation of water from soil or plants is not important.

**Table B4. Ingestion Dose from Animal Products from Tritium**

| **Essential Dose Calculation for Irrigation with Contaminated Water.**<br>The activity intake rates are computed using the formulas below.<br>These are converted to annual dose equivalent by means of the factor,<br>$C_{w,H3}\, F_q\, Q_{aq}\, D_{ing,H3}\, T_{ing}$. | |
|---|---|
| Trace Soil Ingestion: | $8.94\, F_{Hs}\, I/(I+P)\, Q_{sq}$ |
| Fodder -- Root Uptake: | $8.94\, F_{Hp}\, I/(I+P)\, Q_{pq}$ |
| Drinking Water Ingestion: | $Q_{wq}$ |
| Correction for Radioactive Decay and Progeny In-growth -- Beef | |
| Trace Soil Ingestion: | $IDR(T_{beef})$ |
| Fresh Grass: | $IDR(T_{beef})$ |
| Stored Hay and Grain: | $DR(T_s) \cong IDR(T_{beef})$ |
| Drinking Water: | $IDR(T_{beef})$ |
| Correction for Radioactive Decay and Progeny In-growth -- Milk, Poultry, Eggs | |
| Trace Soil Ingestion: | $[T_{irr} + T_{no} \cong IDR(T_{no})]/T_{ing}$ |
| Fresh Grass: | $[T_{irr} + T_{no} \cong IDR(T_{no})]/T_{ing}$ |
| Stored Hay and Grain: | $DR(T_s) \cong IDR(T_{an})$ |
| Drinking Water: | no decay |

Notes: Beef is harvested and consumed over a period of time. Milk, poultry, and eggs are consumed continuously during the year. The decay factors are unitless fractions shown in Equation (50). Progeny in-growth is computed using the method shown in Section B2.

Explanation of Symbols Used in Table B4.

$C_{w,H3}$ = concentration of tritium (H-3) in the irrigation water, in pCi/L.

$D_{ing,H3}$ = ingestion dose factor for tritium, in mrem per pCi ingested. Value is given in Table A24.

$F_q$ = equilibrium transfer factor for animal product q for tritium, in d/kg (or d/L for milk). Value is given in Table A36.

$F_{Hs}$ = fraction of hydrogen in garden soil. The value used is listed in Table A37. The factor of 8.94 converts the hydrogen fraction to an effective water fraction that includes organically bound hydrogen.

$F_{Hp}$ = fraction of hydrogen in plant type p. Values are listed in Table A37. The factor of 8.94 converts the hydrogen fraction to an effective water fraction that includes organically bound hydrogen.

I = total irrigation water applied to the soil during the irrigation season, 82.3 cm/y (63.5 for populations).

p = index for animal fodder. There are 3 types of animal fodder, fresh grass, stored hay, and stored grain.

P = total natural precipitation water reaching the surface soil during the irrigation period, 5.77 cm/y (PNNL-15160).

q = index for animal products. There are 4 types of animal products, beef, milk, poultry, and eggs.

$Q_{aq}$ = quantity of animal product q eaten by the person during the year, in kg/y (or L/y for milk). See Table A5 for values.

$Q_{pq}$ = quantity of fodder type p eaten by the animal during the year, in kg/y. See Table A35 for values.

$Q_{sq}$ = quantity of contaminated soil ingested by the animal associated with animal product q each day, in kg/d. See Table A35 for values.

$Q_{wq}$ = quantity of contaminated drinking water ingested by the animal associated with animal product q each day, in L/d. See Table A35 for values.

$T_{an}$ = time period over which stored hay and grain are consumed by the milk cow and chickens. Assumed to be the same as $T_{veg}$, 90 d.

$T_{beef}$ = consumption period for beef cattle, assumed to be 120 days.

$T_{ing}$ = ingestion exposure time of the individual, 1 y.

$T_{irr}$ = irrigation period in years. The value of 0.5 yr is assumed based on current practices near the Hanford Site. $T_{no} = 1y - T_{irr}$

$T_s$ = storage time for the stored feed (hay and grain), 90 d.

## B5.0 REFERENCES

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# ATTACHMENT B1. HAND CALCULATIONS FOR TRITIUM

## BA.1 NO WATER INFILTRATION EXPOSURE SCENARIOS

Each of the exposure scenarios listed in Table 2 (of the main text) will be evaluated. Absorption of airborne tritium through the skin is included in the inhalation dose factor for tritium. The doses calculated are the total accumulated during the first year of exposure.

Normally, three significant digits are kept during calculations. Because the spreadsheet software keeps several digits, agreement with the spreadsheet can only be obtained if 4 or 5 significant digits are retained. This is particularly true in the calculation of decay factors.

For tritium, the inhalation dose factor is 9.60E-08 mrem/pCi or 96,000 mrem/Ci inhaled. The ingestion dose factor is 6.40E-08 mrem/pCi or 64,000 mrem/Ci ingested. The external dose rate factor is 0.

### BA.1.1 Offsite Farmer

Assume 1 curie H-3 is released into the air during the year. The bounding annual average air transport factor is 1.0E-04 s/m$^3$.

Inhalation Dose: From Table E1, 0.0237 mrem

### BA.1.2 Onsite Resident

Assume the H-3 emanation rate is 1 pCi/m$^2$/s. The average air concentration in a dwelling with an air exchange to floor area ratio of 5.0E-04 m/s is computed as shown below.

$$C_{eq} = (1\ \text{pCi/m}^2\text{/s})/(5.0\text{E-04 m/s}) = 2{,}000\ \text{pCi/m}^3$$

The individual is present in his dwelling about 8,040 h/y from Table A9 (rural pasture scenario). The total volume of air inhaled during this period is computed as shown below.

$$V_{air} = (3{,}102\ \text{h/y})(0.45\ \text{m}^3\text{/h}) + (4{,}908\ \text{h/y})(1.18\ \text{m}^3\text{/h}) = 7{,}187\ \text{m}^3\text{/y}$$

Inhalation Dose:

$$(2{,}000\ \text{pCi/m}^3)(7{,}187\ \text{m}^3)(9.60\text{E-08 mrem/pCi}) = \underline{1.38\ \text{mrem}}$$

### BA.1.3 Intruder (Well Driller)

The unit dose factors for the Well Driller assume an average soil concentration of 1 Ci/kg. The actual concentration is calculated as the activity removed from the borehole divided by the mass of soil and waste removed. A mass loading approach is used, so that the driller inhales a total of 4.84 mg (4.84E-06 kg) of soil (Table A10). He ingests a total of 500 mg (5.0E-4 kg) soil (Table A8). His external exposure time is 40 hours (Table A18). The inhalation, ingestion, and external dose calculations are shown below.

Inhalation Dose:

(4.84E-06 kg inhaled)(1 Ci/kg)(96,000 mrem/Ci) = 0.465 mrem

Ingestion Dose:

(5.0E-04 kg ingested)(1 Ci/kg)(64,000 mrem/Ci) = 32.0 mrem

External Dose:

Note that the well tailings have a density of 1,500 kg/m$^3$ and are spread to an average thickness of 5 cm. The worker spends 40 hours in the middle of this radiation source.

(40 h)(1 Ci/kg)(1,500 kg/m$^3$)(0.05 m)(0 mrem/h per Ci/m$^2$) = 0 mrem

Total Dose to Driller:

0.465 mrem + 32.0 mrem + 0 mrem = 32.5 mrem per Ci/kg

Note that the well driller dose factor from Table 7 is 32.5 mrem per Ci/kg.

### BA.1.4 Post-Intrusion Suburban Gardener

The unit dose factors for the suburban gardener assume 1 curie H-3 is exhumed from the well and spread over an area of 100 m$^2$. The initial average soil concentration is computed as shown below.

$C_S$ = (1 Ci)/(100 m$^2$)/(225 kg/m$^2$) = 4.444E-5 Ci/kg

This concentration decreases rapidly with time due to leaching from the surface layer (during the irrigation season), evaporation, and radioactive decay. For all practical purposes, none of the initial tritiated water deposited in the garden is present at the end of the irrigation season. Decay factors used in the dose calculations are computed below using equations from Table B2.

$\lambda_r$ = (0.69315)/(12.32 y) = 0.056262 y$^{-1}$

During the irrigation season :

$\lambda_s$ = (5.766+82.3 cm)/(0.2)/(15 cm)/(0.5 y) = 58.71733 y$^{-1}$ (Section A6.0)

$\lambda_t = \lambda_r + \lambda_s$ = 58.77360 y$^{-1}$

During the non-irrigation season :

$\lambda_l$ = (11.963 cm)/(0.2)/(15 cm)/(0.5 y) = 7.97533 y$^{-1}$ (Section A6.0)

$\lambda_t = \lambda_r + \lambda_s$ = 8.03160 y$^{-1}$

$\lambda_t T_{irr}$ = (58.77360 y$^{-1}$)(0.5 y) = 29.3868

$DS(T_{irr})$ = Exp(-29.3868) = 0

$IDS(T_{irr})$ = [1 - Exp(-29.3868)]/(29.3868) = 0.034029

$\lambda_t T_{no}$ = (8.03160 y$^{-1}$)(0.5 y) = 4.01580

$IDR(T_{no})$ = [1 - Exp(-4.01580)]/(4.01580) = 0.244527

$T_{irr} \cong IDS(T_{irr}) + T_{no} \cong DS(T_{irr}) \cong IDR(T_{no})$ =

(0.5y)(0.034029) + (0.5y)(0)(0.244527) = 0.017015 y

$DS(T_h) = Exp[-(58.77360\ y^{-1})(0.25\ y)] = 4.157E-7$

$\lambda_r T_{veg} = (0.056262\ y^{-1})(90\ d)/(365\ d/y) = 0.0138728$
$IDR(T_{veg}) = [1 - Exp(-0.0138728)]/(0.0138728) = 0.99310$
$DS(T_h) \cong IDR(T_{veg}) = (4.157E-7)(0.99310) = 4.128E-7$

A special model described in Section A3.2.1 is used for inhalation dose, so that the resident inhales a total of 1.581E-06 Ci tritium per Ci exhumed over the course of a year. He also ingests a total of 0.018 kg soil during the year (Table A8). The effective external exposure time is 180 h (Table A18). The inhalation, ingestion, and external doses from these sources are shown below. These also match the numbers for tritium shown in Table D1.

Inhalation Dose: (resuspended soil)
(1.581E-6 Ci inhaled/Ci exhumed)(1 Ci exhumed)(96,000 mrem/Ci) = 0.1518 mrem

Ingestion Dose: (soil only)
Note that the decay factor considers that all of the exposure occurs during the first half of the year.
(0.018 kg)(4.444E-5 Ci/kg)(64,000 mrem/Ci)(0.034029 y) = 1.742E-3 mrem

External Dose:
Note that the 1 Ci tritium in the well tailings has been mixed into a garden with an area of 100 $m^2$.
(180 h/y)(1 Ci/100 $m^2$)(0 mrem/h per Ci/$m^2$)(0.034029 y) = 0 mrem

The concentration in vegetable produce from the garden is calculated using the special model for tritium. The concentration in vegetation and the doses from each type are shown below. Grains are not grown in the garden, and all of the other plants have the same hydrogen fraction (0.1). The contaminated food consumption rate is combined with the ingestion period (1 year) so that the column of consumption rates has units of kg rather than kg/y.

$C_{V,H-3} = (4.444E-5\ Ci/kg)(8.94)(0.1)(1.5\ kg/L)/(0.2) = 2.980E-4\ Ci/kg$

Ingestion Dose: (garden produce)
leafy: (0.25)(17.8 kg)(2.980E-4 Ci/kg)(0.034029)(64,000 mrem/Ci)=2.8878 mrem
other: (0.25)(86.5 kg)(2.980E-4 Ci/kg)(4.128E-7)(64,000 mrem/Ci)=1.702E-4 mrem
fruit: (0.25)(85.8 kg)(2.980E-4 Ci/kg)(4.128E-7)(64,000 mrem/Ci)=1.689E-4 mrem
Total from root uptake: 2.8882 mrem

Total Dose: Suburban Garden Scenario:
0.1518 + 0.001742 + 2.8882 mrem = 3.042 mrem per Ci exhumed
Note that the suburban gardener's dose factor from Table 8 is 3.04 mrem/y per Ci exhumed.

### BA.1.5 Post-Intrusion Rural Pasture Scenario

The unit dose factors for the urban pasture scenario assume 1 curie H-3 is exhumed from the well and spread over an area of 5,000 $m^2$. The initial average soil concentration is computed as shown below.

$C_S$ = (1 Ci)/(5,000 $m^2$)/(225 kg/$m^2$) = 8.889E-7 Ci/kg

This concentration decreases rapidly with time due to leaching from the surface layer (during the irrigation season), evaporation, and radioactive decay. For all practical purposes, none of the initial tritiated water deposited in the garden is present at the end of the irrigation season. Decay factors used in the dose calculations are the same as shown for the suburban garden scenario.

A special model described in Section A3.2.1 is used for inhalation dose, so that the resident inhales a total of 2.241E-07 Ci tritium per Ci exhumed. He also ingests a total of 0.018 kg soil during the year (Table A8). The effective external exposure time is 360 h (Table A18). The inhalation, ingestion, and external doses from these sources are shown below. These also match the numbers for tritium shown in Table D2.

Inhalation Dose: (resuspended soil)

(2.236E-7 Ci inhaled/Ci exhumed)(1 Ci exhumed)(96,000 mrem/Ci) = 0.02147 mrem

Ingestion Dose: (soil only)

Note that the decay factor considers that all of the exposure occurs during the first half of the year.

(0.018 kg)(8.889E-7 Ci/kg)(64,000 mrem/Ci)(0.034029 y) = 3.485E-5 mrem

External Dose:

Note that the 1 Ci tritium in the well tailings has been mixed into a garden with an area of 100 $m^2$.

(360 h/y)(1 Ci/5,000 $m^2$)(0 mrem/h per Ci/$m^2$)(0.034029 y) = 0 mrem

Ingestion Dose: (milk)

Contaminated water fraction for the milk cow: 0.54944 / 119.433 = 0.004600

| source | animal intake kg/d | water fraction | total water intake, L/d | Decay | contaminated water intake |
|---|---|---|---|---|---|
| forage | 36 | 0.894 | 32.184 | 0.017015 | 0.54761 |
| hay | 29 | 0.894 | 25.926 | 4.128E-07 | 1.070E-05 |
| grain | 2 | 0.6079 | 1.216 | 4.128E-07 | 5.020E-07 |
| soil | 0.8 | 0.1333 | 0.107 | 0.017015 | 1.821E-03 |
| water | 60 | 1 | 60 | 1 | 0 |
| | total | | 119.433 | | 0.54944 |

tritium conc in milk = (8.889E-7 Ci/kg)/(0.1333 L/kg)(0.9834 L/kg)(0.00460) = 3.016E-8 Ci/kg

Total dose from milk: (3.016E-8 Ci/kg)(58 kg)(64,000 mrem/Ci) = 0.1119 mrem

Total Dose: Rural Pasture Scenario:

0.02147 + 3.485E-5 + 0.1119 mrem = 0.1334 mrem per Ci exhumed

Note that the tritium dose factor from Table 10 is 0.133 mrem/y per Ci exhumed.

### BA.1.6 Post-Intrusion Commercial Farm Scenario

The unit dose factors for the urban pasture scenario assume 1 curie H-3 is exhumed from the well and spread over an area of 647,000 $m^2$. The initial average soil concentration is computed as shown below.

$C_S$ = (1 Ci)/(647,000 $m^2$)/(225 kg/$m^2$) = 6.869E-9 Ci/kg

This concentration decreases rapidly with time due to leaching from the surface layer (during the irrigation season), evaporation, and radioactive decay. For all practical purposes, none of the initial tritiated water deposited in the garden is present at the end of the irrigation season. Decay factors used in the dose calculations are the same as shown for the suburban garden scenario.

A special model described in Section A3.2.1 is used for inhalation dose, so that the resident inhales a total of 1.965E-08 Ci tritium per Ci exhumed. He also ingests a total of 0.018 kg soil during the year (Table A8). The effective external exposure time is 720 h (Table A18). The inhalation, ingestion, and external doses from these sources are shown below.

Inhalation Dose: (resuspended soil)

(1.965E-8 Ci inhaled/Ci exhumed)(1 Ci exhumed)(96,000 mrem/Ci) = 0.001886 mrem

Ingestion Dose: (soil only)

Note that the decay factor considers that all of the exposure occurs during the first half of the year.

(0.018 kg)(6.869E-9 Ci/kg)(64,000 mrem/Ci)(0.034033 y) = 2.693E-7 mrem

External Dose:

Note that the 1 Ci tritium in the well tailings has been mixed into a garden with an area of 100 $m^2$.

(720 h/y)(1 Ci/647,000 $m^2$)(0 mrem/h per Ci/$m^2$)(0.034033 y) = 0 mrem

Total Dose: Commercial Farm Scenario:

0.001886 + 2.693E-7 + 0 mrem = 0.001887 mrem per Ci exhumed

Note that the tritium dose factor from Table 11 is 0.00189 mrem/y per Ci exhumed.

## BA.2 LOW WATER INFILTRATION EXPOSURE SCENARIOS

Each of the exposure scenarios using irrigation water with tritium will be evaluated in this section. The tritium concentration in the irrigation water is assumed constant during the irrigation season. As a result, the tritium concentration in the surface soil is also constant during the irrigation season, but decreases rapidly during the non-irrigation period due to evaporation and radioactive decay. In each exposure scenario the water concentration is 1 pCi/L. Thus the doses computed are per pCi/L. The soil concentration during the irrigation season is calculated as shown below.

$C_S$ = (1.0E-12 Ci/L)(0.2)/(1.5 kg/L)(0.9344) = 1.246E-13 Ci/kg

The external exposures are not computed for tritium because the external dose rate factor for tritium is zero. Absorption through the skin is included in the inhalation dose factor for tritium. The main dose pathway in every case is the drinking water pathway.

Normally, three significant digits are kept during calculations. Because the spreadsheet software keeps several digits, agreement with the spreadsheet can only be obtained if 4 or 5 significant digits are retained. This is particularly true in the calculation of decay factors.

### BA.2.1 All Pathways

The soil concentration decreases with time due to leaching from the surface layer during the irrigation season, evaporation, and radioactive decay. Additional decay factors used in the dose calculations for tritium are computed below from the equations in the discussion following Table B2.

$\lambda_t T_{no}$ = (8.03160 $y^{-1}$)(0.5 y) = 4.01580
$IDR(T_{no})$ = [1 - Exp(-4.01580)]/(4.01580) = 0.244527

$T_{irr} + T_{no} \cong IDR(T_{no})$ = (0.5y) + (0.5y)(0.244527) = 0.62226 y

$\lambda_r T_{veg}$ = (0.056262 $y^{-1}$)(90 d)/(365 d/y) = 0.0138728
$DR(T_{veg})$ = Exp(-0.0138728) = 0.98622
$IDR(T_{veg})$ = [1 - Exp(-0.0138728)]/(0.0138728) = 0.99310

$\lambda_r T_{beef}$ = (0.056262 $y^{-1}$)(120 d)/(365 d/y) = 0.018497
$IDR(T_{beef})$ = [1 - Exp(-0.018497)]/(0.018497) = 0.99081

Because tritium is bound to water, the inhalation dose from suspended soil is part of the inhalation dose from water, described in Section A3.2.2 Table A16. The farmer also ingests a total of 0.0365 kg soil during the year (Table A8). The inhalation and ingestion doses from these sources are shown below. They match the doses shown in Table D3.

<u>Inhalation Dose:</u> (showering and ambient humidity)
(48 L/y)(1.0E-12 Ci/L)(96,000 mrem/Ci)(1 y) = 4.608E-6 mrem

<u>Ingestion Dose:</u> (drinking)
(545 L/y)(1.0E-12 Ci/L)(64,000 mrem/Ci)(1 y) = 3.488E-5 mrem
Note that the all pathways farmer's drinking water dose factor from Table 12 is 3.49E-5 mrem/y per pCi/L.

<u>Ingestion Dose:</u> (soil only)
(0.0365 kg/y)(1.246E-13 Ci/kg)(64,000 mrem/Ci)(0.62226 y) = 1.811E-10 mrem

The vegetable produce contamination is based on the plant moisture having the same tritium concentration as the irrigation water (adjusted for natural precipitation by the factor 0.9344). The contaminated food consumption rate is combined with the ingestion period (1 year)

so that the column of consumption rates has units of kg rather than kg/y. The product of plant water concentration and ingestion dose factor is combined into a single quantity to simplify the calculation.

(0.9344)(1.0E-12 Ci/L)(64,000 mrem/Ci)=5.980E-8 mrem/L

The factors 0.894 L/kg and 0.6079 L/kg in the calculations below are the equivalent volume of water per kilogram of plant. They are calculated from the hydrogen fractions shown in Table A37 multiplied by 8.94 kg water per kg hydrogen, and divided by the density of water, 1.0 kg/L. Grains are not irrigated, and are not shown.

Ingestion Dose: (garden produce)

(5.980E-8 mrem/L)(0.894 L/kg) ( 4.45 kg) (1.00000) = 2.379E-7 mrem
(5.980E-8 mrem/L)(0.894 L/kg)(21.625 kg)(0.99310) = 1.148E-7 mrem
(5.980E-8 mrem/L)(0.894 L/kg)(25.45 kg) (0.99310) = 1.139E-7 mrem
Total from garden produce: 2.525E-6 mrem

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed, stored hay, stored grain, soil, and drinking water. Each of these has a common factor made of the water concentration, the effective water fraction in the animal product, the annual amount consumed by the individual, the ingestion dose factor, and the ingestion period. The fraction of water intake that is contaminated is multiplied by this common factor to obtain the ingestion dose from consumption of the animal product.

Ingestion Dose: (beef)

Contaminated water fraction for the beef cow: 84.164 / 88.558 = 0.95038

| source | animal intake kg/d | water fraction | total water intake, L/d | rain dilution | decay | contaminated water intake |
|---|---|---|---|---|---|---|
| forage | 27 | 0.894 | 24.138 | 0.9344 | 1 | 22.555 |
| hay | 14 | 0.894 | 12.516 | 0.9344 | 0.98622 | 11.534 |
| grain | 3 | 0.6079 | 1.824 | 0 | 0.98622 | 0 |
| soil | 0.6 | 0.1333 | 0.080 | 0.9344 | 1 | 0.075 |
| water | 50 | 1 | 50 | 1 | 1 | 50 |
| | total | | 88.558 | | | 84.164 |

tritium concentration in beef = (1.0E-12 Ci/L)(0.894 L/kg)(0.95038) = 8.496E-13 Ci/kg

Total dose from beef: (8.497E-13 Ci/kg)(25.15 kg)(64,000 mrem/Ci)(0.99081) = 1.355E-6 mrem

Ingestion Dose: (milk)

Contaminated water fraction for the milk cow: 102.502 / 119.433 = 0.85824

| source | animal intake kg/d | water fraction | total water intake, L/d | rain dilution | decay | contaminated water intake |
|---|---|---|---|---|---|---|
| forage | 36 | 0.894 | 32.184 | 0.9344 | 0.62226 | 18.713 |
| hay | 29 | 0.894 | 25.926 | 0.9344 | 0.97942 | 23.727 |
| grain | 2 | 0.6079 | 1.216 | 0 | 0.97942 | 0 |
| soil | 0.8 | 0.1333 | 0.107 | 0.9344 | 0.62226 | 0.062 |
| water | 60 | 1 | 60 | 1 | 1 | 60 |
| | total | | 119.433 | | | 102.502 |

tritium concentration in milk = (1.0E-12 Ci/L)(0.9834 L/kg)(0.85824) = 8.440E-13 Ci/kg

Total dose from milk: (8.440E-13 Ci/kg)(58 kg)(64,000 mrem/Ci) = 3.133E-6 mrem

Ingestion Dose: (poultry)

Contaminated water fraction for the chicken: 0.36842 / 0.47240 = 0.77989

| source | animal intake kg/d | water fraction | total water intake, L/d | rain dilution | decay | contaminated water intake |
|---|---|---|---|---|---|---|
| forage | 0.13 | 0.894 | 0.11622 | 0.9344 | 0.62226 | 0.06757 |
| hay | 0 | 0.894 | 0 | 0.9344 | 0.97942 | 0 |
| grain | 0.09 | 0.6079 | 0.05471 | 0 | 0.97942 | 0 |
| soil | 0.011 | 0.1333 | 0.00147 | 0.9344 | 0.62226 | 0.00085 |
| water | 0.3 | 1 | 0.3 | 1 | 1 | 0.3 |
| | total | | 0.47240 | | | 0.36842 |

tritium concentration in poultry = (1.0E-12 Ci/L)(0.894 L/kg)(0.77989) = 6.972E-13 Ci/kg

Total dose from poultry: (6.972E-13 Ci/kg)(14.7 kg)(64,000 mrem/Ci) = 6.559E-7 mrem

tritium concentration in eggs = (1.0E-12 Ci/L)(0.9834 L/kg)(0.77989) = 7.669E-13 Ci/kg

Total dose from eggs: (7.670E-13 Ci/kg)(6.8 kg)(64,000 mrem/Ci) = 3.338E-7 mrem

Total dose for all animal pathways = 5.478E-6 mrem

Total Dose for the All Pathways Farmer (irrigation from a well):

4.608E-6 + 3.488E-5 + 1.811E-10 + 2.525E-6 + 5.478E-6 = 4.749E-5 mrem per pCi/L

Note that the all pathways farmer's total dose factor from Table 12 is 4.75E-5 mrem/y per pCi/L.

