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Interagency Steering Committee on Radiation Standards



Draft Report

ISCORS Assessment of Radioactivity in Sewage Sludge: Modeling to Assess Radiation Doses



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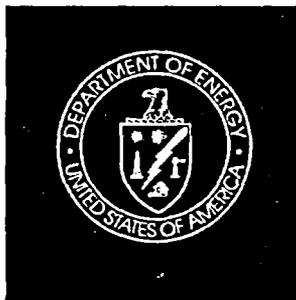
ISCORS Assessment of Radioactivity in Sewage Sludge: Modeling to Assess Radiation Doses

Developed by the Sewage Sludge
Subcommittee on Radiation Standards

**United States
Nuclear
Regulatory
Commission**



**United States
Department
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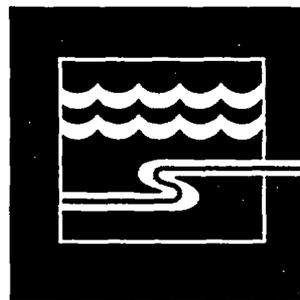
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1 **ABSTRACT**

2 The treatment of municipal sewage at publicly owned treatment works (POTWs) leads to the
3 production of considerable amounts of residual solid material known as sewage sludge, which is
4 widely used in agriculture and land reclamation. Elevated levels of naturally-occurring and
5 man-made radionuclides have been found in sludge samples, suggesting the possible radiation
6 exposure of POTW workers and members of the public. The Interagency Steering Committee on
7 Radiation Standards (ISCORS) therefore conducted a limited survey of radioactivity in sludge
8 across the United States. Concurrently, to assess the levels of the associated doses to people, it
9 undertook to model the transport of the relevant radionuclides from sludge into the local
10 environment. The modeling work consisted of two steps: First, seven general scenarios were
11 constructed to represent typical situations in which members of the public or POTW workers
12 may be exposed to sludge. Then, the RESRAD multi-pathway environmental transport model
13 generated sludge concentration-to-dose conversion factors. This Report describes the results of
14 this dose modeling effort, and provides a complete description and justification of the dose
15 assessment methodology.

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1 INTRODUCTION

2 1.1 BACKGROUND

3 The treatment of municipal sewage at publicly owned treatment works (POTWs) leads to the
4 production of considerable amounts of residual solid material, which is known as sewage sludge
5 (or “municipal sewage sludge,” or “sludge”).

6 Sewage flowing into a POTW may contain naturally occurring radioactive materials (NORM) or
7 manmade radionuclides. Groundwater, surface water, water residues from drinking water
8 treatment plants, and waste streams from certain industries (ceramics, electronics, optics) that
9 discharge into sanitary sewers may contain elevated NORM radionuclides. Also entering sewers
10 may be surface water runoff containing fallout; excreta from individuals undergoing medical
11 diagnosis or therapy; licensed discharges of limited quantities of radioactive materials from
12 DOE facilities, NRC licensees, and Agreement State licensees; and anthropogenic materials
13 exempt from licensing. (NRC regulations allowing licensees to dispose of small amounts of
14 licensed radionuclides into a sanitary sewer system may be found in the *Code of Federal
15 Regulations* at 10 CFR 20.2003.) The sewage treatment process, in turn, may lead to
16 concentration in sludge of the radioactive materials that entered into the sanitary sewer system.

17 Radioactive materials in sludge may cause radiation exposure both of POTW workers and of
18 members of the public. Municipal sewage sludge is often used as a source of organic material in
19 agriculture and land reclamation, for example, and thus may expose farmers and consumers of
20 the farm products, or those who spend time on reclaimed land. EPA’s current standard at 40
21 CFR Part 503 for the use or disposal of municipal sewage sludge protects humans from heavy
22 metals and pathogens, but it does not include radionuclide limits. Indeed, there are currently no
23 federal regulations regarding radionuclides in sewage sludge or in the ash from incinerated
24 sewage sludge (or “sewage sludge ash,” or “ash”).

25 There have been a number of cases of radionuclides discovered in sewage sludge and ash, and
26 some of these have lead to expensive cleanup projects (GAO, 1994). These incidents made clear
27 the need for a comprehensive determination of the prevalence of radionuclides in POTW sewage
28 sludge and ash around the country, and the level of potential threat posed to human health and
29 the environment by various levels of such materials.

30 In response to this need, the Interagency Steering Committee on Radiation Standards (ISCORS)¹
31 formed a Sewage Sludge Subcommittee (SSS)² to coordinate, evaluate, and resolve issues

1 ISCORS is co-chaired by the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC), and has representatives from the Department of Defense (DOD), Department of Energy (DOE), Department of Health and Human Services, Department of Labor, and observers from White House Office of Management and Budget, the Office of Science and Technology Policy, and various states.

2 SSS members are EPA and NRC, co-chairs, and DoD, DOE, the State of New Jersey, the Middlesex County Utilities Authority, and the Northeast Ohio Regional Sewer District.

1 regarding radioactive materials in sewage sludge and ash. To provide a reasonable bound on the
2 amounts of radionuclides that actually occur in sewage sludge and ash, EPA and NRC, in
3 consultations with ISCORS's SSS, have conducted a limited survey of radioactivity in sludge
4 and ash across the United States. Concurrently, the Dose Modeling Workgroup of the
5 Subcommittee has undertaken a dose assessment to help assess the potential threat that these
6 materials may pose to human health. This Report describes the methodology and results of that
7 dose modeling effort.

8 **1.2 PREVIOUS DOSE ASSESSMENTS OF RADIONUCLIDES IN** 9 **SEWAGE SLUDGE**

10 In the past, several groups have carried out examinations of potential radiation doses from
11 radionuclides in sewage sludge.

12 The DOE's Pacific Northwest National Laboratory (PNNL) conducted a scoping study in 1992
13 for the NRC (NRC 1992a) to evaluate the potential radiological doses to POTW workers and
14 members of the public from exposure to radionuclides in sewage sludge. The first part of the
15 analysis examined known cases of radioactive materials detected at POTWs and estimated the
16 potential doses to workers. The doses from these actual case studies were generally within
17 regulatory dose limits for members of the public.

18 The PNNL study went on to estimate maximum radiation exposures to POTW workers and
19 others who could be affected by low levels of man-made radioactivity in wastewater (Kennedy
20 et al. 1992). The study, which did not consider NORM/TENORM, used scenarios, assumptions,
21 and parameter values generally selected in a manner to produce prudently conservative estimates
22 of individual radiation doses. However, the quantities of radionuclides released into the sewer
23 systems were assumed to be the maximum allowed under NRC regulations at the time. Thus, the
24 calculations were not intended to be based on realistic or prudently conservative conditions at
25 POTWs, but based on maximized releases to sewer systems. The estimates of these hypothetical
26 exposures to workers range from zero to a dose roughly equal to natural background levels
27 (Kennedy et al. 1992). Table 1.1 summarizes the results for some of the scenarios considered.

28 The PNNL study concluded that although concentration of radionuclides in sewage sludge was
29 likely to occur, more information on the physical and chemical processes was necessary before
30 reliable quantitative dose estimates could be made. The calculated doses were based on
31 estimated rather than measured concentrations of radionuclides. In addition, a relatively small
32 number of radionuclides were considered.

33

Table 1.1 Hypothetical Maximum Doses (mrem/yr) from PNNL Study

| Individual | Exposure Source | Primary Exposure Pathway | Hypothetical Maximum Doses (mrem/yr) |
|----------------------------------|---------------------------------|--|--------------------------------------|
| POTW sludge process operator | Sludge in processing equipment | External | 360 |
| POTW incinerator operator | Incinerator ash | Inhalation of dust | 340 |
| POTW heavy equipment operator | Sludge or ash in truck | External | 210 |
| Farmers or commercial operators | Land applied sludge | Ingestion via local crops, external | 17 |
| Landfill equipment operator | Ash disposed in landfill | External | 64 |
| Resident on former landfill site | Ash disposed in former landfill | Inhalation via resuspension of dust, ingestion via garden vegetables | 170 |
| Source: Kennedy et al. 1992. | | | |

The State of Washington assessed potential risks to POTW workers, to farmers who spread sludge on wheat croplands, and to workers at a municipal landfill laying down sludge as cover material. This study was published as *The Presence of Radionuclides in Sewage Sludge and Their Effect on Human Health* (Washington State Department of Health, 1997). The report is based on sludge samples taken at six POTWs in the State, which were analyzed for 16 radionuclides, total uranium, and gross beta. Two exposure scenarios, involving wheat farmers and workers at a municipal landfill, incorporated information obtained in interviews with people who had direct experience in the management and use of sludge in these practices. The report concluded that doses from radionuclides in sewage sludge are extremely low compared to background or to generally accepted regulatory dose limits, and that there is no indication that radioactive materials in biosolids in the State of Washington pose a health risk.