The above total applies to the inland well situation in which does not include a dose from fish. When the Columbia River is the source of tritium, the fish dose is calculated as shown below and added to the above total.

Ingestion Dose: (fish)

(1.0E-12 Ci/L)(1 L/kg)(0.50)(6.58 kg)(64,000 mrem/Ci)(1 y) = 2.106E-7 mrem

Note that the all pathways farmer's fish dose factor from Table 13 is 2.11E-7 mrem/y per pCi/L.

Ingestion Dose: (shoreline sediment)

(1.0E-12 Ci/L)(0.1333 L/kg)(0.0007 kg)(64,000 mrem/Ci)(1 y) = 5.973E-12 mrem

Total Dose for the All Pathways Farmer (irrigation from the Columbia River):

4.696E-5 + 2.106E-7 + 5.973E-12 = 4.770E-5 mrem per pCi/L

Note that the all pathways farmer's total dose factor from Table 13 is 4.77E-5 mrem/y per pCi/L.

## BA.2.2 COLUMBIA RIVER POPULATION

The collective doses for each pathway are calculated in the same manner as the All Pathways Irrigator case scaled up for a population of 5 million, with a lower irrigation rate, and reduced by a factor of 1000 to convert from mrem to rem. The inhalation and ingestion doses are adjusted for the population and unit conversion as shown below. The new soil concentration during the irrigation period is shown also. The decay and leaching factors during the non-irrigation season are not changed.

Inhalation: (9.60E-8 mrem/pCi)(5.0E+6)(0.001 rem/mrem) = 4.80E-4 person-rem/pCi
Ingestion: (6.40E-8 mrem/pCi)(5.0E+6)(0.001 rem/mrem) = 3.20E-4 person-rem/pCi

$C_{s,H3}$ = (8.94)(0.022)(1 pCi/L)(63.5 cm)/(63.5 + 5.766 cm)/(1 kg/L)
$C_{s,H3}$ = 0.1222 pCi/kg

Inhalation Dose: (showering and ambient humidity)

(46 L/y)(1 pCi/L)(4.80E-4 person-rem/pCi)(1 y) = 2.208E-2 person-rem

Ingestion Dose: (drinking)

(545 L/y)(1 pCi/L)(3.20E-4 person-rem/pCi)(1 y) = 0.1744 person-rem

Ingestion Dose: (soil)

(0.0365 kg/y)(0.1222 pCi/kg)(3.20E-4 person-rem/pCi)(0.62226 y) = 8.882E-7 person-rem

External Dose:

(4380 h/y)(0.1222 pCi/kg)(225 kg/m$^2$)(0 mrem/h per Ci/m$^2$)(0.9930 y) = 0 mrem

With a lower irrigation rate, the irrigation dilution factor changes to become (63.5 cm)/(63.5+5.776cm)=0.9166. The common factor used in the garden produce calculation is shown below.

(0.9166)(1 pCi/L)(3.20E-4 person-rem/pCi)=2.934E-4 person-rem/L

Ingestion Dose: (garden produce)

(2.934E-4 person-rem/L)(0.894 L/kg) ( 8.90 kg)(1.0000) = 2.334E-3 person-rem
(2.934E-4 person-rem/L)(0.894 L/kg)(43.25 kg)(0.9931) = 1.126E-2 person-rem
(2.934E-4 person-rem/L)(0.894 L/kg)(42.90 kg)(0.9931) = 1.117E-2 person-rem
Total from garden produce: 2.477E-2 person-rem

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed, stored hay, stored grain, soil, and drinking water. Each of these has a common factor made of the water concentration, the effective water fraction in the animal

product, the annual amount consumed by the individual, the ingestion dose factor, and the ingestion period. The fraction of water intake that is contaminated is multiplied by this common factor to obtain the ingestion dose from consumption of the animal product.

Ingestion Dose: (beef)

Contaminated water fraction for the beef cow: 83.512 / 88.558 = 0.94302

| source | animal intake kg/d | water fraction | total water intake, L/d | rain dilution | decay | contaminated water intake |
|---|---|---|---|---|---|---|
| forage | 27 | 0.894 | 24.138 | 0.9166 | 1 | 22.125 |
| hay | 14 | 0.894 | 12.516 | 0.9166 | 0.98622 | 11.314 |
| grain | 3 | 0.6079 | 1.824 | 0 | 0.98622 | 0 |
| soil | 0.6 | 0.13333 | 0.08 | 0.9166 | 1 | 0.073 |
| water | 50 | 1 | 50 | 1 | 1 | 50 |
| | total | | 88.558 | | | 83.512 |

tritium concentration in beef = (1.0E-12 Ci/L)(0.894 L/kg)(0.94302) = 8.431E-13 Ci/kg

Total dose from beef:

(8.431E-13 Ci/kg)(25.15 kg)(3.20E-4 person-rem/Ci)(0.99081) = 6.723E-3 person-rem

Ingestion Dose: (milk)

Contaminated water fraction for the milk cow: 101.693 / 119.433 = 0.85146

| source | animal intake kg/d | water fraction | total water intake, L/d | rain dilution | decay | contaminated water intake |
|---|---|---|---|---|---|---|
| forage | 36 | 0.894 | 32.184 | 0.9166 | 0.62226 | 18.357 |
| hay | 29 | 0.894 | 25.926 | 0.9166 | 0.97942 | 23.275 |
| grain | 2 | 0.6079 | 1.216 | 0 | 0.97942 | 0 |
| soil | 0.8 | 0.13333 | 0.107 | 0.9166 | 0.62226 | 0.061 |
| water | 60 | 1 | 60 | 1 | 1 | 60 |
| | total | | 119.433 | | | 101.693 |

tritium concentration in milk = (1.0E-12 Ci/L)(0.9834 L/kg)(0.85146) = 8.373E-13 Ci/kg

Total dose from milk:

(8.373E-13 Ci/kg)(58 kg)(3.20E-4 person-rem/Ci) = 1.554E-2 person-rem

Ingestion Dose: (poultry)

Contaminated water fraction for the chicken: 0.36713 / 0.47240 = 0.77716

| source | animal intake kg/d | water fraction | total water intake, L/d | rain dilution | decay | contaminated water intake |
|---|---|---|---|---|---|---|
| forage | 0.13 | 0.894 | 0.11622 | 0.9166 | 0.62226 | 0.06629 |
| hay | 0 | 0.894 | 0 | 0.9166 | 0.97942 | 0 |
| grain | 0.09 | 0.6079 | 0.05471 | 0 | 0.97942 | 0 |
| soil | 0.011 | 0.13333 | 0.00147 | 0.9166 | 0.62226 | 0.00084 |
| water | 0.3 | 1 | 0.3 | 1 | 1 | 0.3 |
| | total | | 0.4724 | | | 0.36713 |

tritium concentration in poultry = (1.0E-12 Ci/L)(0.894 L/kg)(0.77716) = 6.948E-13 Ci/kg

Total dose from poultry:

(6.948E-13 Ci/kg)(14.7 kg)(3.20E-4 person-rem/Ci) = 3.268E-3 person-rem

tritium concentration in eggs = (1.0E-12 Ci/L)(0.9834 L/kg)(0.77716) = 7.643E-13 Ci/kg

Total dose from eggs:

(7.643E-13 Ci/kg)(6.8 kg)(3.20E-4 person-rem/Ci) = 1.663E-3 person-rem

Ingestion Dose: (fish)

(1.0 pCi/L)(1 L/kg)(0.003 kg)(3.20E-4 person-rem/pCi)(1 y) = 9.600E-7 person-rem

Total dose for all animal pathways = 2.270E-2 person-rem

Ingestion Dose: (shoreline sediment)

(1.0 pCi/L)(0.1333 L/kg)(0.0005 kg)(3.20E-4 person-rem/pCi)(1 y) = 2.133E-8 person-rem

Total Collective Dose to the Population:

0.02208 + 0.1744 + 8.882E-7 + 0.02477 + 0.02270 = 0.2484 person-rem per pCi/L

Note that the Columbia River Population dose factor from Table 16 is 0.248 person-rem/y per pCi/L.

### BA.2.3 HSRAM and Other Scenarios

The other scenarios require calculating a lifetime cancer morbidity risk. Because tritium is removed from the soil rapidly, there is essentially no carryover from year to year. Each year the soil contamination starts at zero. In the case of contaminated surface water, the sediment concentration does not change from year to year. Thus the cumulative dose (or lifetime risk) is the sum of the doses (or cancer risks) calculated for each year.

The next attachment shows the lifetime cancer risk calculation for the All Pathways Farmer to illustrate the method used.

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# ATTACHMENT B2.
# HAND CALCULATIONS FOR TC-99

Four of the exposure scenarios will be evaluated for Tc-99 in this section. These four scenarios are the well drilling, suburban garden, rural pasture, and all pathways irrigator. They exercise all of the relevant calculations used for nuclides other than tritium.

The nuclide selected (Tc-99) has a very long half life (211,096 y), so its radioactive decay has little effect on the doses, even after 70 years. The leaching factor for Tc-99 (0.20833 per year) is large enough to affect the calculated intakes. Tc-99 decays to stable Ru-99 so decay chain formulas are not needed.

Normally, three significant digits are kept during calculations. Because the spreadsheet software keeps several digits, agreement with the spreadsheet can only be obtained if 4 or 5 significant digits are retained. This is particularly true in the calculation of decay factors.

## BB.1 Intruder (Well Driller)

The unit dose factors for the Well Driller use an average soil concentration of 1 Ci/kg. This is calculated as the activity removed from the borehole divided by the mass of soil and waste removed. A mass loading approach is used, so that the driller inhales a total of 4.84 mg (4.84E-06 kg) of soil (Table A10). He ingests a total of 500 mg (5.0E-4 kg) soil (Table A8). His external exposure time is 40 hours (Table A18). The inhalation, ingestion, and external dose calculations are shown below.

<u>Inhalation Dose:</u>

(1 Ci/kg)(4.84E-06 kg inhaled)(8,325,000 mrem/Ci) = 40.29 mrem

<u>External Dose:</u>

Note that the well tailings have a density of 1,500 kg/m$^3$ and are spread to an average thickness of 5 cm. The worker spends 40 hours in the middle of this radiation source. The intake factor for external exposure is (40 h)(1,500 kg/m$^3$)(0.05 m) = 3,000 h-kg/m$^2$.

(1 Ci/kg)(3,000 h-kg/m$^2$.)(0.16316 mrem/h per Ci/m$^2$) = 489.48 mrem

<u>Ingestion Dose:</u>

(1 Ci/kg)(5.0E-04 kg ingested)(1,462,000 mrem/Ci) = 730.75 mrem

<u>Total Dose to Driller:</u>

40.29 mrem + 489.48 mrem + 730.75 mrem = <u>1260.5 mrem per Ci/kg</u>

Note that the well driller dose factor from Table 7 is 1260 mrem per Ci/kg.

## BB.2 Post-Intrusion Suburban Gardener

The unit dose factors for the suburban garden scenario assume 1 curie Tc-99 is exhumed from the well and spread over an area of 100 m$^2$. The initial average soil concentration is

computed as shown below. For the external dose calculation, the soil concentration is 0.01 $Ci/m^2$.

$C_S = (1\ Ci)/(100\ m^2)/(225\ kg/m^2) = 4.444E\text{-}5\ Ci/kg$

This concentration decreases rapidly with time due to leaching from the surface layer (during the irrigation season) and radioactive decay. Decay and leaching factors used in the dose calculations are computed below using equations from Table B2. Tc-99 has a very long half life with a modest leaching factor. For all practical purposes, there is no radioactive decay.

$\lambda_r = (0.69315)/(211{,}096\ y) = 3.2836E\text{-}6\ y^{-1}$

During the irrigation season :

$\lambda_s = (10\ cm)/[(15\ cm)(0.2+(1.5g/ml)(2\ ml/g))] = 0.208333\ y^{-1}$ (Section A6.0)

$\lambda_t = \lambda_r + \lambda_s = 0.208336\ y^{-1}$

Midway through the irrigation season :

$DS(T_h) = Exp[-(0.208336\ y^{-1})(0.25\ y)] = 0.949249$

At the end of the irrigation season:

$\lambda_t T_{irr} = (0.208336\ y^{-1})(0.5\ y) = 0.104168$

$DS(T_{irr}) = Exp(-0.104168) = 0.90107$

$IDS(T_{irr}) = [1 - Exp(-0.104168)]/(0.104168) = 0.949678$

During the no-irrigation season:

$\lambda_r T_{no} = (3.28355E\text{-}6\ y^{-1})(0.5\ y) = 1.64178E\text{-}6$

$DR(T_{no}) = Exp(-1.64178E\text{-}6) = 0.999998$

$IDR(T_{no}) = [1 - Exp(-1.64178E\text{-}6)]/(1.64178E\text{-}6) = 1$

Time integral over the first year:

$T_{irr} \cong IDS(T_{irr}) + T_{no} \cong DS(T_{irr}) \cong IDR(T_{no}) =$

$(0.5y)(0.949678) + (0.5y)(0.90107)(1) = 0.925376\ y$

Time integral during the vegetable consumption period :

$\lambda_r T_{veg} = (3.28355E\text{-}6\ y^{-1})(90\ d)/(365\ d/y) = 8.09642E\text{-}7$

$IDR(T_{veg}) = [1 - Exp(-8.09642E\text{-}7)]/(8.09642E\text{-}7) = 1$

Harvest midway through the irrigation season followed by the consumption period:

$DS(T_h) \cong IDR(T_{veg}) = (0.949249)(1) = 0.949249$

The inhalation, external, and ingestion doses from the soil contamination are calculated as shown below. These match the numbers shown in Table D1.

<u>Inhalation Dose:</u> (suspended soil, Table A9)

Note that the decay factor assumes the exposure occurs during the entire year.

$(4.444E\text{-}5\ Ci/kg)(8.70E\text{-}5\ kg/y\ inhaled)(0.925376\ y)(8{,}330{,}000\ mrem/Ci) = 0.0298\ mrem$

<u>External Dose:</u> (Table A18)

Note that the decay factor assumes the exposure occurs during the first half of the year.

$(1\ Ci/100\ m^2)(180\ h/y)(0.949678\ y)(0.06346\ mrem/h\ per\ Ci/m^2) = 0.1085\ mrem$

<u>Ingestion Dose:</u> (soil only, Table A8)

Note that the decay factor assumes the exposure occurs during the first half of the year.

$(4.444E\text{-}5\ Ci/kg)(0.018\ kg/y\ ingested)(0.949678\ y)(1{,}462{,}000\ mrem/Ci) = 1.1103\ mrem$

Ingestion Dose: (garden produce, Section A5.0)

The concentration in vegetable produce from the garden is calculated using root uptake and rain splash (soil adherence). The human intakes from vegetables by way of rain splash are calculated using the table below. The rain splash factor must be included to obtain the numbers shown for annual intake. This rain splash factor is 2.7E-4 kg/m$^2$ per day as discussed in Section A5.2. Note that none of the factors on this table are unique to technetium.

| Vegetable | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield (kg/m$^2$) | Annual Food Consumption (kg/y) | Annual Soil Intake (kg/y) |
|---|---|---|---|---|---|---|
| leafy | 0.4067 | 18.02 | 1 | 2 | 4.45 | 4.403E-03 |
| other | 0.8347 | 19.96 | 0.1 | 2 | 21.625 | 4.864E-03 |
| fruit | 0.8569 | 19.96 | 0.1 | 3 | 21.45 | 3.302E-03 |
| grain | 0.3712 | 19.96 | 0.1 | 0.8 | 20.475 | 5.120E-03 |

The Annual Soil Intake from Rain Splash is calculated as
(Splash factor)(Interception fraction)(Translocation)(Growing Time)(Annual food eaten) / (Biomass)
The splash factor is 2.7E-4 kg/m$^2$ per day as discussed in the text.

The human intakes from vegetables by way of root uptake are calculated using the table below. The only numbers unique to technetium are the concentration ratios. This table also shows the combined intakes for Tc-99 from root uptake and rain splash.

| | Concentration Ratio for Tc | dry-to-wet ratio | Annual Food Consumption (kg/y) | Annual Soil Intake (kg/y) | Total Soil Intake (kg/y) |
|---|---|---|---|---|---|
| leafy | 180 | 0.09 | 4.45 | 72.0900 | 72.0944 |
| other | 0.77 | 0.25 | 21.625 | 4.1628 | 4.1677 |
| fruit | 1.5 | 0.18 | 21.45 | 5.7915 | 5.7948 |
| grain | 0.73 | 0.91 | 20.475 | 13.6015 | 13.6066 |

The Annual Soil Intake from Root Uptake into plants is calculated as
(Conc ratio)(dry-to-wet ratio)(Annual food eaten)
The "Total Soil Intake" is the sum of the intakes from rain splash (previous table) and root uptake.

The ingestion dose is the product of the soil concentration, the annual soil intake, the appropriate decay and leaching factor, and the ingestion dose factor, as shown below. The first row shows the dose from leafy vegetables. The second row shows the dose from fruit and other vegetables. Note that the fruit and other vegetable intakes have been combined. Also note that grains have been omitted due to their absence from the garden.

(4.444E-5 Ci/kg)(72.0944 kg/y)(0.949678 y)(1,462,000 mrem/Ci) = 4,446.8 mrem
(4.444E-5 Ci/kg)( 9.9625 kg/y)(0.949249 y)(1,462,000 mrem/Ci) = 614.2 mrem

Total Dose: Suburban Garden Scenario:

0.0298 + 0.1085 + 1.1103 + 5,061.0 mrem = 5,062 mrem per Ci exhumed

Note that the suburban gardener's dose factor from Table 8 is 5,060 mrem/y per Ci exhumed.

**BB.3 Post-Intrusion Rural Pasture Scenario**

The unit dose factors for the rural pasture scenario assume 1 curie Tc-99 is exhumed from the well and spread over an area of 5,000 $m^2$. The initial average soil concentration is computed as shown below. For the external dose calculation, the soil concentration is 0.0002 $Ci/m^2$.

$C_S$ = (1 Ci)/(5,000 $m^2$)/(225 $kg/m^2$) = 8.889E-7 Ci/kg

This concentration decreases rapidly with time due to leaching from the surface layer (during the irrigation season) and radioactive decay. Decay and leaching factors used in the dose calculations are from the previous section.

The inhalation, external, and ingestion doses from the soil contamination are calculated as shown below. These match the numbers shown in Table D2.

Inhalation Dose: (suspended soil, Table A9)

Note that the decay factor assumes the exposure occurs during the entire year.

(8.889E-7 Ci/kg)(1.69E-4 kg/y inhaled)(0.925376 y)(8,325,000 mrem/Ci) = 1.157E-3 mrem

External Dose: (Table A18)

Note that the decay factor assumes the exposure occurs during the first half of the year.

(1 Ci/5,000 $m^2$)(360 h/y)(0.949678 y)(0.06346 mrem/h per $Ci/m^2$) = 4.339E-3 mrem

Ingestion Dose: (soil only, Table A8)

Note that the decay factor assumes the exposure occurs during the first half of the year.

(8.889E-7 Ci/kg)(0.018 kg/y ingested)(0.949678 y)(1,462,000 mrem/Ci) = 0.02221 mrem

Ingestion Dose: (milk, Section A4.0)

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed (like leafy vegetables), stored hay (also like leafy vegetables, but is harvested and stored), stored grain (like grains), and soil. The feed, hay, and grain have two components, root uptake and rain splash. The rain splash is shown first. The root uptake factor is calculated using the information in the second table below. The third table shows the calculation of ingestion dose from milk the first year after the start of irrigation.

| Rain Splash Intake Factors for Milk Cows | | | | | | |
|---|---|---|---|---|---|---|
| Animal Feed Type | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Daily Feed Intake by Animal (kg/d) | Annual Soil Intake (kg/y) |
| fresh forage | 0.6160 | 15.62 | 1 | 1.5 | 36 | 5.0628E-04 |
| stored hay | 0.4717 | 18.02 | 1 | 1 | 29 | 5.4043E-04 |
| stored grain | 0.4717 | 19.96 | 0.1 | 1 | 2 | 4.1283E-06 |
| soil | | | | | 0.8 | 0.0064960 |

The last column shows the effective annual soil intake by humans from rain splash onto the vegetation eaten by the milk cow. It is calculated using the formula below.

(Annual milk)(Transfer)(Splash)(Interception)(Translocation)(Growing Time)(Daily feed) / (Yield)

The annual amount of contaminated milk eaten is 58 kg from Table A5. The equilibrium transfer factor for milk is 1.4E-4 d/kg from Table A37. The splash factor is 0.00027 $kg/m^2$ per day as discussed in Section A5.2. The annual soil intake by humans from soil eaten by the milk cow (0.8 kg/d from Table A32) is calculated as

(Annual milk)(Transfer)(Soil intake)

| Root Uptake Intake Factors for Milk Cows | | | | | |
|---|---|---|---|---|---|
| | Concentration Ratio for Tc | dry-to-wet ratio | Annual Milk Consumption (kg/y) | Annual Soil Intake (kg/y) | Total Soil Intake (kg/y) |
| fresh forage | 180 | 0.22 | 58 | 11.57587 | 11.5764 |
| stored hay | 180 | 0.22 | 58 | 9.32501 | 9.3256 |
| stored grain | 0.73 | 0.22 | 58 | 0.002608 | 0.002612 |

The second last column shows the effective annual soil intake by humans from root uptake into the vegetation eaten by the milk cow. It is calculated using the formula below.

(Annual milk)(Transfer)(Conc ratio)(dry-to-wet ratio)(Daily feed intake)

The Daily feed intakes are shown in the previous table. The equilibrium transfer factor for milk is 1.4E-4 d/kg from Table A36.

The "Total Soil Intake" is the sum of the intakes from rain splash (previous table) and root uptake.

| Calculation of the Annual Dose by Pathway | | | | | |
|---|---|---|---|---|---|
| Component | Soil Concentration (Ci/kg) | Soil Intake Factor (kg/y) | Decay & Leaching Factor | Ingestion Dose Factor (mrem/Ci) | Annual Dose (mrem/y) |
| soil | 8.8890E-07 | 0.006496 | 0.925376 | 1.462E+06 | 7.809E-03 |
| forage - root uptake & rain splash | 8.8890E-07 | 11.5764 | 0.925376 | 1.462E+06 | 13.92 |
| stored hay - root uptake & rain splash | 8.8890E-07 | 9.3256 | 0.949249 | 1.462E+06 | 11.50 |
| stored grain - root uptake & rain splash | 8.8890E-07 | 0.002612 | 0.949249 | 1.462E+06 | 3.221E-03 |
| | | | | Total dose | 25.43 |

The annual dose is the product of the soil concentration, the effective mass of soil ingested per year, the decay and leaching factor, and the ingestion dose factor.

Total Dose: Rural Pasture Scenario:

0.001157 + 0.004339 + 0.02221 + 25.43 mrem = 25.46 mrem per Ci exhumed

Note that the dose factor from Table 10 is 25.5 mrem/y per Ci exhumed.

**BB.4 All Pathways Farmer**

The Tc-99 concentration in the irrigation water is assumed constant during the irrigation season. As a result, the Tc-99 concentration in the surface soil is increasing. The increase is offset by leaching from the surface layer during the irrigation season and radioactive decay. This section shows calculations for both annual dose and lifetime cancer risk for Tc-99. The numbers used for dose accumulation in the presence of decay and leaching are shown below.

$T_{irr} + T_{no} \cong IDR(T_{no}) = (0.5y) + (0.5y)(0.244528) = 0.62226$ y

At the end of the irrigation season:

$\lambda_r T_{irr} = (0.208336\ y^{-1})(0.5\ y) = 0.104168$

$DI(T_{irr}) = [1 - Exp(-0.104168)]/(0.104168) = 0.949678$

$IDI(T_{irr}) = [(0.104168) - 1 + Exp(-0.104168)]/(0.104168)^2 = 0.483081$

Time integral over the first year:

$T_{irr} \cong IDI(T_{irr}) + T_{no} \cong DI(T_{irr}) \cong IDR(T_{no}) =$

$(0.5y)(0.483081) + (0.5y)(0.949678)(1) = 0.716379$ y

Decay during storage:

$\lambda_r T_{sto} = (3.28355E\text{-}6\ y^{-1})(90\ d)/(365\ d/y) = 8.09642E\text{-}7$

$DR(T_{sto}) = Exp(-8.09642E\text{-}7) = 1$

Time integral during the beef consumption period :

$\lambda_r T_{beef} = (3.28355E\text{-}6\ y^{-1})(120\ d)/(365\ d/y) = 1.07952E\text{-}6$

$IDR(T_{beef}) = [1 - Exp(-1.07952E\text{-}6)]/(1.07952E\text{-}6) = 1$

Harvest after the irrigation season followed by the consumption period:

$DI(T_{irr}) \cong IDR(T_{beef}) = (0.949678)(1) = 0.949678$

The numbers used for the accumulated risk in the presence of radioactive decay and leaching from the soil are shown below.

Decay and leaching during the year for contamination present at the start of the year:

$W = (0.90107)(0.999998) = 0.90107$

Lifetime average soil concentration factor (30 y):

$[30 - (1 - 0.90107^{30})/(1-0.90107)]/(1-0.90107) = 205.56$

The rate of increase of the soil concentration during the irrigation season is calculated as shown below. Also shown is the soil concentration at the end of the irrigation season. After 30 years of irrigation, the cumulative soil concentration is calculated as shown.

Deposition rate during the irrigation season:

$ID = (1.0E\text{-}12\ Ci/L)(82.3\ cm)(10\ L/m^2\ per\ cm) / (0.5\ y) = 1.646E\text{-}9\ Ci/m^2$ per year

End of year soil concentration - without decay and leaching:

$C_{S0} = (1.646E\text{-}9\ Ci/m^2\ per\ y)(0.5\ y) / (225\ kg/m^2) = 3.6578E\text{-}12\ Ci/kg$

Lifetime cumulative soil concentration:

$C_{S30}$ = (3.6578E-12 Ci/kg)(30 y) = 1.0973E-10 Ci/kg

End of year soil concentration - with decay and leaching:

$C_{S1}$ = (3.6578E-12 Ci/kg)(0.949678)(0.999998) = 3.4737E-12 Ci/kg

Lifetime cumulative soil concentration:

$C_{S1}^{Cum}$ = (3.4737E-12 Ci/kg)(205.56) = 7.1405E-10 Ci/kg

The inhalation, external, and ingestion doses and cancer risks from the soil contamination are calculated as shown below. Note the water only pathways calculate the incremental cancer risk using the cumulative water concentration, (30)(1.0E-12 Ci/L)=3.0E-11 Ci/L. Note that the soil pathways calculate incremental cancer risk as the sum of two parts. The first part is 30 times the risk from water added to the soil that year ($C_{S30}$). The second part is the risk from residual soil contamination ($C_{S1}^{Cum}$). The doses match the numbers shown in Table D3.

Inhalation Dose: (shower plus ambient, Table A16)

(1.0E-12 Ci/L)(0.0011 L inhaled)(8,325,000 mrem/Ci) = 9.1583E-9 mrem

(3.0E-11 Ci/L)(0.0011 L inhaled)(14.10 risk/Ci) = 4.652E-13 risk

Inhalation Dose: (suspended soil, Table A9)

(3.6578E-12 Ci/kg)(5.39E-4 kg/y)(0.716379 y)(8.325E6 mrem/Ci) = 1.176E-8 mrem

(1.0973E-10 Ci/kg)(5.39E-4 kg/y inhaled)(0.716379 y)(14.1 risk/Ci) = 5.973E-13 risk

(7.1405E-10 Ci/kg)(5.39E-4 kg/y inhaled)(0.925376 y)(14.1 risk/Ci) = 5.021E-12 risk

Total lifetime cancer risk from dust inhalation = 5.618E-12

External Dose: (Table A18)

Note that the soil concentrations are multiplied by 225 kg/m$^2$ to convert them into area concentrations (Ci/m$^2$) suitable for the external dose rate factor.

(8.230E-10 Ci/m$^2$)(4,120 h/y)(0.716379 y)(0.06346 mrem/h per Ci/m$^2$) = 1.542 E-7 mrem

(1.4690E-8 Ci/m$^2$)(4,120 h/y)(0.716379 y)(4.13E-8 risk/h per Ci/m$^2$) = 3.007E-12 risk

(1.6066E-7 Ci/m$^2$)(4,120 h/y)(0.925376 y)(4.13E-8 risk/h per Ci/m$^2$) = 2.527E-11 risk

Total lifetime cancer risk from external exposure = 2.828E-11

Ingestion Dose: (soil only, Table A8)

(3.6578E-12 Ci/kg)(0.0365 kg/y)(0.716379 y)(1.462E6 mrem/Ci) = 1.398E-7 mrem

(1.0973E-10 Ci/kg)(0.0365 kg/y ingested)(0.716379 y)(7.66 risk/Ci) = 2.198E-11 risk

(7.1405E-10 Ci/kg)(0.0365 kg/y ingested)(0.925376 y)(7.66 risk/Ci) = 1.847E-10 risk

Total lifetime cancer risk from soil ingestion = 2.067E-10

Ingestion Dose: (drinking water, Table A5)

(1.0E-12 Ci/L)(545 L)(1.462E6 mrem/Ci) = 7.965E-4 mrem

(3.0E-11 Ci/L)(545 L)(7.66 risk/Ci) = 4.501E-8 risk

Ingestion Dose: (garden produce, Section A5.0)

The intake factor for direct deposition of contaminants in irrigation water on foliage is calculated as shown in the table below.

| Vegetable | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Annual Food Consumption (kg/y) | Annual Water Intake ($m^2$) |
|---|---|---|---|---|---|---|
| leafy | 0.1036 | 18.02 | 1 | 2 | 4.45 | 0.01138 |
| other | 0.2877 | 19.96 | 0.1 | 2 | 21.625 | 0.017011 |
| fruit | 0.3107 | 19.96 | 0.1 | 3 | 21.45 | 0.012148 |
| grain | 0.0921 | 19.96 | 0.1 | 0.8 | 20.475 | 0.01289 |
| The Water Intake from Direct Deposition on Foliage is calculated as (Interception fraction)(Translocation Factor)(Growing Time)(Annual food eaten) / (Biomass) / (365 d/y) | | | | | | |

The ingestion dose calculation is shown below. Note that the first lines show doses from leafy vegetables while the second lines combine fruit and other vegetable intakes. The root uptake and rain splash soil intake numbers are from Section BB.2 (Suburban Garden). Also note that grains have been omitted because they are not irrigated.

Ingestion dose from root uptake and rain splash:

(3.6578E-12 Ci/kg)(72.0944 kg/y)(0.483081 y)(1.462E6 mrem/Ci) = 1.862E-4 mrem

(3.6578E-12 Ci/kg)( 9.9625 kg/y)(0.949678 y)(1.462E6 mrem/Ci) = 5.058E-5 mrem

Ingestion dose from direct deposition:

(1.646E-9 Ci/$m^2$ per y)(0.01138 $m^2$)(1 y)(1.462E6 mrem/Ci) = 2.738E-5 mrem

(4.938E-8 Ci/$m^2$ per y)(0.029159 $m^2$)(1 y)(1.462E6 mrem/Ci) = 7.015E-5 mrem

Total ingestion dose from garden vegetables = 3.343E-4 mrem

Ingestion risk from root uptake and rain splash:

(1.0973E-10 Ci/kg)(72.0944 kg/y)(0.483081 y)(3.996 risk/Ci) = 1.527E-8 risk

(1.0973E-10 Ci/kg)( 9.9625 kg/y)(0.949678 y)(3.996 risk/Ci) = 4.149E-9 risk

(7.1405E-10 Ci/kg)(72.0944 kg/y)(0.949678 y)(3.996 risk/Ci) = 1.954E-7 risk

(7.1405E-10 Ci/kg)( 9.9625 kg/y)(0.949249 y)(3.996 risk/Ci) = 2.698E-8 risk

Ingestion risk from direct deposition:

(4.938E-8 Ci/$m^2$ per y)(0.01138 $m^2$)(1 y)(3.996 risk/Ci) = 2.246E-9 risk

(4.938E-8 Ci/$m^2$ per y)(0.029159 $m^2$)(1 y)(3.996 risk/Ci) = 5.754E-9 risk

Total lifetime cancer risk from garden vegetables = 2.498E-7

Ingestion Dose: (beef, Section A4.0)

The dose for each pathway is the sum of contributions to the animal's diet. In particular, there is fresh feed (like leafy vegetables), stored hay (also like leafy vegetables, but is harvested and stored), stored grain (like grains), soil, and drinking water. The feed, hay, and grain have three components, root uptake, rain splash, and direct deposition. The direct deposition and rain splash are shown first.

| Direct Deposition Intake Factors for Beef Cattle | | | | | | |
|---|---|---|---|---|---|---|
| Animal Feed Type | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Daily Feed Intake by Animal (kg/d) | Annual Water Intake ($m^2$) |
| fresh forage | 0.1899 | 15.62 | 1 | 1.5 | 27 | 3.6789E-4 |
| stored hay | 0.1266 | 18.02 | 1 | 1 | 14 | 2.2007E-4 |
| stored grain | 0.0921 | 19.96 | 0.1 | 1 | 3 | 3.8000E-6 |
| water | | | | | 50 | 0.12575 |
| Rain Splash Intake Factors for Beef Cattle | | | | | | |
| Animal Feed Type | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Daily Feed Intake by Animal (kg/d) | Annual Soil Intake (kg/y) |
| fresh forage | 0.6160 | 15.62 | 1 | 1.5 | 27 | 1.1761E-04 |
| stored hay | 0.4717 | 18.02 | 1 | 1 | 14 | 8.0807E-05 |
| stored grain | 0.4717 | 19.96 | 0.1 | 1 | 3 | 1.9180E-06 |
| soil | | | | | 0.6 | 1.509E-03 |

For direct deposition, the last column shows the effective annual water intake by humans from direct deposition onto the vegetation eaten by the beef cattle. It is calculated using the formula below.

(Annual beef)(Transfer)(Interception)(Translocation)(Growing Time)(Daily feed) / (Yield) / (365 d/y)

For rain splash, the last column shows the effective annual soil intake by humans from rain splash onto the vegetation eaten by the beef cattle. It is calculated using the formula below.

(Annual beef)(Transfer)(Splash)(Interception)(Translocation)(Growing Time)(Daily feed) / (Yield)

The annual amount of contaminated beef eaten is 25.15 kg from Table A5. The equilibrium transfer factor for beef is 1.0E-4 d/kg from Table A36. The splash factor is 0.00027 $kg/m^2$ per day as discussed in Section A5.2. The annual soil intake by humans from soil eaten by the beef cattle (0.6 kg/d from Table A35) is calculated as

(Annual beef)(Transfer)(Soil intake)

The root uptake factor is calculated using the information in the table below.

| Root Uptake Intake Factors for Beef Cattle | | | | | |
|---|---|---|---|---|---|
| | Concentration Ratio for Tc | dry-to-wet ratio | Annual Food Consumption (kg/y) | Annual Soil Intake (kg/y) | Total Soil Intake (kg/y) |
| fresh forage | 180 | 0.22 | 25.15 | 2.689038 | 2.68916 |
| stored hay | 180 | 0.22 | 25.15 | 1.394316 | 1.3944 |
| stored grain | 0.73 | 0.22 | 25.15 | 0.0012117 | 0.0012136 |

The second last column shows the effective annual soil intake by humans from root uptake into the vegetation eaten by the beef cattle. It is calculated using the formula below.

(Annual beef)(Transfer)(Conc ratio)(dry-to-wet ratio)(Daily feed intake)

The daily feed intakes are shown in the previous table. The equilibrium transfer factor for beef is 1.0E-4 d/kg from Table A36.

The "Total Soil Intake" is the sum of the intakes from rain splash (previous table) and root uptake.

The calculation of ingestion dose the first year after the start of irrigation from the consumption of contaminated beef is summarized in the table below.

| Calculation of Ingestion Dose from Beef | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Dose Factor (mrem/Ci) | Annual Dose (mrem) |
| water | 1.0E-12 | 0.12575 | 0.999999 | 1.462E+06 | 1.838E-07 |
| soil | 3.6578E-12 | 0.001509 | 0.949678 | 1.462E+06 | 7.661E-09 |
| forage - root uptake & rain splash | 3.6578E-12 | 2.68916 | 0.949678 | 1.462E+06 | 1.365E-05 |
| forage - direct deposition | 1.6460E-09 | 3.6789E-04 | 0.999999 | 1.462E+06 | 8.850E-07 |
| stored hay - root uptake & rain splash | 3.6578E-12 | 1.3944 | 0.949677 | 1.462E+06 | 7.079E-06 |
| stored hay - direct deposition | 1.6460E-09 | 2.2007E-04 | 0.999999 | 1.462E+06 | 5.294E-07 |
| | | | | Total dose | 2.234E-05 |

The calculation of lifetime cancer risk from consumption of beef is summarized in the table below. The lower portion of the table has the contribution from residual contamination due to prior irrigation. The upper portion of the table shows the contribution from 30 years of active irrigation.

| Calculation of Lifetime Cancer Risk from Beef | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Risk Factor (risk/Ci) | Lifetime Cancer Risk |
| water | 3.0E-11 | 0.12575 | 0.999999 | 3.996 | 1.509E-11 |
| soil | 1.0973E-10 | 0.001509 | 0.949678 | 3.996 | 6.284E-13 |
| forage - root uptake & rain splash | 1.0973E-10 | 2.68916 | 0.949678 | 3.996 | 1.120E-09 |
| forage - direct deposition | 4.9380E-08 | 3.6789E-04 | 0.999999 | 3.996 | 7.259E-11 |
| stored hay - root uptake & rain splash | 1.0973E-10 | 1.3944 | 0.949677 | 3.996 | 5.807E-10 |
| stored hay - direct deposition | 4.9380E-08 | 2.2007E-04 | 0.999999 | 3.996 | 4.342E-11 |
| soil | 7.1405E-10 | 0.001509 | 0.949248 | 3.996 | 4.087E-12 |
| forage - root uptake & rain splash | 7.1405E-10 | 2.68916 | 0.949248 | 3.996 | 7.284E-09 |
| stored hay - root uptake & rain splash | 7.1405E-10 | 1.3944 | 0.949248 | 3.996 | 3.777E-09 |
| | | | | Total risk | 1.290E-08 |

Ingestion Dose: (milk, Section A4.0)

The dose for each pathway is calculated using the same approach as used for beef cattle.

| Direct Deposition Intake Factors for Milk Cows | | | | | | |
|---|---|---|---|---|---|---|
| Animal Feed Type | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Daily Feed Intake by Animal (kg/d) | Annual Water Intake ($m^2$) |
| fresh forage | 0.1899 | 15.62 | 1 | 1.5 | 36 | 1.5837E-03 |
| stored hay | 0.1266 | 18.02 | 1 | 1 | 29 | 1.4718E-03 |
| stored grain | 0.0921 | 19.96 | 0.1 | 1 | 2 | 8.1792E-06 |
| water | | | | | 60 | 0.48720 |
| Rain Splash Intake Factors for Milk Cows | | | | | | |
| Animal Feed Type | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Daily Feed Intake by Animal (kg/d) | Annual Soil Intake (kg/y) |
| fresh forage | 0.6160 | 15.62 | 1 | 1.5 | 36 | 5.0628E-04 |
| stored hay | 0.4717 | 18.02 | 1 | 1 | 29 | 5.4043E-04 |
| stored grain | 0.4717 | 19.96 | 0.1 | 1 | 2 | 4.1283E-06 |
| soil | | | | | 0.8 | 0.006496 |

For direct deposition, the last column shows the effective annual water intake by humans from direct deposition onto the vegetation eaten by the milk cow. It is calculated using the formula below.

(Annual milk)(Transfer)(Interception)(Translocation)(Growing Time)(Daily feed) / (Yield) / (365 d/y)

For rain splash, the last column shows the effective annual soil intake by humans from rain splash onto the vegetation eaten by the milk cow. It is calculated using the formula below.

(Annual milk)(Transfer)(Splash)(Interception)(Translocation)(Growing Time)(Daily feed) / (Yield)

The annual amount of contaminated milk intake is 58 kg from Table A5. The equilibrium transfer factor for milk is 1.4E-4 d/kg from Table A36. The splash factor is 0.00027 $kg/m^2$ per day as discussed in Section A5.2. The annual soil intake by humans from soil eaten by the milk cow (0.8 kg/d from Table A35) is calculated as

(Annual milk)(Transfer)(Soil intake)

| Root Uptake Intake Factors for Milk Cows | | | | | |
|---|---|---|---|---|---|
| | Concentration Ratio for Tc | dry-to-wet ratio | Annual Food Consumption (kg/y) | Annual Soil Intake (kg/y) | Total Soil Intake (kg/y) |
| fresh forage | 180 | 0.22 | 58 | 11.575872 | 11.576378 |
| stored hay | 180 | 0.22 | 58 | 9.325008 | 9.325548 |
| stored grain | 0.73 | 0.22 | 58 | 0.002608 | 0.0026121 |

The second last column shows the effective annual soil intake by humans from root uptake into the vegetation eaten by the milk cow. It is calculated using the formula below.

(Annual milk)(Transfer)(Conc ratio)(dry-to-wet ratio)(Daily feed intake)

The daily feed intakes are shown in the previous table. The equilibrium transfer factor for milk is 1.4E-4 d/kg from Table A36.

The "Total Soil Intake" is the sum of the intakes from rain splash (previous table) and root uptake.

The calculation of ingestion dose the first year after the start of irrigation from the consumption of contaminated milk is summarized in the table below.

| Calculation of Ingestion Dose from Milk | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Dose Factor (mrem/Ci) | Annual Dose (mrem) |
| water | 1.0E-12 | 0.4872 | 1 | 1.462E+06 | 7.120E-07 |
| soil | 3.6578E-12 | 0.006496 | 0.716379 | 1.462E+06 | 2.488E-08 |
| forage - root uptake & rain splash | 3.6578E-12 | 11.576378 | 0.716379 | 1.462E+06 | 4.433E-05 |
| forage - direct deposition | 1.6460E-09 | 1.5837E-03 | 1 | 1.462E+06 | 3.810E-06 |
| stored hay - root uptake & rain splash | 3.6578E-12 | 9.325548 | 0.949677 | 1.462E+06 | 4.734E-05 |
| stored hay - direct deposition | 1.6460E-09 | 1.4718E-03 | 0.999999 | 1.462E+06 | 3.541E-06 |
| | | | | Total dose | 9.977E-05 |

The calculation of lifetime cancer risk from consumption of milk is summarized in the table below. The lower portion of the table has the contribution from residual contamination due to prior irrigation. The upper portion of the table shows the contribution from 30 years of active irrigation.

| Calculation of Lifetime Cancer Risk from Milk | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Risk Factor (risk/Ci) | Lifetime Cancer Risk |
| water | 3.0E-11 | 0.4872 | 1 | 3.996 | 5.841E-11 |
| soil | 1.0973E-10 | 0.006496 | 0.716379 | 3.996 | 2.041E-12 |
| forage - root uptake & rain splash | 1.0973E-10 | 11.576378 | 0.716379 | 3.996 | 3.636E-09 |
| forage - direct deposition | 4.9380E-08 | 1.5837E-03 | 1 | 3.996 | 3.125E-10 |
| stored hay - root uptake & rain splash | 1.0973E-10 | 9.325548 | 0.949677 | 3.996 | 3.883E-09 |
| stored hay - direct deposition | 4.9380E-08 | 1.4718E-03 | 0.999999 | 3.996 | 2.904E-10 |
| soil | 7.1405E-10 | 0.006496 | 0.925376 | 3.996 | 1.715E-11 |
| forage - root uptake & rain splash | 7.1405E-10 | 11.576378 | 0.925376 | 3.996 | 3.057E-08 |
| stored hay - root uptake & rain splash | 7.1405E-10 | 9.325548 | 0.949248 | 3.996 | 2.526E-08 |
| | | | | Total risk | 6.403E-08 |

Ingestion Dose: (poultry, Section A4.0)

The dose for each pathway is calculated using the same approach as used for beef cattle.

| Direct Deposition Intake Factors for Poultry | | | | | | |
|---|---|---|---|---|---|---|
| Animal Feed Type | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Daily Feed Intake by Animal (kg/d) | Annual Water Intake ($m^2$) |
| fresh forage | 0.1899 | 15.62 | 1 | 1.5 | 0.13 | 3.106E-04 |
| stored hay | 0.1266 | 18.02 | 1 | 1 | 0 | 0 |
| stored grain | 0.0921 | 19.96 | 0.1 | 1 | 0.09 | 1.999E-05 |
| water | | | | | 0.3 | 0.1323 |
| Rain Splash Intake Factors for Poultry | | | | | | |
| Animal Feed Type | Interception Fraction | Effective Growing Period (days) | Trans-location Factor | Crop Yield ($kg/m^2$) | Daily Feed Intake by Animal (kg/d) | Annual Soil Intake (kg/y) |
| fresh forage | 0.6160 | 15.62 | 1 | 1.5 | 0.13 | 9.9292E-05 |
| stored hay | 0.4717 | 18.02 | 1 | 1 | 0 | 0 |
| stored grain | 0.4717 | 19.96 | 0.1 | 1 | 0.09 | 1.0090E-05 |
| soil | | | | | 0.011 | 0.004851 |

For direct deposition, the last column shows the effective annual water intake by humans from direct deposition onto the vegetation eaten by the chicken. It is calculated using the formula below.

(Annual poultry)(Transfer)(Interception)(Translocation)(Growing Time)(Daily feed) / (Yield) / (365 d/y)

For rain splash, the last column shows the effective annual soil intake by humans from rain splash onto the vegetation eaten by the chicken. It is calculated using the formula below.

(Annual poultry)(Transfer)(Splash)(Interception)(Translocation)(Growing Time)(Daily feed) / (Yield)

The annual amount of poultry intake is 11.7 kg from Table A5. The equilibrium transfer factor for poultry is 0.03 d/kg from Table A36. The splash factor is 0.00027 $kg/m^2$ per day as discussed in Section A5.2.

The annual soil intake by humans from soil eaten by the chicken (0.011 kg/d from Table A35) is calculated as

(Annual poultry)(Transfer)(Soil intake)

| Root Uptake Intake Factors for Poultry | | | | | |
|---|---|---|---|---|---|
| | Concentration Ratio for Tc | dry-to-wet ratio | Annual Food Consumption (kg/y) | Annual Soil Intake (kg/y) | Total Soil Intake (kg/y) |
| fresh forage | 180 | 0.22 | 14.7 | 2.270268 | 2.2703673 |
| stored hay | 180 | 0.22 | 14.7 | 0 | 0 |
| stored grain | 0.73 | 0.22 | 14.7 | 0.006374 | 0.0063841 |

The second last column shows the effective annual soil intake by humans from root uptake into the vegetation eaten by the chicken. It is calculated using the formula below.

(Annual poultry)(Transfer)(Conc ratio)(dry-to-wet ratio)(Daily feed intake)

The daily feed intakes are shown in the previous table. The equilibrium transfer factor for poultry is 0.03 d/kg from Table A36.