1.3 PURPOSE OF THE PRESENT ASSESSMENT

The purpose of the present assessment is to extend and expand upon work already performed in evaluating the potential risks to humans posed by radionuclides in sewage sludge and ash. The assessment described here differs from previous ones in that it uses information obtained in the ISCORS national survey on radionuclides present in sewage sludge and ash. In addition, the exposure scenarios in this dose estimation are more detailed and comprehensive than those considered previously.

1 The information generated here will be used by NRC and EPA to determine if levels typically
2 occurring in POTW sludge and ash warrant additional testing or further analysis, and if they are
3 suggestive of the appropriateness of the development of a national regulatory program to reduce
4 radionuclide levels in sludge, or to control sludge management and the use of sludge products.

5 **1.4 GENERAL APPROACH**

6 The general approach of the study is a standard one that has been employed elsewhere (e.g.,
7 NCRP 1999). It consists essentially of two steps: First, seven general, fairly generic scenarios
8 (and some sub-scenarios) are constructed to represent typical situations in which members of the
9 public or POTW workers are likely to be exposed to sludge. The selection of radionuclides for
10 consideration was based on the results of the ISCORS survey of sewage sludge and ash at various
11 POTWs, and includes manmade and naturally-occurring isotopes. Second, assuming a unit
12 specific activity of a radionuclide in dry sludge, a widely-accepted multi-pathway environmental
13 transport model (the RESRAD family of codes) is employed to obtain sludge
14 concentration-to-dose conversion factors (To avoid possible confusion with the Dose
15 Conversion Factors of the Federal Guidance Reports (FGR 11, FGR 12, FGR 13), this study will
16 refer to these computed conversion factors as dose-to-source ratios, or DSRs). The ratios can
17 then be combined with data on radionuclide concentrations in sludge from the sewage sludge and
18 ash survey to estimate doses for all the scenarios.

19 The primary output of this assessment is calculated dose-to-source ratios for a number of
20 radionuclides and a variety of reasonably likely exposure scenarios. A DSR is defined here as
21 the dose received by a receptor for a unit activity concentration of radionuclide (37 Bq/kg or
22 1 pCi/g dry weight of sludge/ash), and it is used to convert a known activity concentration in
23 sludge to a committed Total Effective Dose Equivalent (TEDE)³ by means of the appropriate
24 RESRAD code. In some cases, additional information on indoor Radon and non-Radon
25 components of the radiation dose were also calculated.

26 **1.5 ORGANIZATION OF THIS REPORT**

27 This report provides a complete description of the dose assessment process conducted by the
28 ISCORS SSS Dose Modeling Work Group. Chapter 2 provides an overview of the scenarios
29 developed for the assessment and the rationale for the dose modeling approach. Chapter 3
30 discusses the sources of radioactive material considered in the dose assessment for each scenario.
31 Chapter 4 describes each of the scenarios and presents detailed information on input parameters
32 used and assumptions made in constructing each scenario. Chapter 5 presents analyses
33 conducted to assess uncertainty and variability in the scenarios and to identify sensitive

3 In this report, the generic term "dose" refers to "total effective dose equivalent," or "TEDE." The TEDE is defined as the sum of the effective dose equivalent (EDE) from external radiation and the 50-year committed effective dose equivalent from internal radiation, and is based on the methodology in ICRP Reports No. 26 and 30 (ICRP 1977 & 1979). TEDE is currently the basis of standards and regulations for radiation exposure in the United States. Background radiation is also generally characterized in terms of TEDE.

1 parameters and assumptions. Chapter 6 (with additional detail in Appendix E) presents the
2 results of the dose assessment: the dose-to-source ratios for each radionuclide in each scenario.
3 Chapter 7 presents dose calculations combining these dose-to-source ratios with measured
4 radionuclide concentrations, including some discussion of indoor Radon and non-Radon
5 components. Conclusions of this dose assessment are presented Chapter 8, and references are
6 listed in Chapter 9.

7 Table 1.1 identifies various source documents used to develop the guidance in this volume.
8 Source documents that have been superseded are identified in Table 1.2 in Section 1.3.3.

2 ASSESSMENT METHODS OVERVIEW

2.1 OUTLINE OF THIS DOSE ASSESSMENT

As noted in the last chapter, seven generic scenarios have been constructed in this study to represent some of the most likely situations in which workers or members of the general public might be exposed to sludge. The RESRAD family of codes was then employed to determine, for each scenario, the peak Total Effective Dose Equivalent (TEDE) to an individual exposed to sludge that contains a reference quantity of specific activity (1 pCi per gram of dry sludge, or 37 Bq per kg) of each radionuclide of concern. The result is a computed conversion factor, called the dose-to-sludge ratio (DSR), and there is one for every scenario and for each relevant radionuclide. Based on the results of the survey and the dose assessment, a decision will be made on whether additional actions should be initiated to assure protection of public health.

The scenarios were designed to estimate potential radiation doses from exposure of "average members of the critical group" (i.e., those who may come into contact with municipal sewage sludge or incinerator ash). The rationale for this approach is based on the charge to ISCORS to conduct a survey of municipal sewage sludge to determine the extent to which radioactive contamination of sewage sludge or ash is occurring, possibly causing exposure of people. The results of the dose assessment tend to be conservative (i.e., estimated doses are probably higher than actual for each scenario) as a result of choices made by the Dose Modeling Work Group of the SSS on specific input parameters and assumptions in each scenario, such as the use of the 95th percentile Dose-to-Source Ratios for calculating doses, and to extend the modeling out to 1,000 years following application of sludge.

Because the analysis in this report needs to have general applicability across the range of conditions across the country, the basic approach of the dose assessment is to model sites in a generic manner. Because a wide range of variability must be accounted for in a consistent manner, relatively simple conceptual models are used. There is no attempt to incorporate unique or heterogeneous environmental pathways that may be present and important at specific sites, so caution should be employed in applying the results of this analysis to particular sites. A summary of the limitations of this assessment is presented at the end of this chapter.

2.2 EXPOSURE SCENARIOS

Each hypothetical scenario presented in this assessment consists of a narrative description and a set of exposure pathways. Guided in part by examples from previous assessments by DOE, EPA, and NRC, the Work Group developed scenarios that are generic (i.e., not based on the characteristics of any particular site) but that account for sludge and ash management practices. The scenarios are intended to represent a variety of different uses or disposal options for sewage sludge, and situations where radiation exposure is likely. For each, all the standard environmental transport (resuspension of dust, leaching into groundwater, etc.) and exposure (external exposure, inhalation, and ingestion) pathways were considered.

1 The seven scenarios created for this assessment fall into four general categories of sludge/ash
2 management and processing practices. They reflect the observation that most exposure of the
3 public to sludge results from its land application, disposal in a landfill, or incineration.
4 Exposures of a worker through proximity to or direct contact with the sludge can occur during
5 processing, sampling, loading, transport, or application. The scenarios have been designed so
6 that exposures to the seven following groups may be explored:

- 7 1. Residents of houses built on agricultural fields formerly applied with sludge;
- 8 2. Recreational users of a park where sludge has been used for land reclamation;
- 9 3. Residents of a town near fields upon which sludge has been applied;
- 10 4. Neighbors of a landfill that contains sludge and/or ash;
- 11 5. Neighbors of a sludge incinerator;
- 12 6. Agricultural workers who operate equipment to apply sludge to agricultural lands; and
- 13 7. Workers at a POTW involved in sampling, transport, and biosolids loading operations.

14 Scenarios 1 through 3 consider different kinds of intentional land application of sludge. For the
15 first two, people are exposed while living on a site of former application, and are said to be
16 “onsite.” The residents of the nearby town, by contrast, are not located at a site where sludge
17 actually has been or is being applied, but rather are exposed to radionuclides that are transferred
18 away from the source field by wind, groundwater flow, or other pathways; they are said to be
19 “offsite.” Scenarios 4 and 5 treat two other kinds of sludge or ash disposal for which the exposed
20 populations are also offsite. The distinction is important because dose assessment for offsite
21 populations is more complex than for onsite, and requires more sophisticated modeling. The last
22 two scenarios consider possible exposure of agricultural and POTW workers.