The "Total Soil Intake" is the sum of the intakes from rain splash (previous table) and root uptake.

The calculation of ingestion dose the first year after the start of irrigation from the consumption of contaminated poultry is summarized in the table below.

| Calculation of Ingestion Dose from Poultry | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Dose Factor (mrem/Ci) | Annual Dose (mrem) |
| water | 1.0E-12 | 0.1323 | 1 | 1.462E+06 | 1.934E-07 |
| soil | 3.6578E-12 | 0.004851 | 0.716379 | 1.462E+06 | 1.858E-08 |
| forage - root uptake & rain splash | 3.6578E-12 | 2.2703673 | 0.716379 | 1.462E+06 | 8.695E-06 |
| forage - direct deposition | 1.6460E-09 | 3.106E-04 | 1 | 1.462E+06 | 7.472E-07 |
| stored hay - root uptake & rain splash | 3.6578E-12 | 0 | 0.949677 | 1.462E+06 | 0 |
| stored hay - direct deposition | 1.6460E-09 | 0 | 0.999999 | 1.462E+06 | 0 |
| | | | | Total dose | 9.654E-06 |

The calculation of lifetime cancer risk from consumption of poultry is summarized in the table below. The lower portion of the table has the contribution from residual contamination due to prior irrigation. The upper portion of the table shows the contribution from 30 years of active irrigation.

| Calculation of Lifetime Cancer Risk from Poultry | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Risk Factor (risk/Ci) | Lifetime Cancer Risk |
| water | 3.0E-11 | 0.1323 | 1 | 3.996 | 1.586E-11 |
| soil | 1.0973E-10 | 0.004851 | 0.716379 | 3.996 | 1.524E-12 |
| forage - root uptake & rain splash | 1.0973E-10 | 2.2703673 | 0.716379 | 3.996 | 7.132E-10 |
| forage - direct deposition | 4.9380E-08 | 3.106E-04 | 1 | 3.996 | 6.129E-11 |
| stored hay - root uptake & rain splash | 1.0973E-10 | 0 | 0.949677 | 3.996 | 0 |
| stored hay - direct deposition | 4.9380E-08 | 0 | 0.999999 | 3.996 | 0 |
| soil | 7.1405E-10 | 0.004851 | 0.925376 | 3.996 | 1.281E-11 |
| forage - root uptake & rain splash | 7.1405E-10 | 2.2703673 | 0.925376 | 3.996 | 5.995E-09 |
| stored hay - root uptake & rain splash | 7.1405E-10 | 0 | 0.949248 | 3.996 | 0 |
| | | | | Total risk | 6.799E-09 |

Ingestion Dose: (eggs, Section A4.0)

The dose for each pathway is calculated using the same data used for poultry since both are chickens. The difference is only in the equilibrium transfer factor (3.0 d/kg for eggs) and the annual consumption (6.8 kg egg per year). These lead to different intake factors than the poultry tables. The resulting doses and risks are shown in the tables below.

| Calculation of Ingestion Dose from Eggs | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Dose Factor (mrem/Ci) | Annual Dose (mrem) |
| water | 1.0E-12 | 6.12 | 1 | 1.462E+06 | 8.944E-06 |
| soil | 3.6578E-12 | 0.2244 | 0.716379 | 1.462E+06 | 8.594E-07 |
| forage - root uptake & rain splash | 3.6578E-12 | 105.02379 | 0.716379 | 1.462E+06 | 4.022E-04 |
| forage - direct deposition | 1.6460E-09 | 1.4368E-02 | 1 | 1.462E+06 | 3.456E-05 |
| stored hay - root uptake & rain splash | 3.6578E-12 | 0 | 0.949677 | 1.462E+06 | 0 |
| stored hay - direct deposition | 1.6460E-09 | 0 | 0.999999 | 1.462E+06 | 0 |
| | | | | Total dose | 4.466E-04 |

| Calculation of Lifetime Cancer Risk from Eggs | | | | | |
|---|---|---|---|---|---|
| Component | Media Concentration | Intake Factor | Decay & Leaching Factor | Ingestion Risk Factor (risk/Ci) | Lifetime Cancer Risk |
| water | 3.0E-11 | 6.12 | 1 | 3.996 | 7.337E-10 |
| soil | 1.0973E-10 | 0.2244 | 0.716379 | 3.996 | 7.049E-11 |
| forage - root uptake & rain splash | 1.0973E-10 | 105.02379 | 0.716379 | 3.996 | 3.299E-08 |
| forage - direct deposition | 4.9380E-08 | 1.4368E-02 | 1 | 3.996 | 2.835E-09 |
| stored hay - root uptake & rain splash | 1.0973E-10 | 0 | 0.949677 | 3.996 | 0 |
| stored hay - direct deposition | 4.9380E-08 | 0 | 0.999999 | 3.996 | 0 |
| soil | 7.1405E-10 | 0.2244 | 0.925376 | 3.996 | 5.925E-10 |
| forage - root uptake & rain splash | 7.1405E-10 | 105.02379 | 0.925376 | 3.996 | 2.773E-07 |
| stored hay - root uptake & rain splash | 7.1405E-10 | 0 | 0.949248 | 3.996 | 0 |
| | | | | Total risk | 3.145E-07 |

Total dose and risk for the animal pathways:

2.234E-5 + 9.977E-5 + 9.654E-6 + 4.466E-4 = 5.783E-4 mrem
1.290E-8 + 6.403E-8 + 6.799E-9 + 3.145E-7 = 3.983E-7

Total Dose for the All Pathways Farmer (irrigation from a well):

9.158E-9 + 1.176E-8 + 1.542E-7 + 1.398E-7 + 7.965E-4 + 3.343E-4 + 5.783E-4 mrem = 1.709E-3 mrem per pCi/L

Note that the all pathways farmer's total dose factor from Table 12 is 1.71E-3 mrem/y per pCi/L.

Total Lifetime Cancer Risk for the All Pathways Farmer (irrigation from a well):

4.652E-13 + 5.618E-12 + 2.828E-11 + 2.067E-10 + 4.501E-8 + 2.498E-7 + 3.983E-7 = 6.933E-7 per pCi/L

Note that the all pathways farmer's total risk factor from Table 14 is 6.94E-7 per pCi/L.

The above total applies to the inland well situation in which does not include a dose from fish. When the Columbia River is the source of Tc-99, the fish dose is calculated as shown below and added to the above total. The concentration ratio for technetium in fish is 20 L/kg. The intake factor is this concentration ratio multiplied by the annual intake of fish, 3.29 kg.

Ingestion Dose: (fish, Table A5)

(1.0E-12 Ci/L)(65.8 L)(1.462E6 mrem/Ci) = 9.617E-5 mrem
(3.0E-11 Ci/L)(65.8 L)(3.996 risk/Ci) = 7.888E-9 risk

Note that the all pathways farmer's fish dose factor from Table 11 is 9.62E-5 mrem/y per pCi/L.

The cumulative concentration of Tc-99 in sediment after a 20-year accumulation period is calculated as shown below. The first three rows are for a one-year exposure. The second three rows are for a 30-year exposure.

Exp[-(20)(0.208336 $y^{-1}$)] = 0.0155030 Exp[-(21)(0.208336 $y^{-1}$)] = 0.0125874
1-year case = [(1y) - (0.0155030 - 0.0125874)/(0.208336 $y^{-1}$)]/(0.208336) = 4.73277 y
Sediment Conc = (1.0E-12 Ci/L)(25,300 L/$m^2$/y)(4.73277 y) = 1.1974E-7 Ci/$m^2$

Exp[-(50)(0.208336 $y^{-1}$)] = 0.00002993
30-year case = [(30y) - (0.0155030 - 0.00002993)/(0.208336 $y^{-1}$)]/(0.208336) = 143.642 y
Sediment Conc = (1.0E-12 Ci/L)(25,300 L/$m^2$/y)(4.73277 y) = 3.6341E-6 Ci/$m^2$

External Dose: (shoreline sediment)

(1.197E-7 Ci/$m^2$)(11 h)(0.06346 mrem/h per Ci/$m^2$) = 8.359E-8 mrem
(3.634E-6 Ci/$m^2$)(11 h)(4.13E-8 risk/h per Ci/$m^2$) = 1.649E-12 risk

Ingestion Dose: (soil only, Table A8)

Note that the sediment concentrations used for external dose are divided by 225 kg/$m^2$ to convert them into mass concentrations (Ci/kg).

(5.322E-10 Ci/kg)(0.0007 kg)(1.462E6 mrem/Ci) = 5.444E-7 mrem
(1.615E-8 Ci/kg)(0.0007 kg)(7.66 risk/Ci) = 8.661E-11 risk

Total Dose for the All Pathways Farmer (irrigation from the Columbia River):

1.709E-3 + 9.617E-5 + 8.359E-8 + 5.444E-7 = 1.806E-3 mrem per pCi/L

Note that the all pathways farmer's total dose factor from Table 13 is 1.81E-3 mrem/y per pCi/L.

Total Lifetime Cancer Risk for the All Pathways Farmer (irrigation from the Columbia River):

6.933E-7 + 7.888E-9 + 1.649E-12 + 8.661E-11 = 7.012E-7 per pCi/L

Note that the all pathways farmer's total dose factor from Table 14 is 7.02E-7 per pCi/L.

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# APPENDIX C

# COMPARISON OF ALL PATHWAYS FARMER UNIT DOSE FACTORS

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## COMPARISON OF ALL PATHWAYS FARMER UNIT DOSE FACTORS

This appendix presents two alternate methods for calculating the unit dose factors for the All Pathways Farmer scenario described in Section 3.5. These alternate methods explore the effect of the accumulation of radioactivity in the soil as the well is being used year after year.

The first method uses a preliminary irrigation period ranging from 10 to 100 years. The well is used each year to irrigate fields and pastures, so that the radioactivity can accumulate in the soil before the dose factors are calculated. The farmer is exposed during the 1$^{st}$, 11$^{th}$, 21$^{st}$, 31$^{st}$, 41$^{st}$, 51$^{st}$, 71$^{st}$, or 101$^{th}$ year, and then moves away from the farm. Because the performance objective for radiation exposure is the annual dose, total doses over several years of exposure are not computed.

The second method calculates the average annual dose using an averaging periods of 10, 20, 30, 40, 50, 70, and 100 years. In this approach the farmer lives in an increasingly contaminated setting. The average dose over the selected period is used for the unit dose factor.

Table C1 shows the All Pathways Farmer unit dose factors as radioactivity accumulates in the soil due to irrigation. Table C2 shows the unit dose factor ratios between the later years and the first year. Many nuclides (e.g., H-3, Ru-106, and TRU) show little increase during the first 100 years. Some nuclides (e.g., K-40, Sr-90, Tc-99, and Cs-137) reach a steady state where annual additions from irrigation water are balanced by annual losses from radioactive decay and leaching. A few nuclides (e.g., Al-26, Nb-94, Ag-108, and Ho-166m) show significant accumulation even after 100 years.

### TABLE C1. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS PRELIMINARY IRRIGATION PERIODS

| Nuclide | Year of Exposure for the Unit Dose Factor (mrem/y per pCi/L) – Groundwater Only | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1$^{st}$ year | 11$^{th}$ year | 21$^{st}$ year | 31$^{st}$ year | 41$^{st}$ year | 51$^{st}$ year | 71$^{st}$ year | 101$^{st}$ year |
| H-3 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 |
| Be-10 | 2.95E-03 | 3.00E-03 | 3.05E-03 | 3.10E-03 | 3.15E-03 | 3.20E-03 | 3.30E-03 | 3.44E-03 |
| C-14 | 3.68E-03 | 5.27E-03 | 6.43E-03 | 7.28E-03 | 7.90E-03 | 8.35E-03 | 8.93E-03 | 9.33E-03 |
| Na-22 | 3.83E-02 | 9.77E-02 | 1.02E-01 | 1.02E-01 | 1.02E-01 | 1.02E-01 | 1.02E-01 | 1.02E-01 |
| Al-26 | 2.81E-02 | 2.76E-01 | 5.24E-01 | 7.72E-01 | 1.02E+00 | 1.27E+00 | 1.76E+00 | 2.49E+00 |
| Si-32+D | 6.90E-03 | 7.49E-03 | 8.00E-03 | 8.46E-03 | 8.87E-03 | 9.24E-03 | 9.84E-03 | 1.05E-02 |
| Cl-36 | 2.33E-02 | 1.11E-01 | 1.23E-01 | 1.25E-01 | 1.25E-01 | 1.25E-01 | 1.25E-01 | 1.25E-01 |
| K-40 | 2.32E-02 | 4.66E-02 | 6.54E-02 | 8.05E-02 | 9.26E-02 | 1.02E-01 | 1.16E-01 | 1.29E-01 |
| Ca-41 | 1.03E-03 | 1.66E-03 | 2.16E-03 | 2.55E-03 | 2.85E-03 | 3.09E-03 | 3.42E-03 | 3.70E-03 |
| Ti-44+D | 4.80E-02 | 2.39E-01 | 4.09E-01 | 5.60E-01 | 6.95E-01 | 8.14E-01 | 1.01E+00 | 1.24E+00 |
| V-49 | 3.95E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 |
| Mn-53 | 6.80E-05 | 7.87E-05 | 8.94E-05 | 1.00E-04 | 1.11E-04 | 1.22E-04 | 1.43E-04 | 1.75E-04 |
| Mn-54 | 6.02E-03 | 1.12E-02 | 1.12E-02 | 1.12E-02 | 1.12E-02 | 1.12E-02 | 1.12E-02 | 1.12E-02 |
| Fe-55 | 5.16E-04 | 5.21E-04 | 5.21E-04 | 5.21E-04 | 5.21E-04 | 5.21E-04 | 5.21E-04 | 5.21E-04 |
| Fe-60+D | 1.33E-01 | 2.52E-01 | 4.55E-01 | 6.79E-01 | 9.08E-01 | 1.14E+00 | 1.60E+00 | 2.29E+00 |

## TABLE C1. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS PRELIMINARY IRRIGATION PERIODS

| Nuclide | Year of Exposure for the Unit Dose Factor (mrem/y per pCi/L) – Groundwater Only | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1st year | 11th year | 21st year | 31st year | 41st year | 51st year | 71st year | 101st year |
| Co-60 | 3.75E-02 | 1.54E-01 | 1.84E-01 | 1.92E-01 | 1.94E-01 | 1.94E-01 | 1.94E-01 | 1.94E-01 |
| Ni-59 | 2.74E-04 | 2.93E-04 | 3.11E-04 | 3.30E-04 | 3.49E-04 | 3.68E-04 | 4.05E-04 | 4.61E-04 |
| Ni-63 | 7.53E-04 | 8.03E-04 | 8.49E-04 | 8.92E-04 | 9.33E-04 | 9.70E-04 | 1.04E-03 | 1.12E-03 |
| Se-79 | 1.06E-02 | 1.12E-02 | 1.15E-02 | 1.15E-02 | 1.16E-02 | 1.16E-02 | 1.16E-02 | 1.16E-02 |
| Rb-87 | 6.60E-03 | 1.05E-02 | 1.43E-02 | 1.80E-02 | 2.15E-02 | 2.48E-02 | 3.12E-02 | 3.97E-02 |
| Sr-90+D | 1.34E-01 | 2.23E-01 | 2.92E-01 | 3.46E-01 | 3.88E-01 | 4.20E-01 | 4.65E-01 | 5.02E-01 |
| Zr-93 | 1.01E-03 | 1.02E-03 | 1.03E-03 | 1.04E-03 | 1.05E-03 | 1.06E-03 | 1.08E-03 | 1.11E-03 |
| Nb-91 | 3.34E-04 | 5.30E-04 | 7.22E-04 | 9.08E-04 | 1.09E-03 | 1.27E-03 | 1.61E-03 | 2.10E-03 |
| Nb-93m | 3.20E-04 | 3.24E-04 | 3.27E-04 | 3.29E-04 | 3.30E-04 | 3.31E-04 | 3.32E-04 | 3.32E-04 |
| Nb-94 | 1.53E-02 | 1.60E-01 | 3.02E-01 | 4.42E-01 | 5.81E-01 | 7.17E-01 | 9.84E-01 | 1.37E+00 |
| Mo-93 | 1.02E-03 | 1.44E-03 | 1.76E-03 | 2.00E-03 | 2.17E-03 | 2.31E-03 | 2.48E-03 | 2.60E-03 |
| Tc-97 | 2.01E-04 | 9.91E-04 | 1.27E-03 | 1.37E-03 | 1.40E-03 | 1.42E-03 | 1.42E-03 | 1.42E-03 |
| Tc-99 | 1.71E-03 | 8.38E-03 | 1.07E-02 | 1.16E-02 | 1.19E-02 | 1.20E-02 | 1.20E-02 | 1.20E-02 |
| Ru-106+D | 3.09E-02 | 3.30E-02 | 3.30E-02 | 3.30E-02 | 3.30E-02 | 3.30E-02 | 3.30E-02 | 3.30E-02 |
| Pd-107 | 1.58E-04 | 1.72E-04 | 1.84E-04 | 1.97E-04 | 2.09E-04 | 2.20E-04 | 2.42E-04 | 2.71E-04 |
| Ag-108m+D | 1.64E-02 | 1.61E-01 | 3.01E-01 | 4.34E-01 | 5.63E-01 | 6.86E-01 | 9.18E-01 | 1.23E+00 |
| Cd-109+D | 8.88E-03 | 9.08E-03 | 9.08E-03 | 9.08E-03 | 9.08E-03 | 9.08E-03 | 9.08E-03 | 9.08E-03 |
| Cd-113m | 1.10E-01 | 1.21E-01 | 1.28E-01 | 1.32E-01 | 1.34E-01 | 1.36E-01 | 1.37E-01 | 1.37E-01 |
| In-115 | 1.13E-01 | 1.15E-01 | 1.17E-01 | 1.19E-01 | 1.21E-01 | 1.23E-01 | 1.26E-01 | 1.32E-01 |
| Sn-121m+D | 3.47E-03 | 3.67E-03 | 3.84E-03 | 3.99E-03 | 4.11E-03 | 4.22E-03 | 4.38E-03 | 4.55E-03 |
| Sn-126+D | 4.61E-02 | 2.29E-01 | 4.12E-01 | 5.94E-01 | 7.76E-01 | 9.57E-01 | 1.32E+00 | 1.86E+00 |
| Sb-125 | 4.37E-03 | 1.59E-02 | 1.68E-02 | 1.69E-02 | 1.69E-02 | 1.69E-02 | 1.69E-02 | 1.69E-02 |
| Te-125m | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 |
| I-129 | 4.00E-01 | 4.24E-01 | 4.44E-01 | 4.62E-01 | 4.77E-01 | 4.91E-01 | 5.12E-01 | 5.34E-01 |
| Cs-134 | 1.19E-01 | 1.58E-01 | 1.59E-01 | 1.60E-01 | 1.60E-01 | 1.60E-01 | 1.60E-01 | 1.60E-01 |
| Cs-135 | 1.10E-02 | 1.41E-02 | 1.72E-02 | 2.04E-02 | 2.35E-02 | 2.66E-02 | 3.28E-02 | 4.21E-02 |
| Cs-137+D | 8.14E-02 | 1.46E-01 | 1.98E-01 | 2.39E-01 | 2.71E-01 | 2.97E-01 | 3.33E-01 | 3.64E-01 |
| Ba-133 | 4.50E-03 | 2.63E-02 | 3.71E-02 | 4.25E-02 | 4.52E-02 | 4.65E-02 | 4.76E-02 | 4.78E-02 |
| Ce-144+D | 1.31E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 |
| Pm-147 | 6.94E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 |
| Sm-147 | 1.24E-01 | 1.27E-01 | 1.29E-01 | 1.32E-01 | 1.35E-01 | 1.37E-01 | 1.43E-01 | 1.50E-01 |
| Sm-151 | 2.60E-04 | 2.63E-04 | 2.66E-04 | 2.68E-04 | 2.71E-04 | 2.73E-04 | 2.77E-04 | 2.81E-04 |
| Eu-150 | 1.42E-02 | 1.35E-01 | 2.34E-01 | 3.17E-01 | 3.84E-01 | 4.41E-01 | 5.25E-01 | 6.04E-01 |
| Eu-152 | 1.19E-02 | 8.97E-02 | 1.36E-01 | 1.64E-01 | 1.80E-01 | 1.90E-01 | 1.99E-01 | 2.04E-01 |
| Eu-154 | 1.46E-02 | 8.76E-02 | 1.20E-01 | 1.34E-01 | 1.41E-01 | 1.44E-01 | 1.46E-01 | 1.46E-01 |
| Eu-155 | 1.24E-03 | 2.72E-03 | 3.06E-03 | 3.14E-03 | 3.16E-03 | 3.17E-03 | 3.17E-03 | 3.17E-03 |
| Gd-152 | 1.05E-01 | 1.11E-01 | 1.17E-01 | 1.22E-01 | 1.28E-01 | 1.34E-01 | 1.45E-01 | 1.62E-01 |
| Tb-157 | 8.58E-05 | 1.34E-04 | 1.77E-04 | 2.16E-04 | 2.52E-04 | 2.84E-04 | 3.39E-04 | 4.03E-04 |
| Ho-166m | 1.71E-02 | 1.73E-01 | 3.27E-01 | 4.79E-01 | 6.28E-01 | 7.75E-01 | 1.06E+00 | 1.48E+00 |
| Re-187 | 7.54E-06 | 1.06E-05 | 1.35E-05 | 1.64E-05 | 1.92E-05 | 2.19E-05 | 2.72E-05 | 3.45E-05 |
| Tl-204 | 3.78E-03 | 3.85E-03 | 3.87E-03 | 3.87E-03 | 3.87E-03 | 3.87E-03 | 3.87E-03 | 3.87E-03 |