23 **2.3 SELECTION OF THE MODEL CODE**

24 Because of the many possible pathways of exposure, a multimedia computer code was selected
25 for the calculations, according to the following criteria. The model should accommodate the
26 physical conditions of the scenarios and, in particular, it must

- 27 1. Include (or be able to include) all radionuclides of concern;
- 28 2. Cover the relevant environmental transport pathways;
- 29 3. Include all important exposure pathways;
- 30 4. Contain a manageable number of parameters;
- 31 5. Incorporate established sensitivity and probabilistic uncertainty analyses;
- 32 6. Have undergone extensive verification and peer-review; and
- 33 7. Be widely used and accepted, so that the calculations can be readily replicated or modified.

1 The first three criteria ensure that the essential elements of each scenario's conceptual model are
2 included. The fourth requires that the numbers of parameters involved are in the hundreds, not
3 tens of thousands; it is necessary because of resource constraints, but fully justified by the
4 generic nature of the scenarios. Criterion 5 reflects the preference for using methods that have
5 previously been developed for sensitivity and uncertainty analyses, rather than developing new
6 methods; it also makes it possible for outside parties to reproduce the results. Criterion 6 is
7 needed because, given the complex nature of the assessment, independent verification of every
8 calculation would be intractable. Finally, the model should be widely available, well
9 documented, and user friendly, for use by interested parties in independent verification of study
10 analyses and results.

11 A number of computer models were considered for use in this effort, and Table 2.1 summarizes
12 how the four finalists compare, according to the seven criteria. The RESRAD family of codes,
13 including RESRAD version 6.0, RESRAD-BUILD version 3.0, and RESRAD-OFFSITE
14 version 1.0, was selected largely because of its flexibility in scenario development. It contains
15 the necessary data on most relevant radionuclides, and can easily accommodate others; it
16 accounts for all transport and exposure pathways of interest, yet it employs a manageable number
17 of parameters (about 140 for RESRAD, 300 for RESRAD-OFFSITE, and 40 for
18 RESRAD-BUILD). In addition, it has built-in sensitivity and probabilistic uncertainty analysis
19 modules, has undergone more extensive testing than the others, and is widely used within the
20 remediation community so as to be more familiar than the others to most DOE, DoD, EPA, and
21 NRC users.

22 Because Scenarios 1, 2, and 6 involve only onsite receptors, their doses can be estimated with
23 RESRAD Version 6. Scenarios 3, 4, and 5 are complicated by offsite transport, and hence are
24 examined with the RESRAD-OFFSITE code (in combination with the CAP88-PC code to
25 account for airborne transport of radioactive material away from the source). Workers at the
26 POTW spend nearly all their time indoors, requiring the use of the RESRAD-BUILD code in
27 Scenario 7. A summary of the scenarios and the model codes used is in Table 2.2.

28 RESRAD 6.0 and RESRAD-BUILD are simply relatively recent probabilistic versions of
29 established deterministic codes, but RESRAD OFF-SITE contains newer components, and is
30 currently still under testing and further development. Experience with RESRAD OFF-SITE has
31 revealed no substantive problems with it but, in any case, preliminary scoping calculations have
32 suggested that the magnitude of the off-site doses are relatively very low, so that the status of the
33 code should not be significant to the final results.

34 A description of the RESRAD family of codes, including references to how the calculations are
35 performed, appears in Appendix B.

Table 2.1 Comparison of Models

| Model Selection Criterion | RESRAD Family ⁽¹⁾ | PRESTO CLNCPG Vers. 4.2 | GENII ⁽²⁾ Vers. 2.0 | DandD Vers. 1.0 |
|---|------------------------------|-------------------------|--------------------------------|-----------------|
| (1) Radionuclides of concern | × ⁽³⁾ | × | × | × |
| (2) Environmental transport pathways | | | | |
| (2.1) Resuspension | × | × | × | × |
| (2.2) Groundwater infiltration and transport | × | × | | × |
| (2.3) Surface water run-off ⁽⁴⁾ | × | × | × | |
| (3) Exposure pathways | | | | |
| (3.1) External gamma radiation | × | × | × | × |
| (3.2) Inhalation of airborne particles outdoors | × | × | × | × |
| (3.3) Inhalation of radon (indoors) | × | × | | |
| (3.4) Inhalation of radon (outdoors) | × | × | | |
| (3.5) Ingestion of water from a well | × | × | | × |
| (3.6) Ingestion of surface water | × | × | × | |
| (3.7) Ingestion of vegetables, fruits, grains, milk, and meat produced on treated land | × | × | × | × |
| (3.8) Ingestion of fish from nearby waters | × | × | × | × |
| (3.9) Inadvertent ingestion of soil | × | × | × | × |
| (4) Manageable number of parameters | × | × | × | × |
| (5) Sensitivity and probabilistic uncertainty analyses | × | | × | |
| (6) Extensive validation, verification, and peer review | × | | × | × |
| (7) Widely used and accepted | × | | | |
| <p>Notes:</p> <ol style="list-style-type: none"> 1. In this report, the RESRAD family refers to RESRAD 6.1, RESRAD-OFFSITE 1.0, and RESRAD-BUILD 3.0, all of which are available through the RESRAD website at Argonne National Laboratory. 2. GENII Version 2.0 runs in the FRAMES environment. 3. Additional nuclides can be added to RESRAD 4. RESRAD does not include runoff transport, and the on-site scenarios do not account for it. RESRAD OFF-SITE does incorporate this pathway. | | | | |

1 **Table 2.2 Scenarios and Models in this Assessment**

2

| Scenario | Exposed Individual * | Multiple Applications | Model Code |
|--|----------------------|-----------------------|---------------------------|
| <u>Land Application</u> | | | |
| 1. Onsite residents | on-site | ✓ | RESRAD Version 6 |
| 2. Recreational users – reclamation | on-site | ✓ | RESRAD Version 6 |
| 3. Residents of nearby town | off-site | | RESRAD-OFFSITE/ CAP-88 |
| <u>Landfill Disposal</u> | | | |
| 4. Landfill neighbors – sub-scenarios for MSW and impoundment | off-site | | RESRAD-OFFSITE/ CAP-88 |
| <u>Incineration</u> | | | |
| 5. POTW incinerator neighbors | off-site | ✓ | RESRAD-OFFSITE/ CAP-88 |
| <u>Occupational Exposure</u> | | | |
| 6. Agricultural sludge application worker | on-site | ✓ | RESRAD Version 6 |
| 7. Indoor POTW worker – sub-scenarios for different POTW operations | on-site | | RESRAD-BUILD Version 3 |
| <p>Note:</p> <p>* “Site” refers to the area where sludge is originally applied or, for Scenario 7, produced.</p> | | | |

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23 **2.4 PARAMETER VALUES AND DISTRIBUTIONS**

24 **2.4.1 FIXED VALUE AND DISTRIBUTIONS FOR MODELING**

25 **PARAMETERS**

26 Each scenario must be translated from a qualitative narrative and a list of potential transport and

27 exposure pathways into a specific set of parameter values suitable for use in a particular model.

28 Since probabilistic calculations are needed to assess the uncertainty and variability of the DSR

29 values quantitatively, distributions are generally appropriate for the most sensitive parameters.

30 For parameters that are somehow found to be less sensitive, single parameter values may be used.

1 A fundamental change has recently been occurring in the way radionuclide transport modeling
2 calculations are carried out. A traditional, so-called *deterministic* calculation involves the use of
3 a fixed set of parameter values, and the result is a single curve of dose vs. time.

4 A *probabilistic* (also known as a stochastic or Monte Carlo) calculation, by contrast, requires the
5 performance of hundreds or thousands of separate dose computations, each with its own set of
6 randomly selected parameter values; instead of a single value, a parameter would be represented
7 by a probability distribution function (or a cumulative distribution function, which contains the
8 same information but is presented differently) which records the probability (*i.e.*, the relative
9 frequency) with which a particular value for the parameter will be sampled for inclusion in a run.
10 Statistical combination of the results from all these runs yields a variety of dose vs. time curves,
11 recording the time dependence of the mean dose, the median dose, or any desired percentile dose
12 (*e.g.*, the 95-percentile curve, below which the true dose is 95% likely to occur). In general,
13 probabilistic calculations were employed in this study to determine the evolution of DSRs, as
14 functions of time, for each scenario and radionuclide. The point DSRs recorded in Chapter 6
15 correspond to the peak doses obtained when the calculation is carried out on a steady-state
16 population over a one-thousand year time span; the time of the peak dose will depend, of course,
17 on the properties of both the scenario and the radionuclide.

18 For many parameters, values and distributions were selected that are specific to the scenario at
19 hand. For others, generic (that is, non-scenario-specific) values and distributions are adequate,
20 and usually easier to obtain. This is particularly true for plant and animal transfer factors, food
21 holdup times prior to ingestion, livestock or plant water fractions, soil characteristics, human
22 behavioral data such as inhalation and ingestion rates under various conditions, and other values
23 and distributions that are either based on national databases or accepted by regulatory agencies
24 such as NRC or EPA. Many of these appear as entries in EPA's Exposure Factors
25 Handbook (EPA 1997) and similar compilations. For a number of standard parameters employed
26 by RESRAD, generic distributions have recently become available (NRC 2000b); this document,
27 incidentally, notes that the parameters for which they have provided distributions had been
28 identified as generally having more influence on calculated dose results than parameters not
29 included.

30 Because many of these parameter values and distributions do not change from scenario to
31 scenario, a set of "baseline" parameter values and distributions have been defined for each
32 RESRAD code and listed in tabular form in Appendix A. The relatively small number of
33 scenario-specific parameter values that distinguish the scenarios from one another may thus be
34 thought of as variations from the baseline, and these are addressed individually in each scenario
35 description. For baseline parameters for which values or distributions are not available, the
36 RESRAD default values are used, unless another value is clearly indicated. In all cases, the
37 default RESRAD values are listed for reference (in parentheses if not used).

2.4.2 USE OF DISTRIBUTIONS IN DETERMINISTIC CALCULATIONS

In some cases (in accounting for multiple years of application, as will be discussed below) it is necessary to perform deterministic calculations in addition to the probabilistic ones. Suitable average or central-tendency parameter values must then be derived from the distributions. In deterministic runs, means (arithmetic or geometric) are computed from the distributions to replace them, as denoted in Appendix A.

2.4.3 PRIORITIES IN PARAMETER SELECTION

To summarize, the justifications for parameter values and probability distributions for input into the RESRAD family of codes are as follows, in the order of priority:

1. Scenario-description parameter values and distributions;
2. Other specified generic parameter values and distributions;
3. NRC's NUREG/CR-6697 (NRC 2000b) distributions:
 - for probabilistic runs, default distributions
 - for deterministic runs, find and use sample means (geometric mean for lognormal distributions; arithmetic mean for others);
4. RESRAD default values (Yu et al 2001)

2.5 INTERPRETATION OF RESULTS OF THE PROBABILISTIC CALCULATIONS

For a particular scenario and for the reference amount of specific activity of some radionuclide, the probabilistic version of RESRAD carries out J realizations, labeled $j = 1, 2, \dots, J$. That is, for each j , the Monte Carlo module quasi-randomly selects a value for every RESRAD variable parameter, where the probability of selection of any particular value is determined by that parameter's distribution function, and RESRAD then computes the dose, $d_{sr_j}(t)$, as a function of time. The program then searches for the global maximum in $d_{sr_j}(t)$, which we call DSR_j , for every realization. (The maxima in $d_{sr_j}(t)$ is likely to occur at different times for different realizations, or values of the index j).

The values of DSR_j for the J realizations themselves form a distribution, with a mean, a 95-th percentile value, *etc.*, and these are the DSR-entities tabulated in this report.

2.6 SENSITIVITY, UNCERTAINTY, AND VARIABILITY

The sensitivity analysis in this dose assessments relies to a large extent on previous work in analyzing parameter sensitivities of the RESRAD codes. For RESRAD and RESRAD-BUILD, categorization and ranking of parameter sensitivities is documented in NRC (2000ab). Additional sensitivity analysis was done in some cases, and are described in Chapter 5.

1 Any modeling contains both quantitative and qualitative uncertainties and variabilities. There are
2 a number of known, but largely unavoidable, sources of quantitative uncertainty both in the
3 RESRAD modeling of physical transport and exposure and in the ICRP metabolic determination
4 of the dose conversion factors that convert intake to committed total effective dose equivalent.
5 Measurement of a physical parameter such as soil hydraulic conductivities or an element-specific
6 partition coefficient will yield a range of values, because of both normal experimental error and
7 physical variations among samples. Uncertainty and variability may be addressed to some extent
8 through the specification of sub-scenarios within each exposure scenario, or more generally
9 through the use of sampling of probability distributions for parameter values (*e.g.*, by way of the
10 Latin Hypercube method.)

11 Qualitative uncertainties and variabilities are those that are known to exist, but which cannot be
12 readily quantified. A significant source of qualitative variability is in the specification of the
13 exposure scenarios. In the present assessment, these qualitative issues are addressed through
14 discussions with peer review groups and experts.

15 A unique source of uncertainty arises in dealing with multiple years of application. RESRAD, in
16 its current configuration, can carry out a Monte Carlo analysis only for the case of a single
17 application of sludge. Approximate scaling factors were therefore developed, employing only
18 deterministic calculations, to handle scenarios with multiple years of agricultural application. It
19 is believed the approach taken, described in the next chapter, introduces an error that is small but
20 that, at present, has not been estimated quantitatively.

21 **2.7 ASSESSMENT OF CONTRIBUTIONS FROM INDOOR RADON** 22 **PATHWAY**

23 Additional calculations separating radon and non-radon components were performed in cases
24 where the indoor radon pathway contributed more than 10% of the calculated dose. In these
25 cases, radon exposure was also calculated in terms of Working-Level units as well as air
26 concentrations (pCi/L) for the different radon daughters. This separation was done for several
27 reasons. From the source perspective, indoor radon levels are highly variable and there is
28 insufficient data to capture the extent of this variability in the probabilistic assessment. In
29 addition, radon dosimetry is complex, and doses other than TEDE may be more informative.
30 Finally, indoor radon standards and benchmarks are often based on either Working-Level units or
31 air concentrations, rather than TEDE.

32 **2.8 LIMITATIONS OF THE CURRENT ASSESSMENT**

33 There are important limitations to this modeling effort, brought about by the need to carry out a
34 generic assessment across a diverse range of possible situations and environments, by the
35 insufficiency of parameter information, and by bounds on the capabilities of the models
36 available. The contributions of some of these to the uncertainties in the assessment results are
37 discussed in detail in Chapter 5.

1 **2.8.1 SOURCES**

2 This assessment evaluates DSRs for the processing, use, or disposal of municipal sewage sludge
3 and ash. Although more than forty radionuclides were included in this assessment, it is possible
4 that other radionuclides that are not anticipated to be present in the sewage may exist in the
5 system. It may not account for all the sources of radiation exposure associated with the treatment
6 of municipal sewage such as the presence of radionuclides in liquid influent and effluent. In
7 some cases, POTWs, may use treated effluent as irrigation water on agricultural lands or other
8 fields. Because the current joint NRC/EPA survey only measured radioactivity in sludge and
9 ash, dose modeling of radionuclides is only limited to sludge and ash. Nevertheless, it should be
10 noted that additional radiation exposure from POTW liquid effluent is possible.

11 **2.8.2 SCENARIOS**

12 The scenarios evaluated in this assessment were developed to represent relatively common, real
13 conditions, that would be likely to lead to radiation exposures that are typical, rather than worst
14 case. While it is possible to consider only a few hypothetical situations, great effort has been
15 made to ensure that the scenarios considered in this Report represent a reasonable range of
16 exposures without being overly conservative. In certain unique or unusual circumstances,
17 radiation exposure may be greater.

18 **2.8.3 MODELS**

19 This study utilizes existing models and generalized scenarios which make possible an overall
20 assessment without having to gather a large amount of site-specific data. There are many site-
21 specific factors – such as fracture flow, soluble and colloidal transport, the impact of the POTW
22 sludge de-watering operations on the transport and bioavailability of radionuclides, and year-to-
23 year and seasonal changes in environmental conditions – that will impact individual assessments
24 but are not considered or needed here in the general assessment. Thus while the study does
25 include the average effects of some of these processes in a generic manner, it has not attempted
26 to model unique or heterogeneous environmental conditions that may be important at specific
27 sites. Caution should therefore be exercised in applying the results of this assessment to
28 individual sites.