## TABLE C1. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS PRELIMINARY IRRIGATION PERIODS

| Nuclide | Year of Exposure for the Unit Dose Factor (mrem/y per pCi/L) – Groundwater Only | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1st year | 11th year | 21st year | 31st year | 41st year | 51st year | 71st year | 101st year |
| Pb-205 | 1.04E-03 | 1.06E-03 | 1.07E-03 | 1.09E-03 | 1.10E-03 | 1.12E-03 | 1.14E-03 | 1.19E-03 |
| Pb-210+D | 3.49E+00 | 3.58E+00 | 3.65E+00 | 3.70E+00 | 3.74E+00 | 3.76E+00 | 3.80E+00 | 3.82E+00 |
| Bi-207 | 1.39E-02 | 1.38E-01 | 2.37E-01 | 3.18E-01 | 3.83E-01 | 4.36E-01 | 5.13E-01 | 5.81E-01 |
| Po-209 | 1.83E+00 | 1.90E+00 | 1.97E+00 | 2.04E+00 | 2.10E+00 | 2.15E+00 | 2.25E+00 | 2.38E+00 |
| Po-210 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 |
| Ra-226+D | 9.08E-01 | 1.10E+00 | 1.31E+00 | 1.54E+00 | 1.78E+00 | 2.03E+00 | 2.54E+00 | 3.32E+00 |
| Ra-228+D | 9.76E-01 | 1.10E+00 | 1.15E+00 | 1.17E+00 | 1.17E+00 | 1.18E+00 | 1.18E+00 | 1.18E+00 |
| Ac-227+D | 9.05E+00 | 9.13E+00 | 9.18E+00 | 9.22E+00 | 9.25E+00 | 9.27E+00 | 9.29E+00 | 9.31E+00 |
| Th-228+D | 5.05E-01 | 5.36E-01 | 5.36E-01 | 5.36E-01 | 5.36E-01 | 5.36E-01 | 5.36E-01 | 5.36E-01 |
| Th-229+D | 2.47E+00 | 2.54E+00 | 2.61E+00 | 2.67E+00 | 2.74E+00 | 2.81E+00 | 2.94E+00 | 3.14E+00 |
| Th-230 | 3.36E-01 | 3.43E-01 | 3.50E-01 | 3.59E-01 | 3.68E-01 | 3.78E-01 | 4.02E-01 | 4.45E-01 |
| Th-232 | 1.68E+00 | 1.80E+00 | 2.03E+00 | 2.29E+00 | 2.57E+00 | 2.85E+00 | 3.41E+00 | 4.25E+00 |
| Pa-231 | 6.48E+00 | 6.54E+00 | 6.62E+00 | 6.71E+00 | 6.81E+00 | 6.91E+00 | 7.15E+00 | 7.51E+00 |
| U-232 | 8.72E-01 | 9.88E-01 | 1.09E+00 | 1.15E+00 | 1.20E+00 | 1.23E+00 | 1.26E+00 | 1.28E+00 |
| U-233 | 1.92E-01 | 1.96E-01 | 1.98E-01 | 2.01E-01 | 2.02E-01 | 2.03E-01 | 2.05E-01 | 2.07E-01 |
| U-234 | 1.88E-01 | 1.92E-01 | 1.94E-01 | 1.96E-01 | 1.98E-01 | 1.99E-01 | 2.00E-01 | 2.01E-01 |
| U-235+D | 1.78E-01 | 1.92E-01 | 2.03E-01 | 2.10E-01 | 2.16E-01 | 2.20E-01 | 2.25E-01 | 2.29E-01 |
| U-236 | 1.78E-01 | 1.82E-01 | 1.84E-01 | 1.86E-01 | 1.88E-01 | 1.89E-01 | 1.90E-01 | 1.91E-01 |
| U-238+D | 1.78E-01 | 1.83E-01 | 1.87E-01 | 1.90E-01 | 1.92E-01 | 1.93E-01 | 1.95E-01 | 1.97E-01 |
| Np-237+D | 2.77E+00 | 2.83E+00 | 2.89E+00 | 2.94E+00 | 2.98E+00 | 3.02E+00 | 3.10E+00 | 3.18E+00 |
| Pu-236 | 7.12E-01 | 7.17E-01 | 7.21E-01 | 7.25E-01 | 7.27E-01 | 7.28E-01 | 7.30E-01 | 7.31E-01 |
| Pu-238 | 1.96E+00 | 1.97E+00 | 1.99E+00 | 2.00E+00 | 2.01E+00 | 2.02E+00 | 2.03E+00 | 2.06E+00 |
| Pu-239 | 2.17E+00 | 2.18E+00 | 2.20E+00 | 2.21E+00 | 2.23E+00 | 2.24E+00 | 2.27E+00 | 2.32E+00 |
| Pu-240 | 2.17E+00 | 2.18E+00 | 2.20E+00 | 2.21E+00 | 2.23E+00 | 2.24E+00 | 2.27E+00 | 2.32E+00 |
| Pu-241+D | 4.19E-02 | 4.23E-02 | 4.27E-02 | 4.32E-02 | 4.37E-02 | 4.42E-02 | 4.52E-02 | 4.66E-02 |
| Pu-242 | 2.06E+00 | 2.07E+00 | 2.09E+00 | 2.10E+00 | 2.12E+00 | 2.13E+00 | 2.16E+00 | 2.20E+00 |
| Pu-244+D | 2.04E+00 | 2.08E+00 | 2.13E+00 | 2.17E+00 | 2.22E+00 | 2.26E+00 | 2.35E+00 | 2.49E+00 |
| Am-241 | 2.23E+00 | 2.25E+00 | 2.26E+00 | 2.28E+00 | 2.30E+00 | 2.31E+00 | 2.34E+00 | 2.38E+00 |
| Am-242m+D | 2.16E+00 | 2.17E+00 | 2.19E+00 | 2.22E+00 | 2.24E+00 | 2.27E+00 | 2.32E+00 | 2.41E+00 |
| Am-243+D | 2.22E+00 | 2.25E+00 | 2.28E+00 | 2.32E+00 | 2.35E+00 | 2.38E+00 | 2.44E+00 | 2.53E+00 |
| Cm-242 | 6.95E-02 | 6.96E-02 | 6.96E-02 | 6.97E-02 | 6.98E-02 | 6.98E-02 | 6.99E-02 | 7.00E-02 |
| Cm-243 | 1.54E+00 | 1.56E+00 | 1.57E+00 | 1.58E+00 | 1.59E+00 | 1.60E+00 | 1.61E+00 | 1.62E+00 |
| Cm-244 | 1.24E+00 | 1.24E+00 | 1.25E+00 | 1.25E+00 | 1.25E+00 | 1.26E+00 | 1.26E+00 | 1.26E+00 |
| Cm-245 | 2.29E+00 | 2.31E+00 | 2.34E+00 | 2.36E+00 | 2.38E+00 | 2.40E+00 | 2.45E+00 | 2.52E+00 |
| Cm-246 | 2.27E+00 | 2.28E+00 | 2.30E+00 | 2.32E+00 | 2.33E+00 | 2.35E+00 | 2.38E+00 | 2.43E+00 |
| Cm-247+D | 2.10E+00 | 2.14E+00 | 2.19E+00 | 2.23E+00 | 2.28E+00 | 2.32E+00 | 2.41E+00 | 2.54E+00 |
| Cm-248 | 8.35E+00 | 8.41E+00 | 8.47E+00 | 8.53E+00 | 8.59E+00 | 8.64E+00 | 8.76E+00 | 8.94E+00 |
| Cm-250+D | 4.76E+01 | 4.80E+01 | 4.84E+01 | 4.87E+01 | 4.91E+01 | 4.95E+01 | 5.02E+01 | 5.13E+01 |
| Bk-247 | 2.88E+00 | 2.91E+00 | 2.94E+00 | 2.96E+00 | 2.99E+00 | 3.02E+00 | 3.07E+00 | 3.15E+00 |
| Cf-248 | 2.19E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 | 2.21E-01 | 2.21E-01 | 2.21E-01 |
| Cf-249 | 3.16E+00 | 3.25E+00 | 3.33E+00 | 3.40E+00 | 3.48E+00 | 3.56E+00 | 3.70E+00 | 3.90E+00 |

## TABLE C1. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS PRELIMINARY IRRIGATION PERIODS

| Nuclide | Year of Exposure for the Unit Dose Factor (mrem/y per pCi/L) – Groundwater Only | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1st year | 11th year | 21st year | 31st year | 41st year | 51st year | 71st year | 101st year |
| Cf-250 | 1.42E+00 | 1.44E+00 | 1.45E+00 | 1.46E+00 | 1.46E+00 | 1.46E+00 | 1.46E+00 | 1.46E+00 |
| Cf-251 | 3.24E+00 | 3.30E+00 | 3.36E+00 | 3.42E+00 | 3.49E+00 | 3.55E+00 | 3.66E+00 | 3.84E+00 |
| Cf-252 | 7.18E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 |

The prior irrigation periods are 0, 10, 20, 30, 40, 50, 70, and 100 years. The exposure period is 1 year.
The unit dose factors in the first column are the same as the ones shown in Table 12.

## TABLE C2. COMPARISON RATIOS FOR VARIOUS PRELIMINARY IRRIGATION PERIODS

| Nuclide | Preliminary Irrigation Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 years | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| H-3 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Be-10 | 1.00 | 1.02 | 1.03 | 1.05 | 1.07 | 1.09 | 1.12 | 1.17 |
| C-14 | 1.00 | 1.43 | 1.75 | 1.98 | 2.15 | 2.27 | 2.43 | 2.54 |
| Na-22 | 1.00 | 2.55 | 2.66 | 2.66 | 2.67 | 2.67 | 2.67 | 2.67 |
| Al-26 | 1.00 | 9.83 | 18.65 | 27.45 | 36.24 | 45.02 | 62.53 | 88.71 |
| Si-32+D | 1.00 | 1.08 | 1.16 | 1.23 | 1.29 | 1.34 | 1.43 | 1.52 |
| Cl-36 | 1.00 | 4.75 | 5.28 | 5.35 | 5.36 | 5.36 | 5.36 | 5.36 |
| K-40 | 1.00 | 2.01 | 2.82 | 3.47 | 3.99 | 4.41 | 5.02 | 5.55 |
| Ca-41 | 1.00 | 1.62 | 2.10 | 2.48 | 2.78 | 3.01 | 3.34 | 3.61 |
| Ti-44+D | 1.00 | 4.98 | 8.53 | 11.67 | 14.47 | 16.96 | 21.14 | 25.82 |
| V-49 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mn-53 | 1.00 | 1.16 | 1.32 | 1.47 | 1.63 | 1.79 | 2.10 | 2.57 |
| Mn-54 | 1.00 | 1.87 | 1.87 | 1.87 | 1.87 | 1.87 | 1.87 | 1.87 |
| Fe-55 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| Fe-60+D | 1.00 | 1.90 | 3.42 | 5.11 | 6.83 | 8.57 | 12.05 | 17.26 |
| Co-60 | 1.00 | 4.10 | 4.90 | 5.11 | 5.16 | 5.18 | 5.18 | 5.18 |
| Ni-59 | 1.00 | 1.07 | 1.14 | 1.21 | 1.27 | 1.34 | 1.48 | 1.68 |
| Ni-63 | 1.00 | 1.07 | 1.13 | 1.18 | 1.24 | 1.29 | 1.38 | 1.49 |
| Se-79 | 1.00 | 1.06 | 1.08 | 1.08 | 1.09 | 1.09 | 1.09 | 1.09 |
| Rb-87 | 1.00 | 1.60 | 2.17 | 2.72 | 3.25 | 3.76 | 4.72 | 6.02 |
| Sr-90+D | 1.00 | 1.67 | 2.19 | 2.59 | 2.90 | 3.15 | 3.48 | 3.75 |
| Zr-93 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.06 | 1.09 |
| Nb-91 | 1.00 | 1.59 | 2.16 | 2.72 | 3.26 | 3.80 | 4.83 | 6.28 |
| Nb-93m | 1.00 | 1.01 | 1.02 | 1.03 | 1.03 | 1.04 | 1.04 | 1.04 |
| Nb-94 | 1.00 | 10.45 | 19.77 | 28.95 | 38.00 | 46.93 | 64.41 | 89.71 |
| Mo-93 | 1.00 | 1.42 | 1.73 | 1.97 | 2.14 | 2.27 | 2.44 | 2.56 |
| Tc-97 | 1.00 | 4.92 | 6.31 | 6.80 | 6.97 | 7.03 | 7.06 | 7.06 |
| Tc-99 | 1.00 | 4.90 | 6.28 | 6.77 | 6.94 | 7.00 | 7.03 | 7.03 |
| Ru-106+D | 1.00 | 1.07 | 1.07 | 1.07 | 1.07 | 1.07 | 1.07 | 1.07 |
| Pd-107 | 1.00 | 1.08 | 1.17 | 1.25 | 1.32 | 1.39 | 1.53 | 1.71 |
| Ag-108m+D | 1.00 | 9.84 | 18.33 | 26.48 | 34.31 | 41.82 | 55.98 | 75.17 |

## TABLE C2. COMPARISON RATIOS FOR VARIOUS PRELIMINARY IRRIGATION PERIODS

| Nuclide | Preliminary Irrigation Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 years | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| Cd-109+D | 1.00 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| Cd-113m | 1.00 | 1.10 | 1.17 | 1.20 | 1.22 | 1.24 | 1.25 | 1.25 |
| In-115 | 1.00 | 1.02 | 1.03 | 1.05 | 1.07 | 1.08 | 1.12 | 1.17 |
| Sn-121m+D | 1.00 | 1.06 | 1.11 | 1.15 | 1.18 | 1.21 | 1.26 | 1.31 |
| Sn-126+D | 1.00 | 4.97 | 8.93 | 12.88 | 16.82 | 20.76 | 28.59 | 40.27 |
| Sb-125 | 1.00 | 3.64 | 3.85 | 3.87 | 3.87 | 3.87 | 3.87 | 3.87 |
| Te-125m | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| I-129 | 1.00 | 1.06 | 1.11 | 1.15 | 1.19 | 1.23 | 1.28 | 1.33 |
| Cs-134 | 1.00 | 1.33 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 |
| Cs-135 | 1.00 | 1.28 | 1.57 | 1.85 | 2.13 | 2.41 | 2.98 | 3.82 |
| Cs-137+D | 1.00 | 1.80 | 2.43 | 2.93 | 3.33 | 3.64 | 4.09 | 4.47 |
| Ba-133 | 1.00 | 5.83 | 8.24 | 9.44 | 10.04 | 10.34 | 10.56 | 10.62 |
| Ce-144+D | 1.00 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| Pm-147 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Sm-147 | 1.00 | 1.02 | 1.04 | 1.07 | 1.09 | 1.11 | 1.15 | 1.21 |
| Sm-151 | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 | 1.08 |
| Eu-150 | 1.00 | 9.46 | 16.45 | 22.22 | 26.99 | 30.92 | 36.86 | 42.42 |
| Eu-152 | 1.00 | 7.52 | 11.41 | 13.73 | 15.12 | 15.94 | 16.73 | 17.07 |
| Eu-154 | 1.00 | 6.00 | 8.23 | 9.22 | 9.66 | 9.86 | 9.98 | 10.01 |
| Eu-155 | 1.00 | 2.20 | 2.47 | 2.54 | 2.55 | 2.56 | 2.56 | 2.56 |
| Gd-152 | 1.00 | 1.05 | 1.11 | 1.16 | 1.22 | 1.27 | 1.38 | 1.54 |
| Tb-157 | 1.00 | 1.56 | 2.06 | 2.52 | 2.93 | 3.31 | 3.95 | 4.70 |
| Ho-166m | 1.00 | 10.11 | 19.08 | 27.92 | 36.62 | 45.20 | 61.97 | 86.19 |
| Re-187 | 1.00 | 1.40 | 1.80 | 2.18 | 2.55 | 2.91 | 3.60 | 4.57 |
| Tl-204 | 1.00 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| Pb-205 | 1.00 | 1.01 | 1.03 | 1.04 | 1.06 | 1.07 | 1.10 | 1.14 |
| Pb-210+D | 1.00 | 1.03 | 1.05 | 1.06 | 1.07 | 1.08 | 1.09 | 1.09 |
| Bi-207 | 1.00 | 9.89 | 17.07 | 22.87 | 27.56 | 31.35 | 36.88 | 41.80 |
| Po-209 | 1.00 | 1.04 | 1.08 | 1.11 | 1.15 | 1.18 | 1.23 | 1.30 |
| Po-210 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Ra-226+D | 1.00 | 1.21 | 1.45 | 1.70 | 1.96 | 2.24 | 2.80 | 3.65 |
| Ra-228+D | 1.00 | 1.13 | 1.18 | 1.20 | 1.20 | 1.20 | 1.21 | 1.21 |
| Ac-227+D | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 | 1.03 | 1.03 |
| Th-228+D | 1.00 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 |
| Th-229+D | 1.00 | 1.03 | 1.05 | 1.08 | 1.11 | 1.14 | 1.19 | 1.27 |
| Th-230 | 1.00 | 1.02 | 1.04 | 1.07 | 1.10 | 1.13 | 1.20 | 1.33 |
| Th-232 | 1.00 | 1.07 | 1.21 | 1.37 | 1.53 | 1.70 | 2.03 | 2.53 |
| Pa-231 | 1.00 | 1.01 | 1.02 | 1.03 | 1.05 | 1.07 | 1.10 | 1.16 |
| U-232 | 1.00 | 1.13 | 1.25 | 1.32 | 1.37 | 1.41 | 1.44 | 1.46 |
| U-233 | 1.00 | 1.02 | 1.03 | 1.05 | 1.05 | 1.06 | 1.07 | 1.08 |
| U-234 | 1.00 | 1.02 | 1.03 | 1.04 | 1.05 | 1.06 | 1.07 | 1.07 |

## TABLE C2. COMPARISON RATIOS FOR VARIOUS PRELIMINARY IRRIGATION PERIODS

| Nuclide | Preliminary Irrigation Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 years | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| U-235+D | 1.00 | 1.08 | 1.14 | 1.18 | 1.21 | 1.23 | 1.26 | 1.29 |
| U-236 | 1.00 | 1.02 | 1.03 | 1.04 | 1.05 | 1.06 | 1.07 | 1.07 |
| U-238+D | 1.00 | 1.03 | 1.05 | 1.07 | 1.08 | 1.09 | 1.10 | 1.10 |
| Np-237+D | 1.00 | 1.02 | 1.04 | 1.06 | 1.07 | 1.09 | 1.12 | 1.15 |
| Pu-236 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 | 1.03 |
| Pu-238 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.03 | 1.04 | 1.05 |
| Pu-239 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 |
| Pu-240 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 |
| Pu-241+D | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.08 | 1.11 |
| Pu-242 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 |
| Pu-244+D | 1.00 | 1.02 | 1.04 | 1.07 | 1.09 | 1.11 | 1.15 | 1.22 |
| Am-241 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 |
| Am-242m+D | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.08 | 1.12 |
| Am-243+D | 1.00 | 1.01 | 1.03 | 1.04 | 1.06 | 1.07 | 1.10 | 1.14 |
| Cm-242 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 |
| Cm-243 | 1.00 | 1.01 | 1.02 | 1.03 | 1.03 | 1.04 | 1.04 | 1.05 |
| Cm-244 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 |
| Cm-245 | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 | 1.10 |
| Cm-246 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 |
| Cm-247+D | 1.00 | 1.02 | 1.04 | 1.06 | 1.08 | 1.11 | 1.15 | 1.21 |
| Cm-248 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 |
| Cm-250+D | 1.00 | 1.01 | 1.02 | 1.02 | 1.03 | 1.04 | 1.05 | 1.08 |
| Bk-247 | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 | 1.09 |
| Cf-248 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 |
| Cf-249 | 1.00 | 1.03 | 1.05 | 1.08 | 1.10 | 1.12 | 1.17 | 1.23 |
| Cf-250 | 1.00 | 1.01 | 1.02 | 1.02 | 1.03 | 1.03 | 1.03 | 1.03 |
| Cf-251 | 1.00 | 1.02 | 1.04 | 1.06 | 1.08 | 1.10 | 1.13 | 1.18 |
| Cf-252 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |

All ratios are the alternate unit dose factor from Table C1 divided by the dose factors from Table 12.

Table C3 shows the All Pathways Farmer unit dose factors using various averaging periods. Table C4 shows the unit dose factor ratios between the longer averaging periods and the first year. The averaged unit dose factors in Table C3 are smaller than the prior irrigation unit dose factors from Table C1, for the same time period.

## TABLE C3. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS AVERAGING PERIODS

| Nuclide | Averaging Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 year | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| H-3 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 | 4.75E-05 |
| Be-10 | 2.95E-03 | 2.97E-03 | 3.00E-03 | 3.02E-03 | 3.05E-03 | 3.07E-03 | 3.12E-03 | 3.20E-03 |

## TABLE C3. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS AVERAGING PERIODS

| Nuclide | Averaging Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 year | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| C-14 | 3.68E-03 | 4.43E-03 | 5.13E-03 | 5.69E-03 | 6.16E-03 | 6.55E-03 | 7.15E-03 | 7.75E-03 |
| Na-22 | 3.83E-02 | 7.68E-02 | 8.86E-02 | 9.30E-02 | 9.53E-02 | 9.66E-02 | 9.82E-02 | 9.93E-02 |
| Al-26 | 2.81E-02 | 1.40E-01 | 2.64E-01 | 3.88E-01 | 5.12E-01 | 6.35E-01 | 8.82E-01 | 1.25E+00 |
| Si-32+D | 6.90E-03 | 7.17E-03 | 7.45E-03 | 7.70E-03 | 7.94E-03 | 8.16E-03 | 8.55E-03 | 9.04E-03 |
| Cl-36 | 2.33E-02 | 7.59E-02 | 9.69E-02 | 1.06E-01 | 1.11E-01 | 1.13E-01 | 1.17E-01 | 1.19E-01 |
| K-40 | 2.32E-02 | 3.42E-02 | 4.48E-02 | 5.40E-02 | 6.20E-02 | 6.90E-02 | 8.06E-02 | 9.33E-02 |
| Ca-41 | 1.03E-03 | 1.32E-03 | 1.61E-03 | 1.85E-03 | 2.06E-03 | 2.24E-03 | 2.53E-03 | 2.85E-03 |
| Ti-44+D | 4.80E-02 | 1.36E-01 | 2.27E-01 | 3.11E-01 | 3.89E-01 | 4.61E-01 | 5.90E-01 | 7.52E-01 |
| V-49 | 3.95E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 | 3.96E-05 |
| Mn-53 | 6.80E-05 | 7.28E-05 | 7.82E-05 | 8.35E-05 | 8.89E-05 | 9.43E-05 | 1.05E-04 | 1.21E-04 |
| Mn-54 | 6.02E-03 | 1.03E-02 | 1.08E-02 | 1.09E-02 | 1.10E-02 | 1.11E-02 | 1.11E-02 | 1.12E-02 |
| Fe-55 | 5.16E-04 | 5.19E-04 | 5.20E-04 | 5.20E-04 | 5.21E-04 | 5.21E-04 | 5.21E-04 | 5.21E-04 |
| Fe-60+D | 1.33E-01 | 1.74E-01 | 2.57E-01 | 3.56E-01 | 4.63E-01 | 5.73E-01 | 7.97E-01 | 1.14E+00 |
| Co-60 | 3.75E-02 | 1.02E-01 | 1.37E-01 | 1.54E-01 | 1.64E-01 | 1.70E-01 | 1.77E-01 | 1.82E-01 |
| Ni-59 | 2.74E-04 | 2.82E-04 | 2.92E-04 | 3.01E-04 | 3.11E-04 | 3.20E-04 | 3.39E-04 | 3.67E-04 |
| Ni-63 | 7.53E-04 | 7.76E-04 | 8.00E-04 | 8.23E-04 | 8.45E-04 | 8.66E-04 | 9.05E-04 | 9.58E-04 |
| Se-79 | 1.06E-02 | 1.10E-02 | 1.12E-02 | 1.13E-02 | 1.13E-02 | 1.14E-02 | 1.14E-02 | 1.15E-02 |
| Rb-87 | 6.60E-03 | 8.39E-03 | 1.03E-02 | 1.22E-02 | 1.40E-02 | 1.58E-02 | 1.93E-02 | 2.41E-02 |
| Sr-90+D | 1.34E-01 | 1.76E-01 | 2.16E-01 | 2.50E-01 | 2.79E-01 | 3.04E-01 | 3.44E-01 | 3.86E-01 |
| Zr-93 | 1.01E-03 | 1.02E-03 | 1.02E-03 | 1.03E-03 | 1.03E-03 | 1.03E-03 | 1.04E-03 | 1.06E-03 |
| Nb-91 | 3.34E-04 | 4.23E-04 | 5.20E-04 | 6.15E-04 | 7.09E-04 | 8.01E-04 | 9.82E-04 | 1.24E-03 |
| Nb-93m | 3.20E-04 | 3.22E-04 | 3.24E-04 | 3.25E-04 | 3.26E-04 | 3.27E-04 | 3.28E-04 | 3.30E-04 |
| Nb-94 | 1.53E-02 | 8.04E-02 | 1.52E-01 | 2.23E-01 | 2.94E-01 | 3.63E-01 | 5.01E-01 | 7.02E-01 |
| Mo-93 | 1.02E-03 | 1.22E-03 | 1.41E-03 | 1.56E-03 | 1.69E-03 | 1.80E-03 | 1.97E-03 | 2.14E-03 |
| Tc-97 | 2.01E-04 | 6.24E-04 | 8.82E-04 | 1.03E-03 | 1.12E-03 | 1.18E-03 | 1.25E-03 | 1.30E-03 |
| Tc-99 | 1.71E-03 | 5.28E-03 | 7.46E-03 | 8.70E-03 | 9.46E-03 | 9.95E-03 | 1.05E-02 | 1.10E-02 |
| Ru-106+D | 3.09E-02 | 3.26E-02 | 3.28E-02 | 3.29E-02 | 3.29E-02 | 3.30E-02 | 3.30E-02 | 3.30E-02 |
| Pd-107 | 1.58E-04 | 1.64E-04 | 1.71E-04 | 1.77E-04 | 1.83E-04 | 1.90E-04 | 2.01E-04 | 2.18E-04 |
| Ag-108m+D | 1.64E-02 | 8.21E-02 | 1.53E-01 | 2.23E-01 | 2.90E-01 | 3.56E-01 | 4.82E-01 | 6.60E-01 |
| Cd-109+D | 8.88E-03 | 9.04E-03 | 9.06E-03 | 9.07E-03 | 9.07E-03 | 9.07E-03 | 9.08E-03 | 9.08E-03 |
| Cd-113m | 1.10E-01 | 1.15E-01 | 1.20E-01 | 1.23E-01 | 1.26E-01 | 1.27E-01 | 1.30E-01 | 1.32E-01 |
| In-115 | 1.13E-01 | 1.14E-01 | 1.15E-01 | 1.16E-01 | 1.17E-01 | 1.18E-01 | 1.20E-01 | 1.23E-01 |
| Sn-121m+D | 3.47E-03 | 3.57E-03 | 3.66E-03 | 3.74E-03 | 3.82E-03 | 3.89E-03 | 4.01E-03 | 4.14E-03 |
| Sn-126+D | 4.61E-02 | 1.29E-01 | 2.20E-01 | 3.11E-01 | 4.03E-01 | 4.94E-01 | 6.75E-01 | 9.47E-01 |
| Sb-125 | 4.37E-03 | 1.17E-02 | 1.41E-02 | 1.50E-02 | 1.55E-02 | 1.58E-02 | 1.61E-02 | 1.63E-02 |
| Te-125m | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 | 2.57E-03 |
| I-129 | 4.00E-01 | 4.11E-01 | 4.22E-01 | 4.32E-01 | 4.42E-01 | 4.50E-01 | 4.65E-01 | 4.82E-01 |
| Cs-134 | 1.19E-01 | 1.46E-01 | 1.52E-01 | 1.55E-01 | 1.56E-01 | 1.57E-01 | 1.58E-01 | 1.58E-01 |
| Cs-135 | 1.10E-02 | 1.24E-02 | 1.40E-02 | 1.55E-02 | 1.71E-02 | 1.86E-02 | 2.18E-02 | 2.64E-02 |
| Cs-137+D | 8.14E-02 | 1.12E-01 | 1.41E-01 | 1.66E-01 | 1.88E-01 | 2.07E-01 | 2.38E-01 | 2.72E-01 |
| Ba-133 | 4.50E-03 | 1.55E-02 | 2.36E-02 | 2.90E-02 | 3.28E-02 | 3.54E-02 | 3.87E-02 | 4.14E-02 |