3 SOURCE ANALYSES AND RELATED ISSUES

1 This chapter covers two topics. The first is the rationale for the particular set of radionuclides
2 considered in the dose assessment and the ways in which decay chains are handled. The second
3 is the determination and preparation for entry into RESRAD of the source terms for the various
4 scenarios and sub-scenarios considered.

5 3.1 RADIONUCLIDES CONSIDERED IN THE DOSE ASSESSMENT

6 The principal objective of this dose calculation study is to assist in the analysis of the results of
7 the ISCORS POTW survey, and to support the ISCORS SSS in preparing guidance for POTW
8 operators. As such, it covers all radionuclides identified in the pilot survey conducted in 1997,
9 revised in May, 1999 (EPA 1999a), and any additional radionuclides found by spectrometry
10 analysis during the full survey. These radionuclides are listed in Table 3.1. Information on
11 daughters for radionuclides included in standard RESRAD is presented by Yu *et al.* (RESRAD
12 Manual, Table 3.1, 2001).

13 RESRAD distinguishes between "principal" and "associated" progeny in decay chains. A
14 *principal* radionuclide is one with a half-life longer than a user-specified cutoff (RESRAD
15 allows selection of 30 days or one-half year for the cutoff time). In the present assessment, this
16 cutoff time is selected to be 30 days. An *associated* radionuclide has a half-life less than the
17 cutoff; the nuclides "associated" with a principal radionuclide consist of all decay products down
18 to, but not including, the next principal radionuclide in the chain. This dose assessment assumes
19 that all associated radionuclides (except radon daughters) remain in secular equilibrium with
20 their principal radionuclide in the contaminated zone, along transport pathways, and at the
21 location of human exposure.⁴

22 The radiation dose calculated for a radionuclide listed in Table 3.1 includes the contributions into
23 the future of *all* the daughter radionuclides (principal and associated) in the decay chain from
24 decay of the listed nuclide. This assumption ensures that the assessment does not underestimate
25 the potential impact of that radionuclide.

4 There are many natural and man-made processes which may affect the equilibrium of the nuclides within sludge. For this reason, for site-specific analyses, the processing method of the sludge and the location and type of sludge samples collected at the POTW should be known prior to making assumptions concerning equilibrium when conducting a site-specific dose assessment.

Table 3.1 Radionuclides Included in the Dose Assessment^a

| Radionuclide | Major Radiations | Half-life | Radionuclide | Major Radiations | Half-life |
|---------------------|--------------------|------------|---------------------|------------------|--------------------------|
| Ac-227 ^d | alpha, beta, gamma | 22 years | Po-210 ^c | alpha | 138 days |
| Ac-228 ^e | beta, gamma | 6 hours | Pu-238 | alpha | 88 years |
| Am-241 | alpha, gamma | 432 years | Pu-239 | alpha | 24×10 ³ years |
| Be-7 ^b | gamma | 53 days | Ra-223 ^e | alpha, gamma | 11 days |
| Bi-212 ^c | alpha, beta, gamma | 61 minutes | Ra-224 ^e | alpha, gamma | 4 days |
| Bi-214 ^c | beta, gamma | 20 minutes | Ra-226 | alpha, gamma | 1600 years |
| C-14 | beta | 5730 years | Ra-228 | beta | 6 years |
| Ce-141 | beta, gamma | 33 days | Rn-219 ^c | alpha, gamma | 4 seconds |
| Co-57 | gamma | 271 days | Sm-153 ^b | beta, gamma | 47 hours |
| Co-60 | beta, gamma | 5 years | Sr-89 | beta | 51 days |
| Cr-51 ^b | gamma | 28 days | Sr-90 | beta | 29 years |
| Cs-134 | beta, gamma | 2 years | Th-227 ^c | alpha, gamma | 19 days |
| Cs-137 | beta, gamma | 30 years | Th-228 | alpha, gamma | 2 years |
| Eu-154 | beta, gamma | 9 years | Th-229 ^c | alpha, gamma | 7,340 years |
| Fe-59 | beta, gamma | 45 days | Th-230 | alpha | 77×10 ³ years |
| H-3 | beta | 12 years | Th-232 | alpha | 14×10 ⁹ years |
| I-125 | gamma | 60 days | Th-234 ^c | beta, gamma | 24 days |

Table 3.1 Radionuclides Included in the Dose Assessment^a (continued)

| Radionuclide | Major Radiations | Half-life | Radionuclide | Major Radiations | Half-life |
|----------------------|------------------|----------------------------|----------------------|------------------|-----------------------------|
| I-131 ^b | beta, gamma | 8 days | Tl-201 ^b | gamma | 3 days |
| In-111 ^b | gamma | 3 days | Tl-202 ^b | gamma | 12 days |
| K-40 | beta, gamma | 1.3×10 ⁹ years | Tl-208 ^c | beta, gamma | 3 minutes |
| La-138 ^b | beta, gamma | 135×10 ⁹ years | U-233 ^c | alpha | 158.5×10 ³ years |
| Np-237 ^c | alpha, gamma | 2.14×10 ⁶ years | U-234 | alpha | 245×10 ³ years |
| Pa-231 ^c | alpha, gamma | 32.8×10 ³ years | U-235 | alpha, gamma | 700×10 ⁶ years |
| Pa-234m ^c | beta, gamma | 1 minute | U-238 | alpha | 4.5×10 ⁹ years |
| Pb-210 | beta, gamma | 22 years | Xe-131m ^c | gamma | 12 days |
| Pb-212 ^c | beta, gamma | 11 hours | Zn-65 | beta, gamma | 244 days |
| Pb-214 ^c | beta, gamma | 27 minutes | | | |

Source: EPA 1999b.

Notes:

- a: Information on daughters for standard RESRAD radionuclides is included in Table 3.1 of the RESRAD manual (Yu *et al.*, 2000).
- b: This radionuclide is not included in standard RESRAD, and was added as input to the code specifically for this project.
- c: Although this nuclide was not identified in the previous survey (EPA 1999), it is included in the dose assessment because it is a principal nuclide and its parent nuclide is included in the analysis. Am-241 decays to Np-237, U-233, and Th-229; U-235 decays to Pa-231; Pb-210 decays to Po-210; and I-131 decays to Xe-131m.
- d: Although this nuclide was not identified in the previous survey (EPA 1999), it is included in the assessment because it is the parent nuclide and its daughter nuclides are included in the analysis. Ac-227 is the parent nuclide of Ra-223, Rn-219, and Th-227.
- e: Radiological dose for this radionuclide is included in the dose of its parent nuclide. The parent nuclides are Ra-228 for Ac-228; Th-228 for Bi-212, Pb-212, Ra-224, and Tl-208; Ra-226 for Bi-214 and Pb-214; U-238 for Pa-234m and Th-234; and Ac-227 for Ra-223, Rn-219, and Th-227.

1 Several radionuclides that were not identified in the POTW survey have nonetheless been
2 included in Table 3.1 because they are either a parent or a daughter of a radionuclide that was
3 analyzed in the survey. These are Ac-227, Np-237, Pa-231, Po-210, Th-229, U-233, and
4 Xe-131m. Except for Ac-227, which is a parent radionuclide (of Ra-223, Rn-219, and Th-227),
5 the others are all principal daughter nuclides of which the parent nuclides were detected in the
6 survey.

7 3.2 LAND APPLICATION SCENARIOS

8 In the Onsite Resident (1), Land Reclamation (2), Nearby Town (3), and Agricultural Worker (6)
9 scenarios, sludge is applied directly to agricultural or reclamation land and then mixed into the
10 top fifteen centimeters through tilling and natural processes such as plant root action.
11 Application may occur a single time or annually for 5, 20, 50, or 100 years.

12 3.2.1 SPECIFIC ACTIVITY IN SOIL-SLUDGE MIXTURE

13 The activity concentration (*i.e.*, specific activity) of the source term for RESRAD is that of the
14 soil-sludge mixture, rather than of the sludge alone. The average concentration of a radionuclide
15 in soil depends on its initial concentration in the sludge, the continuous processes of radionuclide
16 decay and ingrowth, the amount of sludge deposited per application, the number of prior (annual)
17 applications that have occurred, the extent of tillage, and other factors. A simple expression for
18 it assumes that sludge of specific activity A_{sludge} [Bq/kg or pCi/g], is applied at a rate of S
19 [metric tons/hectare], and mixed into the top d [m] of soil that has density r [kg/m³]. The
20 specific activity in soil is then

$$21 \quad A_{\text{soil}} = A_{\text{sludge}} \times S / (d \times r) \quad (3.1a)$$

22
23 for a single land application.

24 The present dose assessment assumes for its calculations a reference initial specific activity in
25 dry sludge (1 pCi/g or 37 Bq/kg) of any single radionuclide, and an assumed application rate of
26 10 metric tons dry sludge matter⁵ per hectare per year, or 1 kg/m². (One metric ton is equal to
27 1,000 kg, and a hectare is 10,000 m².) Tillage depth is assumed to be 15 cm, and the soil density

5 Annual applications for agricultural utilization are found to range from 2 to 70 metric tons/hectare (1 – 30 tons/acre), and more typically from 5 to 20 metric tons per hectare-year, as used in the EPA Part 503 rulemaking assessment. A typical rate is 11 metric tons/hectare (5 tons/acre) per year, which was rounded to 10 in this dose assessment. (EPA 1983, EPA 1995, Sopper 1993)

Applying aqueous sludge mixtures at the same mass rate would result in soil radionuclide concentrations that are lower by the mass fraction of solids in the aqueous mixture.

1 value of $r = 1520 \text{ kg/m}^3$ is the mean of the soil density distribution presented in NRC (2000b).⁶
2 Inserting these in Equation 3.1a yields

$$3 \quad A_{\text{soil}} = 0.16 \text{ Bq/kg (0.0044 pCi/g)} \quad (3.1b)$$

4
5 the value used here for direct agricultural application.

6 Other sludge application rates can be accommodated by appropriately scaling this value. For
7 instance, since the application rate assumed for land reclamation was greater by a factor of ten,
8 the resulting initial activity concentration will be 10 times higher, or 1.6 Bq/kg (0.044 pCi/g).

9 **3.2.2 MULTIPLE YEARS OF APPLICATION AND WAITING** 10 **PERIODS**

11 For scenarios that involve multiple years of application, the issue of soil concentration is
12 complicated by the processes such as decay, ingrowth, and leaching, resulting in the need to
13 account for the radioactivity added to the soil in previous years' applications in the dose
14 calculation. The RESRAD code does not include time-dependent source terms, at present, so it
15 cannot carry out a standard Monte Carlo calculation that involves multiple years of application.
16 In addition, if there is a waiting period between the application (whether single or multiple) and
17 the beginning of exposure, the present probabilistic implementation cannot account for this. It is
18 therefore necessary to develop approximate *scaling factors* for each scenario, employing only
19 deterministic calculations, to extrapolate the results for a single year application (obtained with a
20 probabilistic calculation) into multiple-year application results as well as accounting for any
21 waiting periods — a process that can be viewed as creating an “effective” source term for the soil
22 concentration.

23 To estimate the dose rate resulting from n annual sludge applications, one first carries out a
24 single-application, *probabilistic* run at the time of the first application, $n = 1$, which yields the
25 dose D_1^{prob} . This is then scaled for multiple applications by means of a factor, F_n ,

$$26 \quad D_n = D_1^{\text{prob}} \times F_n \quad (3.2)$$

6 RESRAD can employ a probability distribution for soil density and another for specific activity of contaminated soil in its calculations, but it cannot, as currently configured, explicitly link the two parameters through a simple mathematic equation. Several options for dealing with this limitation were considered. It would not be difficult simply to modify the code to incorporate such an equation, thereby accounting for the dependence of the source's specific activity on soil density; this, however, would also make it more difficult for outside parties to reproduce the sludge dose modeling results reported here. Another option would be to employ a correlation between the final soil concentration and the soil density probabilistically. But this would require significant effort to determine, confirm, and test the associated correlation coefficient. Furthermore, the algebraic relationship in Equation 3.1 would not be reproduced exactly by the rank correlation coefficient method used in the Latin Hypercube algorithm. It was, therefore, decided to fix both the soil density and the specific activity of the sludge-soil mixture in this assessment. The range of plausible densities for agricultural soils is not that large and, in any case, the significance of soil density is examined in the sensitivity analysis.

1
 2 where F_n is defined as the ratio, $[D_n^{\text{prob}}/D_1^{\text{prob}}]$, of two doses obtained probabilistically – one
 3 after n annual applications, and the other immediately after a single application, respectively.
 4 But we have no way to calculate D_n^{prob} at present (which, of course, was the problem in the first
 5 place), so we choose estimate F_n using deterministic calculations in the manner that follows.

6 The development of the scaling factors themselves is based on the principle of superposition, and
 7 on the assumption of time shift invariance – that is, that the time dependence of the dose caused
 8 by a particular application of sludge depends only on the difference between the time of interest
 9 and the time of application. Then the composite dose from two applications can be obtained by
 10 superimposing that from the second onto that from the first, but with the time of application
 11 shifted. The specific procedure for this process is as follows.

12 First, the model code is run deterministically for a scenario for a single application at time $t = 0$.
 13 In this calculation, the Monte Carlo distribution for any parameter is replaced by a corresponding
 14 fixed, averaged value, as described in Section 2.4.2. This run gives the dose $D^*(t)$ for any time
 15 in the future from a single application at $t = 0$, where t represents the time *difference* between
 16 the year of application and the year in which dose is calculated. Thus, if an application happened
 17 during year j , then the dose at year t due to that application would be simply $D^*(t-j)$.

18 For a series of n annual applications, the dose at time t would be the sum of $D^*(t-j)$ from
 19 $j = 0$ to $n-1$:

$$20 \quad D_n(t) = \sum D^*(t-j), [j = 0, \dots, n-1], \quad (3.3a)$$

21
 22 where this expression is meaningful only with the constraint

$$23 \quad t \geq (n-1). \quad (3.3a)$$

24
 25 Suppose that residents of the property, or the members of any other relevant critical population
 26 group, come into direct or indirect contact with the source r years after the last (the n -th)
 27 application, in year $(n-1+r)$. The dose from all applications combined is still given by

$$28 \quad D_n(t) = \sum D^*(t-j), [j = 0, \dots, n-1], \quad (3.4a)$$

29
 30 but Equation (3.3b) is replaced by

$$31 \quad t \geq (n-1+r). \quad (3.4b)$$

32
 33 Equations (3.4) are suitable for obtaining F_n , but it is convenient to go one step further. Let us
 34 shift time and rename it from t to t_r , defining its origin, $t_r = 0$, as the moment that people first
 35 become exposed, so that $t_r = t - (n-1+r)$. We also transform the index $k = (n-1+r) - j$, so
 36 that Equations (3.3) become

$$D_n(t_r) = \sum D^*(t_r + k), [k = r, \dots, r + n - 1], t_r \geq 0, \quad (3.5)$$

With this transformation, $k = r$ represents the dose originating from the *most recent* application alone, whereas $k = r + n - 1$ represents the dose originating from the *first* application alone. For the Onsite Resident scenario, where r is set to $r = 1$, the index k runs from 1 to n . It is Equation (3.4) that was used to compute the scaling factors for all seven scenarios, with $n = 1, 5, 20, 50$, and 100 years of application.

Because the quantities of interest are the maximum (peak) doses, the scaling factor, F_n , is defined as the ratio of the peak deterministic doses from n years of application and the basic, single dose-run,

$$F_n = \max[D_n(t_r)] / \max[D^*(t)] \quad (3.6a)$$

or, defining t^{max} as the time where $D(t)$ is greatest, then

$$F_n = D_n(t_r^{max}) / D^*(t^{max}) \quad (3.6b)$$

When re-written so as to account for time, Equation (3.2) then becomes

$$D_n(t) = \sum D^*(t - j), [j = 0, \dots, n - 1], \quad (3.6c)$$

where F_n is independent of time.

A limitation is that thicknesses of the contaminated zone and unsaturated zone need to remain unchanged during the time period of interest ($t_r = 0$ to 1,000 years). The contaminated zone erosion rate and the groundwater table drop rate were therefore set to 0. The dose results obtained with these assumptions might be slightly more conservative than without them.

It should also be noted that even if $n = 1$, the scaling factor may not equal one. In particular, if there is a waiting period after exposure ($r > 0$), and the maximum of $D^*(t)$ occurs at $t = 0$, then the $F_1 < 1$.

3.2.3 OFFSITE AIR EXPOSURES

Wind can blow contaminated dust from agricultural fields or a landfill where sludge is applied, or from the stack of a POTW incinerator where it is burned, to an offsite location where people are actually exposed. This is of importance in the Nearby Town Resident, Landfill Neighbor, and Incinerator Neighbor Scenarios, and it requires additional analysis of the source term. This sub-section addresses only the case of dust from a farm field that is transported by the air pathway to a nearby town, 800 m (0.5 miles) downwind, where it settles upon and contaminates the ground – offsite air exposures for other scenarios will be addressed later.