## TABLE C3. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS AVERAGING PERIODS

| Nuclide | Averaging Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 year | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| Ce-144+D | 1.31E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 | 1.34E-02 |
| Pm-147 | 6.94E-04 | 6.96E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 | 6.97E-04 |
| Sm-147 | 1.24E-01 | 1.25E-01 | 1.27E-01 | 1.28E-01 | 1.29E-01 | 1.31E-01 | 1.33E-01 | 1.37E-01 |
| Sm-151 | 2.60E-04 | 2.61E-04 | 2.62E-04 | 2.64E-04 | 2.65E-04 | 2.67E-04 | 2.69E-04 | 2.72E-04 |
| Eu-150 | 1.42E-02 | 7.04E-02 | 1.26E-01 | 1.75E-01 | 2.18E-01 | 2.57E-01 | 3.21E-01 | 3.95E-01 |
| Eu-152 | 1.19E-02 | 5.02E-02 | 8.14E-02 | 1.04E-01 | 1.21E-01 | 1.34E-01 | 1.51E-01 | 1.67E-01 |
| Eu-154 | 1.46E-02 | 5.22E-02 | 7.83E-02 | 9.47E-02 | 1.05E-01 | 1.13E-01 | 1.22E-01 | 1.29E-01 |
| Eu-155 | 1.24E-03 | 2.08E-03 | 2.50E-03 | 2.70E-03 | 2.81E-03 | 2.88E-03 | 2.96E-03 | 3.02E-03 |
| Gd-152 | 1.05E-01 | 1.08E-01 | 1.11E-01 | 1.14E-01 | 1.16E-01 | 1.19E-01 | 1.25E-01 | 1.33E-01 |
| Tb-157 | 8.58E-05 | 1.08E-04 | 1.31E-04 | 1.52E-04 | 1.72E-04 | 1.91E-04 | 2.25E-04 | 2.69E-04 |
| Ho-166m | 1.71E-02 | 8.76E-02 | 1.65E-01 | 2.42E-01 | 3.18E-01 | 3.93E-01 | 5.41E-01 | 7.58E-01 |
| Re-187 | 7.54E-06 | 8.92E-06 | 1.04E-05 | 1.19E-05 | 1.33E-05 | 1.48E-05 | 1.75E-05 | 2.15E-05 |
| Tl-204 | 3.78E-03 | 3.82E-03 | 3.84E-03 | 3.85E-03 | 3.86E-03 | 3.86E-03 | 3.86E-03 | 3.86E-03 |
| Pb-205 | 1.04E-03 | 1.05E-03 | 1.06E-03 | 1.06E-03 | 1.07E-03 | 1.08E-03 | 1.09E-03 | 1.11E-03 |
| Pb-210+D | 3.49E+00 | 3.53E+00 | 3.57E+00 | 3.61E+00 | 3.63E+00 | 3.66E+00 | 3.69E+00 | 3.73E+00 |
| Bi-207 | 1.39E-02 | 7.17E-02 | 1.28E-01 | 1.77E-01 | 2.20E-01 | 2.58E-01 | 3.20E-01 | 3.89E-01 |
| Po-209 | 1.83E+00 | 1.86E+00 | 1.90E+00 | 1.93E+00 | 1.96E+00 | 2.00E+00 | 2.05E+00 | 2.13E+00 |
| Po-210 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 | 1.41E+00 |
| Ra-226+D | 9.08E-01 | 9.91E-01 | 1.09E+00 | 1.20E+00 | 1.31E+00 | 1.43E+00 | 1.67E+00 | 2.04E+00 |
| Ra-228+D | 9.76E-01 | 1.04E+00 | 1.09E+00 | 1.11E+00 | 1.13E+00 | 1.14E+00 | 1.15E+00 | 1.16E+00 |
| Ac-227+D | 9.05E+00 | 9.09E+00 | 9.12E+00 | 9.15E+00 | 9.17E+00 | 9.18E+00 | 9.21E+00 | 9.24E+00 |
| Th-228+D | 5.05E-01 | 5.26E-01 | 5.31E-01 | 5.33E-01 | 5.34E-01 | 5.34E-01 | 5.35E-01 | 5.35E-01 |
| Th-229+D | 2.47E+00 | 2.50E+00 | 2.54E+00 | 2.57E+00 | 2.60E+00 | 2.64E+00 | 2.70E+00 | 2.80E+00 |
| Th-230 | 3.36E-01 | 3.39E-01 | 3.42E-01 | 3.46E-01 | 3.50E-01 | 3.55E-01 | 3.65E-01 | 3.82E-01 |
| Th-232 | 1.68E+00 | 1.72E+00 | 1.81E+00 | 1.92E+00 | 2.05E+00 | 2.18E+00 | 2.44E+00 | 2.86E+00 |
| Pa-231 | 6.48E+00 | 6.51E+00 | 6.54E+00 | 6.58E+00 | 6.62E+00 | 6.67E+00 | 6.77E+00 | 6.93E+00 |
| U-232 | 8.72E-01 | 9.21E-01 | 9.78E-01 | 1.03E+00 | 1.06E+00 | 1.09E+00 | 1.14E+00 | 1.18E+00 |
| U-233 | 1.92E-01 | 1.94E-01 | 1.95E-01 | 1.97E-01 | 1.98E-01 | 1.99E-01 | 2.00E-01 | 2.02E-01 |
| U-234 | 1.88E-01 | 1.90E-01 | 1.91E-01 | 1.93E-01 | 1.94E-01 | 1.95E-01 | 1.96E-01 | 1.98E-01 |
| U-235+D | 1.78E-01 | 1.85E-01 | 1.91E-01 | 1.96E-01 | 2.00E-01 | 2.04E-01 | 2.09E-01 | 2.15E-01 |
| U-236 | 1.78E-01 | 1.80E-01 | 1.81E-01 | 1.83E-01 | 1.84E-01 | 1.85E-01 | 1.86E-01 | 1.87E-01 |
| U-238+D | 1.78E-01 | 1.81E-01 | 1.83E-01 | 1.85E-01 | 1.86E-01 | 1.88E-01 | 1.90E-01 | 1.91E-01 |
| Np-237+D | 2.77E+00 | 2.80E+00 | 2.83E+00 | 2.86E+00 | 2.88E+00 | 2.90E+00 | 2.95E+00 | 3.01E+00 |
| Pu-236 | 7.12E-01 | 7.14E-01 | 7.17E-01 | 7.19E-01 | 7.20E-01 | 7.22E-01 | 7.24E-01 | 7.26E-01 |
| Pu-238 | 1.96E+00 | 1.97E+00 | 1.97E+00 | 1.98E+00 | 1.98E+00 | 1.99E+00 | 2.00E+00 | 2.01E+00 |
| Pu-239 | 2.17E+00 | 2.17E+00 | 2.18E+00 | 2.19E+00 | 2.20E+00 | 2.20E+00 | 2.22E+00 | 2.24E+00 |
| Pu-240 | 2.17E+00 | 2.17E+00 | 2.18E+00 | 2.19E+00 | 2.20E+00 | 2.20E+00 | 2.22E+00 | 2.24E+00 |
| Pu-241+D | 4.19E-02 | 4.21E-02 | 4.23E-02 | 4.25E-02 | 4.27E-02 | 4.30E-02 | 4.34E-02 | 4.42E-02 |
| Pu-242 | 2.06E+00 | 2.06E+00 | 2.07E+00 | 2.08E+00 | 2.09E+00 | 2.09E+00 | 2.11E+00 | 2.13E+00 |
| Pu-244+D | 2.04E+00 | 2.06E+00 | 2.08E+00 | 2.10E+00 | 2.13E+00 | 2.15E+00 | 2.19E+00 | 2.26E+00 |
| Am-241 | 2.23E+00 | 2.24E+00 | 2.25E+00 | 2.26E+00 | 2.26E+00 | 2.27E+00 | 2.29E+00 | 2.31E+00 |

## TABLE C3. ALL PATHWAYS FARMER UNIT DOSE FACTORS FOR VARIOUS AVERAGING PERIODS

| Nuclide | Averaging Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 year | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| Am-242m+D | 2.16E+00 | 2.16E+00 | 2.17E+00 | 2.18E+00 | 2.20E+00 | 2.21E+00 | 2.23E+00 | 2.27E+00 |
| Am-243+D | 2.22E+00 | 2.24E+00 | 2.25E+00 | 2.27E+00 | 2.28E+00 | 2.30E+00 | 2.33E+00 | 2.37E+00 |
| Cm-242 | 6.95E-02 | 6.95E-02 | 6.96E-02 | 6.96E-02 | 6.96E-02 | 6.97E-02 | 6.97E-02 | 6.98E-02 |
| Cm-243 | 1.54E+00 | 1.55E+00 | 1.56E+00 | 1.56E+00 | 1.57E+00 | 1.58E+00 | 1.58E+00 | 1.59E+00 |
| Cm-244 | 1.24E+00 | 1.24E+00 | 1.24E+00 | 1.24E+00 | 1.25E+00 | 1.25E+00 | 1.25E+00 | 1.25E+00 |
| Cm-245 | 2.29E+00 | 2.30E+00 | 2.31E+00 | 2.32E+00 | 2.34E+00 | 2.35E+00 | 2.37E+00 | 2.40E+00 |
| Cm-246 | 2.27E+00 | 2.28E+00 | 2.28E+00 | 2.29E+00 | 2.30E+00 | 2.31E+00 | 2.32E+00 | 2.35E+00 |
| Cm-247+D | 2.10E+00 | 2.12E+00 | 2.14E+00 | 2.16E+00 | 2.19E+00 | 2.21E+00 | 2.25E+00 | 2.32E+00 |
| Cm-248 | 8.35E+00 | 8.38E+00 | 8.40E+00 | 8.43E+00 | 8.46E+00 | 8.49E+00 | 8.55E+00 | 8.64E+00 |
| Cm-250+D | 4.76E+01 | 4.78E+01 | 4.80E+01 | 4.82E+01 | 4.84E+01 | 4.85E+01 | 4.89E+01 | 4.94E+01 |
| Bk-247 | 2.88E+00 | 2.89E+00 | 2.91E+00 | 2.92E+00 | 2.93E+00 | 2.95E+00 | 2.98E+00 | 3.02E+00 |
| Cf-248 | 2.19E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 |
| Cf-249 | 3.16E+00 | 3.20E+00 | 3.24E+00 | 3.28E+00 | 3.32E+00 | 3.36E+00 | 3.44E+00 | 3.54E+00 |
| Cf-250 | 1.42E+00 | 1.43E+00 | 1.44E+00 | 1.44E+00 | 1.45E+00 | 1.45E+00 | 1.45E+00 | 1.46E+00 |
| Cf-251 | 3.24E+00 | 3.27E+00 | 3.30E+00 | 3.33E+00 | 3.36E+00 | 3.39E+00 | 3.45E+00 | 3.54E+00 |
| Cf-252 | 7.18E-01 | 7.21E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 | 7.22E-01 |

The averaging periods are 1, 10, 20, 30, 40, 50, 70, and 100 years.
The unit dose factors in the first column are the same as the ones shown in Table 12.

## TABLE C4. COMPARISON RATIOS FOR VARIOUS AVERAGING PERIODS

| Nuclide | Averaging Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 year | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| H-3 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Be-10 | 1.00 | 1.01 | 1.02 | 1.03 | 1.03 | 1.04 | 1.06 | 1.08 |
| C-14 | 1.00 | 1.21 | 1.39 | 1.55 | 1.68 | 1.78 | 1.94 | 2.11 |
| Na-22 | 1.00 | 2.01 | 2.31 | 2.43 | 2.49 | 2.52 | 2.56 | 2.59 |
| Al-26 | 1.00 | 4.97 | 9.39 | 13.79 | 18.20 | 22.60 | 31.38 | 44.52 |
| Si-32+D | 1.00 | 1.04 | 1.08 | 1.12 | 1.15 | 1.18 | 1.24 | 1.31 |
| Cl-36 | 1.00 | 3.26 | 4.16 | 4.55 | 4.75 | 4.87 | 5.01 | 5.12 |
| K-40 | 1.00 | 1.47 | 1.93 | 2.33 | 2.67 | 2.98 | 3.47 | 4.02 |
| Ca-41 | 1.00 | 1.29 | 1.57 | 1.81 | 2.01 | 2.19 | 2.47 | 2.78 |
| Ti-44+D | 1.00 | 2.83 | 4.72 | 6.47 | 8.09 | 9.60 | 12.29 | 15.67 |
| V-49 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mn-53 | 1.00 | 1.07 | 1.15 | 1.23 | 1.31 | 1.39 | 1.54 | 1.78 |
| Mn-54 | 1.00 | 1.71 | 1.79 | 1.82 | 1.83 | 1.84 | 1.85 | 1.85 |
| Fe-55 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| Fe-60+D | 1.00 | 1.31 | 1.93 | 2.68 | 3.48 | 4.31 | 6.00 | 8.57 |
| Co-60 | 1.00 | 2.73 | 3.64 | 4.10 | 4.36 | 4.52 | 4.71 | 4.85 |
| Ni-59 | 1.00 | 1.03 | 1.07 | 1.10 | 1.13 | 1.17 | 1.24 | 1.34 |
| Ni-63 | 1.00 | 1.03 | 1.06 | 1.09 | 1.12 | 1.15 | 1.20 | 1.27 |

## TABLE C4. COMPARISON RATIOS FOR VARIOUS AVERAGING PERIODS

| Nuclide | Averaging Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 year | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| Se-79 | 1.00 | 1.03 | 1.05 | 1.06 | 1.06 | 1.07 | 1.07 | 1.08 |
| Rb-87 | 1.00 | 1.27 | 1.56 | 1.85 | 2.13 | 2.40 | 2.92 | 3.65 |
| Sr-90+D | 1.00 | 1.31 | 1.61 | 1.87 | 2.08 | 2.27 | 2.57 | 2.89 |
| Zr-93 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 |
| Nb-91 | 1.00 | 1.27 | 1.56 | 1.84 | 2.12 | 2.40 | 2.94 | 3.72 |
| Nb-93m | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 | 1.03 | 1.03 |
| Nb-94 | 1.00 | 5.26 | 9.96 | 14.61 | 19.21 | 23.78 | 32.78 | 45.96 |
| Mo-93 | 1.00 | 1.20 | 1.38 | 1.54 | 1.66 | 1.77 | 1.94 | 2.11 |
| Tc-97 | 1.00 | 3.10 | 4.38 | 5.11 | 5.55 | 5.84 | 6.19 | 6.45 |
| Tc-99 | 1.00 | 3.09 | 4.36 | 5.09 | 5.53 | 5.82 | 6.16 | 6.42 |
| Ru-106+D | 1.00 | 1.05 | 1.06 | 1.06 | 1.06 | 1.06 | 1.07 | 1.07 |
| Pd-107 | 1.00 | 1.04 | 1.08 | 1.12 | 1.16 | 1.20 | 1.27 | 1.38 |
| Ag-108m+D | 1.00 | 5.01 | 9.35 | 13.57 | 17.69 | 21.69 | 29.39 | 40.21 |
| Cd-109+D | 1.00 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| Cd-113m | 1.00 | 1.05 | 1.09 | 1.12 | 1.15 | 1.16 | 1.19 | 1.21 |
| In-115 | 1.00 | 1.01 | 1.02 | 1.02 | 1.03 | 1.04 | 1.06 | 1.08 |
| Sn-121m+D | 1.00 | 1.03 | 1.05 | 1.08 | 1.10 | 1.12 | 1.15 | 1.19 |
| Sn-126+D | 1.00 | 2.79 | 4.77 | 6.75 | 8.73 | 10.70 | 14.64 | 20.52 |
| Sb-125 | 1.00 | 2.68 | 3.23 | 3.44 | 3.55 | 3.61 | 3.69 | 3.74 |
| Te-125m | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| I-129 | 1.00 | 1.03 | 1.06 | 1.08 | 1.10 | 1.12 | 1.16 | 1.21 |
| Cs-134 | 1.00 | 1.23 | 1.28 | 1.30 | 1.31 | 1.32 | 1.33 | 1.33 |
| Cs-135 | 1.00 | 1.13 | 1.27 | 1.41 | 1.55 | 1.69 | 1.98 | 2.40 |
| Cs-137+D | 1.00 | 1.37 | 1.73 | 2.04 | 2.31 | 2.54 | 2.92 | 3.33 |
| Ba-133 | 1.00 | 3.45 | 5.25 | 6.45 | 7.27 | 7.86 | 8.60 | 9.20 |
| Ce-144+D | 1.00 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| Pm-147 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Sm-147 | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.08 | 1.11 |
| Sm-151 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.03 | 1.04 | 1.05 |
| Eu-150 | 1.00 | 4.94 | 8.83 | 12.26 | 15.31 | 18.01 | 22.56 | 27.73 |
| Eu-152 | 1.00 | 4.21 | 6.82 | 8.73 | 10.15 | 11.23 | 12.70 | 13.97 |
| Eu-154 | 1.00 | 3.58 | 5.37 | 6.49 | 7.23 | 7.74 | 8.36 | 8.85 |
| Eu-155 | 1.00 | 1.68 | 2.01 | 2.18 | 2.27 | 2.33 | 2.39 | 2.44 |
| Gd-152 | 1.00 | 1.02 | 1.05 | 1.08 | 1.11 | 1.13 | 1.19 | 1.27 |
| Tb-157 | 1.00 | 1.26 | 1.52 | 1.77 | 2.01 | 2.23 | 2.62 | 3.14 |
| Ho-166m | 1.00 | 5.11 | 9.63 | 14.11 | 18.54 | 22.93 | 31.58 | 44.24 |
| Re-187 | 1.00 | 1.18 | 1.38 | 1.58 | 1.77 | 1.96 | 2.32 | 2.85 |
| Tl-204 | 1.00 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 |
| Pb-205 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.03 | 1.05 | 1.07 |
| Pb-210+D | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.06 | 1.07 |
| Bi-207 | 1.00 | 5.16 | 9.20 | 12.73 | 15.81 | 18.51 | 22.99 | 27.95 |
| Po-209 | 1.00 | 1.02 | 1.04 | 1.06 | 1.07 | 1.09 | 1.12 | 1.17 |

## TABLE C4. COMPARISON RATIOS FOR VARIOUS AVERAGING PERIODS

| Nuclide | Averaging Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 year | 10 years | 20 years | 30 years | 40 years | 50 years | 70 years | 100 years |
| Po-210 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Ra-226+D | 1.00 | 1.09 | 1.20 | 1.32 | 1.45 | 1.57 | 1.84 | 2.25 |
| Ra-228+D | 1.00 | 1.06 | 1.11 | 1.14 | 1.15 | 1.16 | 1.18 | 1.18 |
| Ac-227+D | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 |
| Th-228+D | 1.00 | 1.04 | 1.05 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 |
| Th-229+D | 1.00 | 1.01 | 1.03 | 1.04 | 1.05 | 1.07 | 1.09 | 1.13 |
| Th-230 | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.06 | 1.09 | 1.14 |
| Th-232 | 1.00 | 1.02 | 1.08 | 1.15 | 1.22 | 1.30 | 1.46 | 1.70 |
| Pa-231 | 1.00 | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 | 1.07 |
| U-232 | 1.00 | 1.06 | 1.12 | 1.18 | 1.22 | 1.25 | 1.30 | 1.35 |
| U-233 | 1.00 | 1.01 | 1.02 | 1.03 | 1.03 | 1.04 | 1.05 | 1.05 |
| U-234 | 1.00 | 1.01 | 1.02 | 1.03 | 1.03 | 1.04 | 1.04 | 1.05 |
| U-235+D | 1.00 | 1.04 | 1.07 | 1.10 | 1.12 | 1.14 | 1.17 | 1.20 |
| U-236 | 1.00 | 1.01 | 1.02 | 1.03 | 1.03 | 1.04 | 1.04 | 1.05 |
| U-238+D | 1.00 | 1.01 | 1.03 | 1.04 | 1.05 | 1.05 | 1.06 | 1.08 |
| Np-237+D | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.06 | 1.08 |
| Pu-236 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 |
| Pu-238 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.03 |
| Pu-239 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.04 |
| Pu-240 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.03 |
| Pu-241+D | 1.00 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.04 | 1.05 |
| Pu-242 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.04 |
| Pu-244+D | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.08 | 1.11 |
| Am-241 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.04 |
| Am-242m+D | 1.00 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.04 | 1.05 |
| Am-243+D | 1.00 | 1.01 | 1.01 | 1.02 | 1.03 | 1.03 | 1.05 | 1.07 |
| Cm-242 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Cm-243 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 | 1.03 | 1.03 |
| Cm-244 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| Cm-245 | 1.00 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.03 | 1.05 |
| Cm-246 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.03 |
| Cm-247+D | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 | 1.10 |
| Cm-248 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.04 |
| Cm-250+D | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.03 | 1.04 |
| Bk-247 | 1.00 | 1.00 | 1.01 | 1.01 | 1.02 | 1.02 | 1.03 | 1.05 |
| Cf-248 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 |
| Cf-249 | 1.00 | 1.01 | 1.02 | 1.04 | 1.05 | 1.06 | 1.09 | 1.12 |
| Cf-250 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 |
| Cf-251 | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.05 | 1.07 | 1.09 |
| Cf-252 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 |

All ratios are the alternate unit dose factor from Table G3 divided by the dose factors from Table 12.

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# APPENDIX D

# DEFINITION OF RISK ASSESSMENT TERMS

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## DEFINITION OF RISK ASSESSMENT TERMS

**Absorbed dose:** The total energy absorbed per unit mass. The energy comes from the interaction of ionizing radiation in the material. Absorbed dose is measured in rad or Gray.

**Acute exposure:** Any relatively short-term exposure period over which there is little change in the body mass, biokinetic parameters, usage functions, and sensitivity of the exposed population.

**Adherence factor:** Describes the amount of soil that adheres to the skin and thus is available for absorption through the skin. Adherence is expressed as the daily mass (of soil) per unit area of skin, averaged over the exposed skin area. In the EPA RAGS Volume 1, Part E, adherence is calculated for specific events, but there is only one such event per day.

**Aerodynamic diameter:** Diameter of a unit density sphere that has the same terminal settling velocity as an irregular shaped aerosol particle.

**AMAD:** Activity Median Aerodynamic Diameter. The diameter of a unit density sphere with the same terminal settling velocity in air as that of an aerosol particle whose activity is the median for the entire aerosol.