1 The assessment consists of three parts – release by the source, transport to the point of exposure,
2 and deposition and exposure there.

3 For sludge applied to a field, the source has a release height of 0 meters and a release velocity of
4 0 m/s, and the dust plume rise is taken to be of the ‘momentum’ type. The rate of release of
5 radionuclide from the field is calculated by RESRAD-OFFSITE.

6 The Gaussian-plume air-dispersion model of CAP88-PC (EPA 1992b) is then run to provide an
7 estimate for the dispersion factor (χ/Q , or “chi over Q”), the ratio that relates air concentration at
8 a target position downwind, $\chi(x,y,z,t)$, to the release rate from the source, $Q(t)$. The
9 meteorological profile used in the assessment is the annual average data for Columbus, Ohio,
10 measured from 1988-1992. (The file containing this data is built into CAP88-PC as one of a
11 number of selectable default options. Columbus was chosen because it has a typical continental
12 United States wind profile, with a strong predominant wind direction.) The assessment grid
13 employed here is circular, centered on the source field, and divided into 16 sectors, each of
14 22.5 degrees circumferential extent. Each sector has 10 radial zones, with their midpoints 800,
15 1600, 2400, 3200, 4000, 4800, 5600, 6400, 7200, and 8000 meters from the center of the circle.

16 The dispersion factor at 800 m, and in the direction of maximum χ/Q , was found to be
17 radionuclide dependent, because the deposition velocity and half-life are, as indicated in
18 Table 3.2.

19 **Table 3.2 Values of Deposition Velocity and Dispersion Factor, χ/Q , for the**
20 **Various Radionuclides, Computed for the Nearby Town Scenario by**
21 **CAP88-PC, for Input to RESRAD-OFFSITE**

| Isotope – Nearby Town | Deposition Velocity (m / s) | χ/Q (at 800 m) (s / m ³) |
|----------------------------|-----------------------------|---|
| H-3, C-14, Xe-131m, Rn-222 | 0 | 7.4×10^{-6} |
| Rn-220 | 0 | 2.3×10^{-7} |
| I-125, I-131 | 0.035 | 8.9×10^{-7} |
| All others | 0.002 | 6.0×10^{-6} |

22
23
24
25
26
27
28 Once χ/Q has been obtained, RESRAD-OFFSITE accounts for the deposition of airborne
29 radionuclides to the ground surface at the receptor location. It is assumed that the material blown
30 from the primary source (field) to the secondary site (Town) is subsequently mixed in with the
31 top 15 cm of soil in a garden or small field by root-zone action, and is taken up by roots; it will
32 deposit on leaves, but it contaminates neither groundwater nor surface water.

33 With minor modifications, the superposition technique discussed in Section 3.2.2 is used to
34 assess the time dependence of offsite deposition and exposures from multiple releases of airborne
35 contaminants.

3.3 LANDFILL/IMPOUNDMENT NEIGHBOR SCENARIO

Two sub-scenarios were designed for the study of the near-surface burial of sludge and ash – disposal in a municipal solid waste landfill and in a surface impoundment. In either case the source is considered to be 1 hectare (about 2 acres) in area and 2 meters deep.

The source term for the municipal solid waste landfill consists of sewage sludge/ash mixed with municipal solid waste. The typical composition of municipal solid waste includes about 2.5% sewage sludge/ash by weight, thereby creating a dilution factor of about 40. Because of the dominant effect of the non-sludge/ash waste on radionuclide transport, the hydraulic properties of the source are taken to be those of municipal solid waste (HELP model defaults from Schroeder *et al.*, 1994), given in Table 3.3 for an activity in sludge of 37 Bq/kg (1 pCi/g).

Table 3.3 Municipal Solid Waste Source Characteristics

| Property of Municipal Solid Waste | Value |
|-----------------------------------|-------------------------------|
| Activity due to Sewage Sludge/Ash | 0.925 Bq/kg (0.025 pCi/g) |
| Saturated Hydraulic Conductivity | 10^{-3} cm/s |
| Particle Density | 2600 – 4700 kg/m ³ |
| Porosity | 0.671 |
| Bulk Density (derived) | 860 – 1500 kg/m ³ |
| Field Capacity | 0.292 |

For a surface impoundment, on the other hand, the source consists entirely of sewage sludge, and the activity is undiluted. It is assumed that the material degrades biologically relatively rapidly, and therefore has the hydrologic characteristics of generic soil.

The air emission source for the landfill/surface impoundment is conceptually similar to that of the agricultural field. Again, the Gaussian plume dispersion model in CAP88-PC is used to determine the dispersion factor. The ground-level values of χ/Q go through a maximum at 150 meters, Table 3.4.

1 **Table 3.4 Values of Deposition Velocity and Dispersion Factor, χ/Q , for the**
 2 **Various Radionuclides, Computed for the Landfill Neighbor Scenario**
 3 **by CAP88-PC, for Input to RESRAD-OFFSITE**

| 4 Isotope – Nearby Town | Deposition Velocity (m / s) | χ/Q (at 150 m) (s / m ³) |
|------------------------------|-----------------------------|---|
| 5 H-3, C-14, Xe-131m, Rn-222 | 0 | 1.7×10^{-4} |
| 6 Rn-220 | 0 | 4.8×10^{-5} |
| 7 I-125, I-131 | 0.035 | 5.1×10^{-5} |
| 8 All others | 0.002 | 1.6×10^{-4} |

9
 10 Multiple years of released and deposition are handled in a way similar to that for the Nearby
 11 Town Resident.

12 3.4 INCINERATOR NEIGHBOR SCENARIO

13 The source term calculation for the incinerator is in three separate parts. First, the activity per
 14 day of radionuclide vented from the stack for each kilogram of dry sludge burned per day is
 15 calculated, where the sludge is assumed to contain a unit concentration 37 Bq/kg (1 pCi/g) of the
 16 radionuclide. (No decay of the radioactive materials in the sludge occurs prior to incineration.)
 17 Then environmental pathway models (CAP88-PC and RESRAD-OFFSITE) are employed to
 18 determine the concentration in air at the point of exposure for a given value of stack release rate
 19 and, finally, the dose to the neighbor.

20 The emission source from the incinerator stack is determined by the activity concentration in the
 21 sludge, the feed rate of sludge, and the total control efficiency of the incineration system,
 22 accounting for any stack gas cleaning systems. With activity A_{sludge} and feed rate R_{feed} , the rate
 23 of radionuclide release from the incinerator stack, R_{release} , is given by

$$24 \quad R_{\text{release}} = A_{\text{sludge}} \times R_{\text{feed}} \times (1 - CE) , \quad (3.7)$$

25
 26 where the control efficiency for the radionuclide of interest, CE , is defined as the fraction of the
 27 radionuclide that is *not* vented as part of the exhaust gas stream. It is generally the quantity
 28 retained by fly ash and bottom ash divided by the total quantity in the feed stream. CE is a
 29 function of the plant design and of the chemical element (different isotopes are assumed to have
 30 the same CE) in question, and of its chemical form, and it can range from 0.0 for noble gases
 31 such as radon to greater than 0.99 for heavy metals such as uranium, thorium, and plutonium.
 32 Further analysis of control efficiencies for sludge incinerators is contained in Appendix C. Based
 33 on the review in Appendix C, control efficiencies, shown in Table 3.5, were developed for this
 34 assessment that provide reasonably conservative estimates of the stack releases.

1 **Table 3.5 Incinerator Control Efficiencies, CE, and Release Rates, R_{release} , for**
 2 **Various Radionuclides**

| 3 Isotope | Control Efficiency | Release Rate |
|--------------------|--------------------|---|
| 4 Radon | 0.0 | 1.76×10^8 Bq/y (4.75×10^{-3} Ci/y) |
| 5 Carbon | 0.05 | 1.67×10^8 Bq/y (4.51×10^{-3} Ci/y) |
| 6 Tritium | 0.1 | 1.58×10^8 Bq/y (4.27×10^{-3} Ci/y) |
| 7 Technetium | 0.1 | 1.58×10^8 Bq/y (4.27×10^{-3} Ci/y) |
| 8 Iodine | 0.3 | 1.23×10^8 Bq/y (3.32×10^{-3} Ci/y) |
| 9 All Other Metals | 0.9 | 1.76×10^7 Bq/y (4.75×10^{-4} Ci/y) |

10
 11 A feed rate of $R_{\text{feed}} = 13$ metric tons (13×10^3 kg) of dry sludge per day ($= 4.75 \times 10^6$ kg per year)
 12 is assumed, the value adopted in the technical support document for the sewage sludge
 13 incineration risk assessment for the Part 503 rule (EPA 1992a, section 5.6.4), and unit specific
 14 activity of radioactivity $A_{\text{sludge}} = 37$ Bq/kg (1 pCi/g). The release rates, calculated as above, are
 15 also provided in Table 3.5.