**ATSDR:** Agency for Toxic Substances and Disease Registry

**Becquerel (Bq):** Special name for the SI unit of radioactivity. 1 Becquerel = 1 per second

**Bioaccumulation:** Process by which some radionuclides or chemicals build up to higher concentrations in an organism relative to concentrations found in the organism's primary environmental media or diet.

**Bioaccumulation factor:** The ratio of the concentration of a radionuclide or chemical in an organism (usually the edible portion of the organism) to the concentration in the organism's primary environmental media or diet.

**CASRN:** Chemical Abstract Service Reference Number

**Chain members:** The sequence of radionuclides formed by successive nuclear transformations, beginning with a radionuclide referred to as the parent.

**Chronic exposure:** Protracted exposure in a given exposure scenario.

**Committed effective dose:** The time integral of the effective dose rate.

**Committed equivalent dose (or Committed Dose Equivalent, CDE):** The time integral of the equivalent dose rate.

**Curie (Ci):** The conventional unit of radioactivity. 1 Curie = $3.7 \times 10^{10}$ per second

**Dermis:** The layer of skin beneath the epidermis. It contains blood vessels and has a thickness ranging from 500 to 3000 μm.

**DOE:** U.S. Department of Energy

**Dose:** The amount of a chemical that enters or is absorbed by the body adjusted for the size of the individual. Chemical dose is expressed in milligrams of chemical per kilogram of body weight (mg/kg). Radiological dose is expressed as the energy absorbed from ionizing radiation per unit mass of body tissue.

**Effective dose (or Effective Dose Equivalent, EDE):** A value used to express the health risk from radiation exposure to organs and tissues in terms of an equivalent whole body exposure. It is a normalized value that allows the risk from radiation exposure received by a specific organ or part of the body to be compared with the risk due to whole body exposure. It is equal to the sum of products of the dose to each tissue or organ multiplied by their respective weighting factor for each tissue or organ. The weighting factor is used to put the dose to the different tissue and organs on an equal basis in terms of health risk. The SI unit of effective dose is J/kg. The special name for this unit is Sievert (1 Sv = 1 J/kg). The conventional unit of effective dose is the rem (1 rem = 0.01 Sv).

**EPA:** U.S. Environmental Protection Agency

**Epidermis:** The outermost layer of skin. It has a thickness of about 100 μm. It is divided into two regions, the stratum corneum (10 to 40 μm thick) and the viable epidermis. The stratum corneum is composed of layers of dead, flattened cells held together by a lipoidal substance. The stratum corneum is continually lost (desquamation) and is completely replaced every two to three weeks. The viable epidermis generates the cells of the stratum corneum.

**Equivalent dose (or dose equivalent):** The product of the absorbed dose in a tissue and the radiation weighting factor. The SI unit of equivalent dose is J/kg. The special name for this unit is Sievert (1 Sv = 1 J/kg). The conventional unit of equivalent dose is the rem (1 rem = 0.01 Sv)

**Exposure pathway:** The course a chemical, radionuclide, or physical agent takes from the source to the exposed organism. An exposure pathway describes a mechanism by which chemicals, radionuclides, or physical agents at or originating from a release site reach an individual or population. Each exposure pathway includes a source or release from a source, an exposure route, and an exposure point. If the exposure point differs from the source, a transport/exposure medium such as air or water is also included. The key exposure transport media are air and water, with most exposures occurring by inhalation, drinking water, eating crops and other foods, and from direct irradiation.

**Exposure route:** Means by which material may gain access to the body (e.g., breathing, eating, and through the skin or eyes). Another route of exposure not involving contact with the material is external radiation by certain radionuclides

**Exposure scenario:** A representative human activity that leads to some form of contact with residual contamination at a waste disposal site.

**External exposure:** Exposure to radiations emitted by radionuclides located outside the body.

**External Effective Dose Equivalent, EEDE:** A value used to express the health risk from external radiation exposure to organs and tissues in terms of an equivalent whole body exposure. It is a normalized value that allows the risk from radiation exposure received by a specific organ or part of the body to be compared with the risk due to whole body exposure. It is equal to the sum of products of the dose to each tissue or organ multiplied by their respective weighting factor for each tissue or organ. EEDE is expressed with units of Sievert (Sv) or rem (1 rem = 0.01 Sv)

**Gray (Gy):** Special name for the SI unit of absorbed dose. It is the amount of radiation needed to deposit 1 joule of energy per kilogram of material. 1 Gray = 1 J/kg = 100 rad

**Half life, radioactive:** Time required for a radionuclide to lose 50% of its activity by spontaneous nuclear transformations, i.e., radiological decay.

**Hazard Index (HI):** The sum of the hazard quotients for a mixture of chemicals.

**Hazard Quotient (HQ):** The ratio of the average lifetime daily dose to a particular chemical to the reference dose for that chemical.

**HEAST:** Heath Effects Assessment Summary Tables

**HSRAM:** Hanford Site Risk Assessment Methodology, DOE/RL-91-45 Rev 3 1995. This report recommends parameters for the industrial, recreational, residential, and agricultural exposure scenarios. No environmental or toxicological parameters are given. This work is largely superseded by more recent guidance from the EPA.

**ICRP:** International Commission on Radiological Protection

**ILCR:** Incremental Lifetime Cancer Risk. The estimated probability for producing any type of cancer in an individual due to a lifetime exposed to a toxin. For radionuclides this represents a reasonable likelihood based on human morbidity statistics. For chemicals this represents an upper bound, often based on extrapolation from animal data.

**Internal exposure:** Exposure to radiations emitted by radionuclides distributed within the body.

**Linear energy transfer:** Energy deposited in a material per unit length of travel by a radiation particle.

**MMAD:** Mass Median Aerodynamic Diameter. The diameter of a unit density sphere with the same terminal settling velocity in air as that of an aerosol particle whose mass is the median for the entire aerosol.

**MCL:** Maximum Contaminant Level. These are drinking water concentration limits placed on specific chemicals and radionuclides found in EPA regulations.

**MTCA:** Model Toxics Control Act of Washington State, Chapter 70.105D RCW creates a comprehensive regulatory scheme to identify, investigate, and clean up contaminated properties that are, or may be, a threat to human health or the environment. The cost of cleaning up such properties can be extraordinarily high. MTCA was approved by state voters as an initiative in 1988 and adopted by the legislature in 1989 in order to raise funds to clean up contaminated sites and to prevent the creation of future hazardous waste sites. Since the adoption of MTCA, private parties that are potentially liable under the Act have funded most of the cleanups conducted in Washington. MTCA's liability reach is so extensive that nearly any person with any connection to a contaminated property is potentially liable for the entire cost of the cleanup.

**NCRP:** U.S. National Council on Radiation Protection and Measurements

**NOAEL:** No Observable Adverse Effect Level. The highest dose of a chemical that does not produce a measurable adverse health effect on a laboratory animal or humans.

**Organ weighting factor:** The factor used to convert equivalent dose to the various organs and tissues of the body to an effective equivalent dose. It accounts for the relative biological effectiveness of a particular radiation. It is chosen to be independent of the tissue or organ under consideration, and of the biological endpoint.

**Performance assessment:** An analysis that predicts the behavior of a system or system component under a given set of conditions. In the context of DOE waste management activities, a systematic analysis of the potential risks posed by waste management systems to the public and environment, and a comparison of those risks to established performance objectives

**rad:** The conventional unit of absorbed dose. It is defined as the amount of radiation needed to deposit 100 erg of energy per gram of material. 1 rad = 0.01 Gray

**Radiation weighting factor:** The factor used to convert absorbed dose to equivalent dose. It accounts for the relative biological effectiveness of a particular radiation. It is chosen to be independent of the tissue or organ under consideration, and of the biological endpoint.

**RAIS:** Risk Assessment Information System. A DOE-sponsored web site http://rais.ornl.gov/ through Oak Ridge National Laboratory (ORNL).

**Reference dose (RfD):** A daily dose of a chemical that the U.S. EPA considers safe for regular consumption by humans without adverse health effects. It is typically generated by taking the NOAEL from animal studies and adding uncertainty factors to account for differences between animals and humans, and susceptibility within the human population. It has units of mg chemical per kg body weight, per day.

**rem:** The conventional unit of equivalent dose (and effective dose). It defines radiation in terms of biological effect. 1 rem = 0.01 Sv

**Risk:** The combination of the frequency or probability of occurrence and the consequence of a specified hazardous event. NOTE: The concept of risk always has two elements: the frequency or probability with which a hazardous event occurs and the consequences of the hazardous event.

**Sensitivity:** Term used to describe the importance of a given input parameter to the final result.

**Sievert (Sv):** Special name for the SI unit of equivalent dose (and effective dose). It is the amount of radiation needed to produce a given biological effect in living cells. 1 Sv = 1 J/kg

**Slope factor:** Plausible, upper bound estimate of the probability of a response-per-unit intake of a material of concern over a lifetime. The slope factor is used to estimate an upper-bound probability of an individual developing cancer as a result of a lifetime of exposure to a particular average level of a potential carcinogen. There are separate slope factors for each route of exposure. For chemicals the slope factor has units of risk per unit daily dose where the unit daily dose has units of mg chemical per kg body weight per day. For radionuclides the slope factor has units of risk per lifetime intake, i.e., risk per Bq.

**Tissue weighting factor:** A factor used to convert equivalent dose into effective dose. It indicates the relative risk of cancer induction or hereditary defects from irradiation of a given tissue or organ.

**Uncertainty:** Term used to describe the level of confidence in a given estimate based on the amount and quality of the evidence (data) available. Uncertainties in the results of a study arise primarily from limitations related to existing measurements, absence of some kinds of measurements because of lack of environmental monitoring at certain locations, lack of knowledge about some physical processes and operational procedures, and the approximate nature of mathematical models used to predict the transport of released materials.

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# APPENDIX E

# EMANATION OF GASEOUS RADIONUCLIDES FROM THE SOIL SURFACE

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## EMANATION OF GASEOUS RADIONUCLIDES FROM THE SOIL SURFACE

This section describes the migration of gaseous radionuclides from the buried waste, through the facility cover to the ground surface, and into the atmosphere. Then the consequences of the air emission are estimated. The gaseous radionuclides are tritium (as water vapor), $^{14}C$ (as carbon dioxide), and $^{222}Rn$ (an inert gas).

### E.1. DIFFUSION FLUX AT THE GROUND SURFACE

For the discussion in this section, the waste is separated into solids and a gas-filled pore space. The solids contain the radioactive inventory, while the pore space collects any gaseous nuclides that may be released from the solids. Vitrified waste is expected to release gases very slowly, while low-level waste could release the gaseous radionuclides rapidly. The quantity of gaseous radionuclides in the waste solids decreases with time by radioactive decay, and by release from the waste solids into the waste pore space. It will be assumed that over the course of one year both the inventory in the waste solids and the fractional release rate are relatively constant. The rate at which the gaseous nuclides are released from the waste solids is calculated using Equation (1).

$$\text{Gas Release Rate} = \lambda_C Q_S \qquad (1)$$

where

$Q_S$ = quantity of a gaseous radionuclide in the waste solids at some time after closure, in Ci

$\lambda_C$ = fraction of the total released from the waste solids into the waste pore space per year. This fraction may vary slowly from year to year.

The gaseous radionuclides released from the solids then diffuse from the waste into the soil surrounding the disposal site. If this diffusion is slow, then the gaseous nuclides accumulate in the pore space until the diffusion rate away from the waste matches the release rate from the solids. If this diffusion is rapid, then the concentration in the waste pore space will be very small, but will be proportional to the concentration in the waste solids.

The diffusion of radioactive gases can be represented using Fick's law of diffusion with a loss term for radioactive decay (Jury 1991 Chapter 6). This is shown in Equation (2). The $^{222}Rn$ will be discussed separately from the $^{3}H$ and $^{14}C$ because it is produced by a decay chain that includes $^{238}U$, $^{234}U$, $^{230}Th$, and $^{226}Ra$. For calculating diffusion in the presence of radioactive decay the source concentration is assumed to be constant because it changes very slowly with time compared to the movement of the diffusing gases. It will further be assumed that the diffusion characteristics of the waste cover are uniform with depth, so that a single diffusion coefficient (D) represents an average for the various soil layers.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - \lambda_R C$$
$$\text{if } \frac{\partial C}{\partial t} = 0 \quad \text{then} \quad D\frac{\partial^2 C}{\partial z^2} = \lambda_R C \tag{2}$$

The source region is assumed to be a homogenous layer of soil with the same diffusion coefficient as the soil cover. In steady-state, the waste region has a constant gas concentration ($C_0$) in the pore space. Because this concentration is proportional to the release rate from the waste solids, it will change slowly with time, as discussed above.

The solution to the differential equation has an exponential dependence in elevation as shown in Equation (3). The boundary conditions that the soil concentration is $C_0$ at the top of the waste (z=0) and zero at the ground surface ($z=z_0$) have been included. The solution is only valid from z=0 to $z=z_0$.

$$C(z) = C_0\left[\frac{e^{-z\mu} - e^{-(2z_0 - z)\mu}}{1 - e^{-2z_0\mu}}\right] \qquad \text{and} \qquad \mu = \sqrt{\frac{\lambda_R}{D}}$$
$$J(z) = -D\frac{\partial C}{\partial z} \qquad \text{thus} \quad J(z) = C_0\,\mu\,D\,\frac{e^{-z\mu} + e^{-(2z_0 - z)\mu}}{1 - e^{-2z_0\mu}}$$
$$J(0) = C_0\,\mu\,D\,\frac{1 + e^{-2z_0\mu}}{1 - e^{-2z_0\mu}} \qquad \text{and} \quad J(z_0) = \frac{2C_0\,\mu\,D\,e^{-z_0\mu}}{1 - e^{-2z_0\mu}} \tag{3}$$

where

- $C(z)$ = concentration of a gaseous radionuclide in the soil at elevation z in the soil above the waste, in Ci per $m^3$ of soil. At the bottom of the soil cover, the soil concentration matches the gas concentration in the waste, i.e., $C=C_0$. At the top of the cover the gas concentration is zero.
- $C_0$ = average gaseous radionuclide concentration in the waste pore space available for diffusion, in Ci per $m^3$ of waste. Note that this is the total gaseous activity in the waste pore space divided by the total volume of the waste.
- D = diffusion coefficient for low atomic number gases moving through waste and soil, 0.01 $cm^2/s$ = 31.56 $m^2/y$
- $J(z)$ = upward diffusion flux at elevation z above the waste, in $Ci/m^2$ per y
- z = vertical position in the soil, in m. The bottom of the soil column is z=0, while the ground surface is $z=z_o$=5 m.
- $\lambda_R$ = radioactive decay constant for the nuclide, per y.
- $\mu$ = inverse length parameter characteristic of gaseous radionuclide with a particular half life diffusing in a particular medium, in $m^{-1}$

Earlier performance assessment calculations did not use the boundary condition that the surface concentration is zero. In effect, an infinite medium was assumed. This underestimates

the surface diffusion flux (J) by at least a factor of two. Longer half-life nuclides show a larger difference. The 2001 ILAW PA included this boundary condition.

Only $^{222}Rn$ is an inert gas that will faithfully follow the above diffusion model. The $^{3}H$ and $^{14}C$ will undergo chemical reactions and be part of compounds that are likely to exist in the soil or the waste corrosion products. For $^{3}H$ these compounds include water and hydroxides. For $^{14}C$ these compounds include carbonates and carbides. The effect of these chemical reactions is to slow the migration to the surface and the resulting release rate from the ground surface. This effect has not been included in the diffusion calculations to maximize estimated consequences.

If the decay half life is very long, then Equation (3) can be simplified to the form shown in Equation (4). In steady-state, the diffusion flux is constant with elevation. These equations represent the diffusion of $^{3}H$ and $^{14}C$ very well due to the long half lives.

$$C(z) = C_0\left(1 - \frac{z}{z_0}\right) \quad \text{and} \quad J(z) = \frac{C_0 D}{z_0} \tag{4}$$

The calculation of gaseous radionuclide flux at the ground surface requires a value for the steady state concentration in the waste matrix ($C_0$). Since the concentration available for diffusion ($C_0$) varies slowly with time, the rate of addition of gas to the pore space equals the rate of removal. This can be stated mathematically as shown in Equation (5) below. The first formula defines "steady state". The second formula says that the rate at which gaseous radionuclides are entering the waste pore space is equal to the rate at which they decay and diffuse. In this simple one-dimensional model the diffusion is either up or down. Hence, the total loss is double the diffusion flux in one direction. In the final formula for steady state concentration the numerator is the rate of addition of gaseous nuclides to the waste pore space.

$$\text{rate of addition} = \text{rate of removal}$$

$$\lambda_C Q_S = \lambda_R Q_0 + 2 A J(0) \quad \text{and} \quad J(0) = \frac{Q_0 \mu D}{A z_W}\Omega$$

$$\lambda_C Q_S = \lambda_R Q_0 + \frac{2 Q_0 \mu D}{z_W}\Omega \quad \text{where} \quad \Omega = \frac{1 + e^{-2 z_0 \mu}}{1 - e^{-2 z_0 \mu}} \tag{5}$$

$$\text{finally,} \quad C_0 = \frac{\lambda_C Q_S}{\lambda_R V + 2 A \mu D \Omega}$$

where

- $A$ = surface area footprint of the waste disposal site, in $m^2$
- $C_0$ = average gaseous radionuclide concentration in the waste pore space available for diffusion, in Ci per $m^3$ of waste. Note that this is the total gaseous activity in the waste pore space ($Q_0$) divided by the total volume of the waste (V).
- $D$ = diffusion coefficient for low atomic number gases moving through waste and soil, 0.01 $cm^2/s$ = 31.56 $m^2/y$
- $J(z)$ = upward diffusion flux at elevation z above the waste, in $Ci/m^2$ per y

$Q_0$ = quantity of a gaseous radionuclide located in the waste pore space, in Ci
$Q_S$ = quantity of a gaseous radionuclide embedded in the waste solids, in Ci
$V$ = total volume of the waste, in $m^3$
$z_0$ = thickness of the soil above the waste, 5 m
$z_W$ = thickness of the waste, in m. The volume of the waste is the product of the footprint area and the thickness: $V = A\, z_W$.
$\lambda_C$ = fraction of the total released from the waste solids into the waste pore space per year.
$\lambda_R$ = radioactive decay constant for the nuclide, per y
$\mu$ = inverse length parameter characteristic of gaseous radionuclide with a particular half life diffusing in a particular medium, in $m^{-1}$

It should be noted that the above equation for gaseous radionuclide concentration in the pore space reduces to the expected form when the radioactive decay constant becomes very small. One way to derive the expected form is to write the no-decay flux in terms of both the source release rate and the surface release rate. By conservation of matter in a simple one-dimensional model, this condition is shown in Equation (6) below. The factor of two in the first equation stems from the assumption that only half the released activity diffuses upward. The other half diffuses downward. This formula can be used to calculate the initial concentration in the waste. The final equation for diffusion flux at the ground surface when radioactive decay is not important is shown below also.

$$J = \frac{D\,C_0}{z_0} = \frac{\lambda_C\, Q_S}{2\,A} \qquad \text{thus} \qquad C_0 = \frac{\lambda_C\, Q_S\, z_0}{2\,A\,D} \tag{6}$$

Determining the initial concentration of $^{222}Rn$ is complicated by two sources of the gas. One is the release from the waste solids. The other is the decay of $^{226}Ra$ that has already been released from the waste solids. The $^{226}Ra$ produces $^{222}Rn$ by radioactive decay. The total amount of $^{226}Ra$ slowly increases for two reasons. First, an increasing fraction of the waste matrix has decomposed. Second, $^{226}Ra$ is being produced by the radioactive decay of $^{238}U$ and $^{234}U$ that have been released. The peak $^{222}Rn$ flux occurs after all the waste has decomposed, and the $^{226}Ra$ has reached radioactive equilibrium with the $^{238}U$. This equilibrium occurs after times greater than $1 \times 10^6$ years after closure. Note that the uranium decay chain is assumed to remain in the waste disposal facility indefinitely. This ignores the mobility of uranium in the soil, but is conservative. For $^{222}Rn$, the steady state concentration in the waste pore space is calculated as shown in the equation below. In the final equation for steady state concentration the numerator is the rate of addition of $^{222}Rn$ to the waste pore space.

$$\text{rate of addition} = \text{rate of removal}$$

$$\lambda_C\, Q_{S,Rn\text{-}222} + \lambda_{Rn\text{-}222}\, Q_{0,Ra\text{-}226} = \lambda_{Rn\text{-}222} Q_{0,Rn\text{-}222} + 2\,A\,J_{Rn\text{-}222}(0) \tag{7}$$

$$\text{finally,} \quad C_{0,Rn\text{-}222} = \frac{\lambda_C\, Q_{S,Rn\text{-}222} + \lambda_{Rn\text{-}222}\, Q_{0,Ra\text{-}226}}{\lambda_{Rn\text{-}222} V + 2\,A\,\mu\,D\,\Omega}$$

If the initial inventory per unit area of $^{238}U$ in the disposal facility is 1 Ci/$m^2$ (i.e., 1 Ci $^{238}U$ per $m^2$ of facility footprint), then after a few million years, the waste solids have decomposed

($Q_S$=0) and the $^{234}U$, $^{230}Th$, $^{226}Ra$, and $^{222}Rn$ are all in radioactive equilibrium with the $^{238}U$. Thus the $^{226}Ra$ inventory in the trench is 1 Ci/m$^2$. It is assumed that no migration of the uranium out of the trench has taken place during this time. If the waste thickness ($z_W$=V/A) is 1 m, the resulting concentration of $^{222}Rn$ is 0.420 Ci/m$^3$. The calculation of the diffusion flux for $^{222}Rn$ is carried out using the formula given previously for $J(z_0)$. The $^{222}Rn$ flux at the ground surface through 5 m of cover with a diffusion coefficient of 0.01 cm$^2$/s is 0.0275 Ci/m$^2$ per year, or 671 pCi/m$^2$ per second. Note that the performance objective for radon emanation is 20 pCi/m$^2$ per second.

## E.2. MECHANISMS AFFECTING THE DIFFUSION FLUX

There are four environmental factors that can affect the rate of gas transport through the soil. These are barometric pressure, temperature, wind, and rain (Jury 1991). Each of these will be discussed in terms of its effect on the gaseous diffusion rate from the ground surface calculated above.

### E.2.1. Atmospheric Pressure

An increase in atmospheric pressure will compress the air above the soil and drive air into the soil. The motion of air into the soil is impeded by the tortuosity of the flow channels and the small diameter of the surface openings between soil grains. When the atmospheric pressure decreases gases in the soil expand and the gas near the surface is released into the atmosphere. The effect on gases diffusing from underground is to slow the release rate while the atmospheric pressure increases, and increase the release rate when the atmospheric pressure decreases.

However, atmospheric pressure variation represents a very small change in the average pressure. The annual standard deviation of barometric pressure variations was at most 0.72% during the years 1988 through 1991 (WHC-EP-0651). The annual extremes for these years were at most 3.1% from the average. Such small variation suggests the influence of atmospheric pressure changes is small. This suspicion is born out in literature cited in *Soil Physics* (Jury 1991). A soil permeable column 3 m deep was affected by typical barometric pressure variations to a depth of at most 0.56 cm. Thus, barometric pressure changes will have little influence on the average diffusion flux from the surface.

### E.2.2. Atmospheric Temperature

The air temperature at the ground surface varies sinusoidally during the day as well as during the year. The daily variation does not penetrate as deeply as the seasonal variation. The seasonal temperature change at a depth of 5 m in sandy soil is about 10% of the seasonal temperature change at the surface (Jury 1991). The variation in temperature decreases exponentially with distance below the surface. In addition, there is a phase shift that increases with depth. The cyclic variation in soil temperature will cause air movement due to the expansion and contraction of the air as the temperature increases and decreases. This air movement can be expected to increase the average diffusion flux at the surface.

However, the influx of air is limited to a shallow layer near the surface, just as with barometric pressure changes. The monthly average air temperature at Hanford typically ranges from -12 C to 30 C with an average around 12 C (PNL-9809). Thus the near-surface soil layer experiences a seasonal temperature variation no more than 10% on the absolute temperature scale. While this variation is an order of magnitude greater than the barometric pressure change, it is confined to a relatively shallow layer near the surface. Thus, temperature changes will have little effect on the average diffusion flux from the surface. If the 10% variation is assumed to accelerate gas transport in the top 10% of the soil cover, then the soil cover thickness is effectively reduced by 0.5 m. With a cover thickness of 4.5 m, the $^{222}$Rn diffusion flux increases from 0.96 pCi/m$^2$ per second to 1.98 pCi/m$^2$ per second.

### E.2.3. Wind

The motion of air over the ground surface will create areas with higher pressure and areas with lower pressure. This varying surface pressure is similar in effect to the barometric pressure variation, but on a much shorter time scale. Experience with temperature changes suggests that the rapid variation will not penetrate as deeply into the soil. Thus the enhanced gaseous release rate will affect gas migration to a depth less than the 0.5 cm predicted for barometric pressure variation. It is concluded that wind effects will have little effect on the average diffusion flux from the surface.

### E.2.4. Rainfall

As the water infiltrates the soil, it displaces some air from the soil pore space. As the water moves deeper, the pore space is refilled with air from the nearby pore space. This air motion will increase the mixing between adjacent layers and should increase the average diffusion flux as well.

However, as the water moves deeper in the soil, the water and air coexist in the pore space so that the motion of water has no effect on the diffusion of gases. Thus the rainfall effect is limited to a shallow surface layer. The overall effect on the average diffusion flux is very small. The largest recorded 24-h rainfall at the Hanford Meteorological Station is 4.85 cm (1.91 in), which occurred on October 1 and 2, 1957. Using a soil porosity of 35% means the water would saturate the soil to a depth of 14.0 cm (5.5 in). Thus the normal rainfall at Hanford affects gas motion in the soil to a depth considerably less than the normal temperature variation.

## E.3. DOSE CONSEQUENCES FROM AIR EMISSIONS

Two cases are described in the "No Infiltration Scenarios" of Table 2 (of the main text). The first is the "Offsite Farmer" who is downwind of the disposal site. The second is the "Onsite Resident" who lives in a dwelling affected by the gaseous emission. These scenarios are presented in more detail below. In addition, the two are compared to show that the offsite dose is always lower than the onsite dose.

The H-3 is normally found as water and would be released as water vapor. The C-14 is assumed bound in an organic compound. Presumably the organic compound could be volatile as

well. The most likely carbon compound to be emitted is carbon dioxide. However, the inhalation dose factor for carbon dioxide is about 90 times smaller than for organically bound C-14, which has been used in this report. Finally, the inhalation dose from radon compounds depends on the ease with which the particulate progeny of the inert gas become attached to dust particles in the air, as well as the relative amounts of the short half life progeny. For this reason, the radon emission is limited to 20 pCi $m^{-2}$ $s^{-1}$ (RPP-13263 and RPP-14283).

The air pathway dose downwind was estimated using Equation (8) below.

$$\text{Air Pathway Dose} = J\ A\ T\ DF \qquad (8)$$

where

J = flux of the radionuclide from the soil surface, Ci/$m^2$ per y

A = cross-sectional area of the disposal facility trenches when viewed from above

T = duration of the release, 1 y

DF = air pathway dose factor from CAP88-PC for an annual release, mrem

The air transport factor and air pathway dose factors presented below originally appeared in Section 3.2.1 of *Exposure Scenarios and Unit Dose Factors for the Hanford Immobilized Low-Activity Tank Waste Performance Assessment* (HNF-SD-WM-TI-707 Revision 1). The air transport factor is a bounding value that applies to annual emission near the border of a large area source. The dose factors were obtained using the CAP88-PC software from EPA (EPA 402-B-92-001).

### E.3.1. Offsite Farmer

Radioactivity released into the air is carried by the wind to locations some distance from the emission source. As the airborne material travels it is diluted, so that the potential doses are lessened. However, the radioactive material may settle on crops and pastures, leading to ingestion pathway doses as well as the initial inhalation dose as the plume passes the receptor location. The inhalation dose to an individual downwind is calculated using Equation (9) below.

$$H_{bt} = Q_{emit}\left(\frac{\chi}{Q'}\right) BR\ D_{inh} \qquad (9)$$

where,

$H_{bt}$ = inhalation dose at a downwind location, mrem

$Q_{emit}$ = activity released into the air as a gas or respirable particles, Ci

$\chi/Q'$ = air transport factor, 1.0E-4 s/$m^3$

BR = average breathing rate, 2.64E-4 $m^3$/s

$D_{inh}$ = inhalation dose factor for a nuclide emanating from the ground surface, in mrem per pCi inhaled. Values are given in Table A25.

Because the emission from the ground surface is assumed to take place over the course of a year, the parameters in the above are chosen to represent the annual average. Thus the annual average breathing rate is 0.95 $m^3$/h, or 2.64E-4 $m^3$/s. In addition, the activity released into the air

is the total released over the course of one year. Finally, the air transport factor (1.0E-4 s/m$^3$) is a bounding value for an annual emission (WHC-SD-WM-TI-616). It includes the normal variation in wind direction, wind speed, and atmospheric stability.

Inserting values for inhalation dose factor, and assuming a 1 Ci emission over the course of a year, leads to unit dose factors of 0.0025 mrem per Ci H-3, and 0.055 mrem per Ci C-14.

An additional method for estimating the offsite dose that takes into account the ingestion pathways is the CAP88-PC software from EPA (EPA 402-B-92-001). **The software predicts that the total doses are 0.0237 mrem per Ci H-3, and 1.32 mrem per Ci C-14.** The program output is listed in the attachment to this appendix. Note that the air transport factor used by CAP88-PC is 7.98E-6 s/m$^3$ because a distance of 1000 m was input. The doses reported by CAP88-PC were then adjusted upward by the ratio of air transport factors, namely, (1.0E-4)/(7.98E-6)=12.5 to give the values reported above. An additional difference with the simple inhalation dose method is the assumed chemical form of the carbon. In CAP88-PC the carbon is in the form of carbon dioxide, while in the simple inhalation calculation, the organic form is used. Although the organic form of carbon leads to larger inhalation doses, the ingestion pathways in CAP88-PC give most of the dose. It should be noted that the various consumption parameters in CAP88-PC are larger. For example the fraction of contaminated vegetables is 100% in CAP88-PC. The value of CAP88-PC is that is can be used to demonstrate compliance with the 10 mrem/y performance objective for airborne emissions.

The CAP88-PC output (see attachment) was interpreted according to the following procedure. From the SYNOPSIS report, the worst-case wind direction was east southeast (ESE). From the CHI/Q TABLE report, the air transport factor for this direction is 7.980E-6 s/m$^3$. From the SUMMARY report, the effective dose equivalent for H-3 is 0.00189 mrem, and for C-14 0.105 mrem.

At a location where the air transport factor is 1.0E-4 s/m$^3$, the CAP88-PC dose is computed as shown below. These values are listed in Table C1.

H-3: (0.00189 mrem)(1.0E-4 s/m$^3$)/(7.98E-6 s/m$^3$) = 0.0237 mrem

C-14: (0.105 mrem)(1.0E-4 s/m$^3$)/(7.98E-6 s/m$^3$) = 1.32 mrem

The EPA default parameter file was used as input to the CAP88-PC calculations rather than the Hanford-specific parameter file.

### E.3.2. Onsite Resident

For modeling the effect of contaminants emanating from the soil into a ventilated building, the equilibrium air concentration is the product of the emanation rate (activity per unit area per unit time) and the floor area divided by the building ventilation rate (volume per unit time). The ratio of ventilation rate to floor area is characteristic of classes of building construction. Typical ratios are less than 0.003 m/s. The individual exposed to gaseous emanations from the disposal site is located in a ventilated dwelling. For a constant emanation rate with a constant ventilation rate, the concentration starts at zero and rises according to Equation (10) below.

$$C = C_{eq}\left[1 - \mathrm{Exp}\left(-\frac{F\,t}{V}\right)\right] \quad \text{where} \quad C_{eq} = \frac{E}{\left(F/A\right)} \qquad (10)$$

Where,

$C$ = time-dependent air concentration inside the building, $Ci/m^3$

$C_{eq}$ = steady-state (or equilibrium) air concentration, $Ci/m^3$

$E$ = contaminant emanation rate, $Ci\ m^{-2}\ s^{-1}$

$A$ = building floor area, $m^2$

$F$ = building ventilation rate, $m^3/s$

$V$ = building volume, $m^3$

The ratio F/A is characteristic of certain dwellings. Two examples are listed below. Typical values will need to be established for dose calculation purposes. For radon, the DOE uses an emanation limit. For gases such as tritium (as water vapor) and carbon-14, a dose calculation can be performed.

house: $F/A = (10\ cfm)/(100\ ft^2) = 1/600\ ft/s = 5.08E\text{-}4\ m/s$

office: $F/A = (100\ cfm)/(200\ ft^2) = 1/120\ ft/s = 2.54E\text{-}3\ m/s$

Using the smaller value to maximize the equilibrium air concentration, and assuming a unit emanation rate ($1\ pCi\ m^{-2}\ s^{-1}$) leads to an equilibrium air concentration of $2000\ pCi/m^3$, or 2 pCi/L in the dirt-floor house.

The inhalation dose received by exposure to radionuclides emanating from the soil into a dwelling is the product of the steady-state air concentration, the volume of air inhaled during the year, and the inhalation dose factor as shown in Equation (11). Any decay factor is expected to be nearly one, since the nuclides that contribute to this pathway (tritium, C-14, Rn-220 and Rn-222) are expected to see very little change in the emanation rate due to radioactive decay.

$$H_{ba} = Q_{ab}\, C_{eq}\, D_{inh}\, T_{inh} \qquad (11)$$

Where

$H_{be}$ = inhalation dose from the emanation of gaseous nuclides during one year, in mrem.

$Q_{ab}$ = quantity of air inhaled by the person while in the dwelling, in $m^3/y$. The value used is 8,040 $m^3/y$ based on the sleeping and indoor data for the rural pasture scenario in Table A9.

$C_{eq}$ = steady-state concentration of gaseous nuclides in the dwelling, in pCi/L.

$D_{inh}$ = inhalation dose factor for a nuclide, in mrem per pCi inhaled. Values are given in Table A25.

$T_{inh}$ = inhalation exposure time of the individual, 1 y.

For H-3 and C-14, the inhalation doses inside a house are calculated as shown below. They are based on a unit emanation rate, 1 pCi $m^{-2}$ $s^{-1}$.

H-3: (8,040 $m^3$/y)(2000 pCi/$m^3$)(9.60E-8 mrem/pCi)(1 y) = 1.54 mrem

C-14: (8,040 $m^3$/y)(2000 pCi/$m^3$)(2.09E-6 mrem/pCi)(1 y) = 33.6 mrem

### E.3.3. Comparison of the Offsite and Onsite Individuals

A basic difference between the two dose calculations is the input radioactivity. For the offsite dose calculation, the total released into the air during one year must be estimated. For the onsite dose calculation, the rate at which activity enters the air per unit area of floor space is needed. To put the two on a comparable level, assume the ground surface directly above the waste site has a surface area of 31,690 $m^2$. A uniform emanation rate of 1 pCi $m^{-2}$ $s^{-1}$ for one year will release 1 Ci of activity into the air.

$$(1 \text{ pCi m}^{-2} \text{ s}^{-1})(31{,}690 \text{ m}^2)(3.156\text{x}10^7 \text{ s/y})(1 \text{ y}) = 1 \text{ Ci}$$

Because the offsite dose is smaller than the onsite dose for unit emission rates (Table E1), the waste site area needs to be increased to raise the offsite dose, which depends on the total emitted during the year. Table E1 shows the calculated doses and required disposal site area for the two doses to be equal. Because the disposal site surface area will be significantly less than a square kilometer (1.0E+6 $m^2$), the onsite dose will always be greater than the offsite dose.

**Table E1. Comparison of Onsite and Offsite Doses.**

| Volatile Nuclide | Onsite Resident (per pCi $m^{-2}$ $s^{-1}$) | Offsite Farmer (per Ci released) | Disposal Facility Surface Area |
|---|---|---|---|
| H-3 | 1.54 mrem | 0.0237 mrem | 2.06E+6 $m^2$ |
| C-14 | 33.6 mrem | 1.32 mrem | 8.07E+5 $m^2$ |

Disposal Site Area is calculated as the Onsite dose multiplied by 31,690 $m^2$ and divided by the Offsite dose.

## E.4. REFERENCES

ENDF/B-VI, Evaluated Nuclear Data File, Release VI. This nuclear data library is maintained by the Cross Section Evaluation Working Group. Data and documentation are available from the National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York. (also provided on www.nndc.bnl.gov).

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C A P 8 8 - P C

Version 1.00

Clean Air Act Assessment Package - 1988

S Y N O P S I S  R E P O R T

Non-Radon Individual Assessment
Nov 30, 1999 7:45 am

Facility: Various Cases
Address:
City: Richland
State: WA Zip: 99352

| Effective Dose Equivalent (mrem/year) |
|---|
| 1.07E-01 |

At This Location: 1000 Meters East Southeast
Source Category:
Source Type: Stack
Emission Year: 1996

Comments:

Dataset Name: ILAW PA
Dataset Date: Nov 30, 1999 7:45 am
Wind File: WNDFILES\HB-200E.WND

Nov 30, 1999 7:45 am

SYNOPSIS
Page 1

MAXIMALLY EXPOSED INDIVIDUAL

Location Of The Individual: 1000 Meters East Southeast
Lifetime Fatal Cancer Risk: 2.61E-06

ORGAN DOSE EQUIVALENT SUMMARY

| Organ | Dose Equivalent (mrem/y) |
|---|---|
| GONADS | 4.68E-02 |
| BREAST | 1.19E-01 |
| R MAR | 2.08E-01 |
| LUNGS | 5.64E-02 |
| THYROID | 5.61E-02 |
| ENDOST | 4.32E-01 |
| RMNDR | 1.02E-01 |
| EFFEC | 1.07E-01 |

Nov 30, 1999 7:45 am

SYNOPSIS
Page 2

RADIONUCLIDE EMISSIONS DURING THE YEAR 1996

| Nuclide | Class | Size | Source #1 Ci/y | TOTAL Ci/y |
|---|---|---|---|---|
| H-3 | * | 0.00 | 1.0E+00 | 1.0E+00 |
| C-14 | * | 0.00 | 1.0E+00 | 1.0E+00 |

SITE INFORMATION

Temperature: 12 degrees C
Precipitation: 17 cm/y
Mixing Height: 1000 m

Nov 30, 1999 7:45 am

SYNOPSIS
Page 3

SOURCE INFORMATION

Source Number: 1

Stack Height (m): 1.00
Diameter (m): 0.10

| Plume Rise Pasquill Cat: | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| Zero: | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

AGRICULTURAL DATA

| | Vegetable | Milk | Meat |
|---|---|---|---|
| Fraction Home Produced: | 1.000 | 1.000 | 1.000 |
| Fraction From Assessment Area: | 0.000 | 0.000 | 0.000 |
| Fraction Imported: | 0.000 | 0.000 | 0.000 |

Food Arrays were not generated for this run.
Default Values used.

DISTANCES USED FOR MAXIMUM INDIVIDUAL ASSESSMENT

1000

C A P 8 8 - P C

Version 1.00

Clean Air Act Assessment Package - 1988

D O S E  A N D  R I S K  E Q U I V A L E N T  S U M M A R I E S

Non-Radon Individual Assessment
Nov 30, 1999 7:45 am

Facility: Various Cases
Address:
City: Richland
State: WA Zip: 99352

Source Category:
Source Type: Stack
Emission Year: 1996

Comments:

Dataset Name: ILAW PA
Dataset Date: Nov 30, 1999 7:45 am
Wind File: WNDFILES\HB-200E.WND

Nov 30, 1999 7:45 am

SUMMARY
Page 1

ORGAN DOSE EQUIVALENT SUMMARY

| Organ | Selected Individual (mrem/y) |
|---|---|
| GONADS | 4.68E-02 |
| BREAST | 1.19E-01 |
| R MAR | 2.08E-01 |
| LUNGS | 5.64E-02 |
| THYROID | 5.61E-02 |
| ENDOST | 4.32E-01 |
| RMNDR | 1.02E-01 |
| EFFEC | 1.07E-01 |

PATHWAY EFFECTIVE DOSE EQUIVALENT SUMMARY

| Pathway | Selected Individual (mrem/y) |
|---|---|
| INGESTION | 1.06E-01 |
| INHALATION | 2.82E-04 |
| AIR IMMERSION | 0.00E+00 |
| GROUND SURFACE | 0.00E+00 |
| INTERNAL | 1.07E-01 |
| EXTERNAL | 0.00E+00 |
| TOTAL | 1.07E-01 |

NUCLIDE EFFECTIVE DOSE EQUIVALENT SUMMARY

| Nuclide | Selected Individual (mrem/y) |
|---|---|
| H-3 | 1.89E-03 |
| C-14 | 1.05E-01 |
| TOTAL | 1.07E-01 |

Nov 30, 1999 7:45 am

SUMMARY
Page 3

CANCER RISK SUMMARY

| Cancer | Selected Individual Total Lifetime Fatal Cancer Risk |
|---|---|
| LEUKEMIA | 6.60E-07 |
| BONE | 7.65E-08 |
| THYROID | 2.55E-08 |
| BREAST | 4.67E-07 |
| LUNG | 2.80E-07 |
| STOMACH | 2.48E-07 |
| BOWEL | 1.26E-07 |
| LIVER | 2.70E-07 |
| PANCREAS | 1.67E-07 |
| URINARY | 8.36E-08 |
| OTHER | 2.04E-07 |
| TOTAL | 2.61E-06 |

PATHWAY RISK SUMMARY

| Pathway | Selected Individual Total Lifetime Fatal Cancer Risk |
|---|---|
| INGESTION | 2.60E-06 |
| INHALATION | 7.62E-09 |
| AIR IMMERSION | 0.00E+00 |
| GROUND SURFACE | 0.00E+00 |
| INTERNAL | 2.61E-06 |
| EXTERNAL | 0.00E+00 |
| TOTAL | 2.61E-06 |

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SUMMARY
Page 4

NUCLIDE RISK SUMMARY

| Nuclide | Selected Individual Total Lifetime Fatal Cancer Risk |
|---|---|
| H-3 | 5.12E-08 |
| C-14 | 2.56E-06 |
| TOTAL | 2.61E-06 |

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SUMMARY
Page 5

INDIVIDUAL EFFECTIVE DOSE EQUIVALENT RATE (mrem/y)
(All Radionuclides and Pathways)

| | Distance (m) |
|---|---|
| Direction | 1000 |
| N | 3.2E-02 |
| NNW | 4.3E-02 |
| NW | 4.2E-02 |
| WNW | 3.4E-02 |
| W | 2.7E-02 |
| WSW | 2.0E-02 |
| SW | 2.1E-02 |
| SSW | 1.9E-02 |
| S | 2.4E-02 |
| SSE | 3.1E-02 |
| SE | 6.2E-02 |
| ESE | 1.1E-01 |
| E | 7.5E-02 |
| ENE | 4.3E-02 |
| NE | 3.1E-02 |
| NNE | 2.6E-02 |

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SUMMARY
Page 6

INDIVIDUAL LIFETIME RISK (deaths)
(All Radionuclides and Pathways)

| | Distance (m) |
|---|---|
| Direction | 1000 |
| N | 7.9E-07 |
| NNW | 1.0E-06 |
| NW | 1.0E-06 |
| WNW | 8.2E-07 |
| W | 6.6E-07 |
| WSW | 5.0E-07 |
| SW | 5.2E-07 |
| SSW | 4.8E-07 |
| S | 5.8E-07 |
| SSE | 7.6E-07 |
| SE | 1.5E-06 |
| ESE | 2.6E-06 |
| E | 1.8E-06 |
| ENE | 1.1E-06 |
| NE | 7.6E-07 |
| NNE | 6.4E-07 |

C A P 8 8 - P C

Version 1.00

Clean Air Act Assessment Package - 1988

C H I / Q T A B L E S

Non-Radon Individual Assessment
Nov 30, 1999 7:45 am

Facility: Various Cases
Address:
City: Richland
State: WA Zip: 99352

Source Category:
Source Type: Stack
Emission Year: 1996

Comments:

Dataset Name: ILAW PA
Dataset Date: Nov 30, 1999 7:45 am
Wind File: WNDFILES\HB-200E.WND

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CHIQ
Page 1

GROUND-LEVEL CHI/Q VALUES FOR H-3
CHI/Q TOWARD INDICATED DIRECTION (SEC/CUBIC METER)

| | Distance (meters) |
|---|---|
| Dir | 1000 |
| N | 2.429E-06 |
| NNW | 3.192E-06 |
| NW | 3.166E-06 |
| WNW | 2.521E-06 |
| W | 2.025E-06 |
| WSW | 1.524E-06 |
| SW | 1.595E-06 |
| SSW | 1.455E-06 |
| S | 1.784E-06 |
| SSE | 2.326E-06 |
| SE | 4.672E-06 |
| ESE | 7.980E-06 |
| E | 5.598E-06 |
| ENE | 3.251E-06 |
| NE | 2.330E-06 |
| NNE | 1.946E-06 |

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CHIQ
Page 2

GROUND-LEVEL CHI/Q VALUES FOR C-14
CHI/Q TOWARD INDICATED DIRECTION (SEC/CUBIC METER)

| | Distance (meters) |
|---|---|
| Dir | 1000 |
| N | 2.429E-06 |
| NNW | 3.192E-06 |
| NW | 3.166E-06 |
| WNW | 2.521E-06 |
| W | 2.025E-06 |
| WSW | 1.524E-06 |
| SW | 1.595E-06 |
| SSW | 1.455E-06 |
| S | 1.784E-06 |
| SSE | 2.326E-06 |
| SE | 4.672E-06 |
| ESE | 7.980E-06 |
| E | 5.598E-06 |
| ENE | 3.251E-06 |
| NE | 2.330E-06 |
| NNE | 1.946E-06 |

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# APPENDIX F

# TECHNICAL PEER REVIEW

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Desk Instruction 2.0, Rev. 1

## CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed - _____

Title: HNF-SD-WM-TI-707, Rev 5, *Exposure Scenarios and Unit Factors for Hanford Tank Waste Performance Assessments*, October, 2007, by Paul D. Rittmann
Scope: Main Text and Appendix A and B

| Yes | No* | NA | | |
|---|---|---|---|---|
| [X] | [ ] | [ ] | | Referenced analyses appropriate. |
| [X] | [ ] | [ ] | | Problem completely defined and all potential configurations considered. |
| [ ] | [ ] | [X] | | Accident scenarios developed in a clear and logical manner. |
| [X] | [ ] | [ ] | | Necessary assumptions explicitly stated and supported. |
| [X] | [ ] | [ ] | | Computer codes and data files documented. |
| [X] | [ ] | [ ] | | Data used in calculations explicitly stated in document. |
| [X] | [ ] | [ ] | | Data checked for consistency with original source information as applicable. |
| [X] | [ ] | [ ] | | Mathematical derivations checked including dimensional consistency of results |
| [X] | [ ] | [ ] | | Models appropriate and used within range of validity, or use outside range of established validity justified. |
| [X] | [ ] | [ ] | | Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations. |
| [X] | [ ] | [ ] | | Software input correct and consistent with document reviewed. |
| [X] | [ ] | [ ] | | Software output consistent with input and with results reported in document reviewed. |
| [ ] | [ ] | [X] | | Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references. |
| [X] | [ ] | [ ] | | Safety margins consistent with good engineering practices. |
| [X] | [ ] | [ ] | | Conclusions consistent with analytical results and applicable limits. |
| [X] | [ ] | [ ] | | Results and conclusions address all points required in the problem statement. |
| [X] | [ ] | [ ] | | Format consistent with applicable guides or other standards. |
| [ ] | [ ] | [X] | ** | Review calculations, comments, and/or notes are attached. |
| [X] | [ ] | [ ] | | Document approved (for example, the reviewer affirms the technical accuracy of the document). |

Robert Marusich Robert Marusich 10/31/07
Technical Peer Reviewer (printed name and signature) Date

* All "no" responses must be explained below or on an additional sheet.

** Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. The material should be labeled and recorded in such a manner as to be understandable to a technically qualified third party.

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