16 The rate of deposition depends on the physical design of the stack. The modeling was based on
 17 data from the Northeast Ohio Regional Sewer District (NEORSD) on the shortest stack for three
 18 of their incineration plants. This stack, which produces the highest ground-level airborne
 19 concentration at a local receptor, is typical of older incinerators. As with the offsite exposure to
 20 agricultural application, the Gaussian Plume air dispersion model in the CAP88-PC code is used
 21 to calculate an activity concentration in the air at various locations as determined by the local
 22 annual average meteorological conditions. The assessment grid is a circular area, centered on the
 23 stack, that is divided into 16 sectors; each sector has eight radial zones, with their midpoints at
 24 200, 400, 800, 1200, 1600, 2400, 3200, and 4000 meters from the center of the circular
 25 assessment area. Since the dose assessment models the exposure to a member of the critical
 26 group who resides at the location of highest χ/Q and who consumes primarily locally grown
 27 food, rather than a regional population, a smaller grid area is appropriate. As before, the
 28 meteorological characteristics adopted were the default values developed from data for
 29 Columbus, Ohio.

30 The point having the highest calculated airborne activity at ground level was found by
 31 CAP88-PC to be 150 meters from the stack. The dispersion factors are provided in Table 3.6.

1 **Table 3.6 Values of Deposition Velocity and Dispersion Factor, χ/Q , for the**
 2 **Various Radionuclides, Computed for the Incinerator Neighbor**
 3 **Scenario by CAP88-PC, for Input to RESRAD-OFFSITE**

| Isotope – Nearby Town | Deposition Velocity (m / s) | χ/Q (at 150 m) (s / m ³) |
|----------------------------|-----------------------------|---|
| H-3, C-14, Xe-131m, Rn-222 | 0 | 1.1×10^{-5} |
| Rn-220 | 0 | 5.8×10^{-6} |
| I-125, I-131 | 0.035 | 1.1×10^{-5} |
| All others | 0.002 | 1.1×10^{-5} |

9
 10 RESRAD-OFFSITE code does not calculate “time-integrated” doses, so for the incinerator
 11 scenario, where exposure from shorter lived radionuclides is common, “instantaneous” dose rates
 12 will overestimate the actual annual dose. An adjustment factor (Decay Factor) is used to account
 13 for the decay during the one-year exposure time period. For example, the decay factor for I-131
 14 is 0.032, while for long-lived radionuclides, the decay factor is 1. The decay factors are listed in
 15 Table 3.7 below.

1 **Table 3.7 Decay Factor Adjustments for Incinerator Neighbor Scenario**

2

| Radionuclide | Decay Factor for 1 year | Radionuclide | Decay Factor for 1 year |
|--------------|-------------------------|--------------|-------------------------|
| Ac-227 | 0.98 | Po-210 | 0.46 |
| Am-241 | 1.00 | Pu-238 | 1.00 |
| Be-7 | 0.21 | Pu-239 | 1.00 |
| C-14 | 1.00 | Ra-226 | 1.00 |
| Ce-141 | 0.13 | Ra-228 | 0.94 |
| Co-57 | 0.65 | Sm-153 | 0.0077 |
| Co-60 | 0.93 | Sr-89 | 0.20 |
| Cr-51 | 0.11 | Sr-90 | 0.99 |
| Cs-134 | 0.85 | Th-228 | 0.85 |
| Cs-137 | 0.99 | Th-229 | 1.00 |
| Eu-154 | 0.96 | Th-230 | 1.00 |
| Fe-59 | 0.99 | Th-232 | 1.00 |
| H-3 | 0.97 | Tl-201 | 0.012 |
| I-125 | 0.23 | Tl-202 | 0.047 |
| I-131 | 0.032 | U-233 | 1.00 |
| In-111 | 0.012 | U-234 | 1.00 |
| K-40 | 1.00 | U-235 | 1.00 |
| La-138 | 1.00 | U-238 | 1.00 |
| Np-237 | 1.00 | Xe-131m | 0.047 |
| Pa-231 | 1.00 | Zn-65 | 0.62 |

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3.5 SLUDGE/ASH MANAGEMENT SCENARIOS

3.5.1 SLUDGE APPLICATION WORKER SOURCE

The sources of exposure to a worker who is applying sludge to a field will be the field itself and, to a lesser extent, the sludge on the truck. The field will contain radioactivity applied not only this year, but also in prior years. Exposures will occur primarily through direct gamma irradiation, which is reduced but not fully eliminated by the shielding the truck provides, and the inhalation of dust.

In view of the great uncertainties in application procedures and type of equipment used, it is necessary to simplify the geometry and other aspects of the problem considerably. The cab of the truck is simply assumed to be a box. The sludge application rate and tilling depth are assumed to be the same as for the on-site resident. Rather than performing a time-integral of dose rate as the driver traverses a field in a raster pattern, an "effective" field size is determined by Monte Carlo averaging over a range of fields. The areas of these fields are assumed to have a uniform distribution, and the dose is calculated for a receptor at the edge of the fields.

3.5.2 PUBLICLY OWNED TREATMENT WORKS WORKER SOURCE

POTW operations are complex, and some readers may find a brief description of them to be helpful. A POTW is a facility that takes in water-borne raw sewage for proper treatment. There are two resulting products: (1) treated effluent water, which typically is released into nearby surface waters, and (2) sludge, which will be processed to a certain degree to meet Federal and/or state regulatory requirements and to be beneficially used or properly disposed.

Because of the large volume of water being managed by the POTW, dilution will result in any radioactivity in the influent sewage first entering the POTW to be of very low concentration. As a result of the various physical, chemical and biological treatment processes, however, certain amounts radioactivity may become concentrated in the sludge and thereby removed from the wastewater, so that the levels of radioactivity present in the final treated effluent water will be even lower. For this reason, the concern for POTW workers centers on operations that require workers to be in close proximity to sludge or ash so as to be directly exposed to the radioactivity sludge or ash.

Solid materials are initially removed from sewage. The wastewater passes through a series of treatment processes separating solids, removing certain dissolved materials, and destroying certain organic materials in the water. Sludge is formed by means of sedimentation of inert and non-organic matter in the primary treatment and by settling within basins ("clarifiers") or lagoons. When removed from the bottoms of sediment tanks, clarifiers, or lagoons, the sludge is still mainly water, containing as little as 0.5% solids. This material is commonly piped to a digester for stabilization and sometimes may be treated with lime. The resulting sludge is around 5% solids. Often it is then hauled to nearby farmland and land-applied as a liquid material. Alternatively, after this thickening it is sent by pipes or conveyers to a drying bed, mechanical de-watering devices (belt presses or centrifuges), and/or thermal de-watering devices. The

1 resulting produces may be "sludge cake," usually 15% to 20% solids, or dry sludge with even
2 higher solids contents.

3 Much sludge is used directly in sludge cake form, sent to a truck via a conveyor system, and
4 shipped to the fields. Some sludge may be held in a composting area⁷ for certain periods of time
5 for pathogen control. Metro (2000) states that sludge that is dealt with in this manner and meets
6 the 40 CFR 503 Rule Class B pathogen requirements is routinely used as a fertilizer and soil
7 amendment in ranching, forestry, and land reclamation projects.

8 Some POTWs may follow digestion and de-watering with biosolids processing, depending on the
9 intended end use or disposal of the final product. The sludge may be processed to a high level
10 and sold as a relatively dry (50-95% solids) soil conditioner (e.g., compost) or fertilizer
11 (generally pelletized) product for application to fields, lawns, parkland, etc. In these cases, the
12 sludge may undergo additional treatments, such as drying, mixing with other materials, or other
13 modifications, during any of which there may occur worker exposure.

14 For POTW operations, three different worker exposure sub-scenarios have been designed,
15 involving the sampling, processing, and loading of biosolids. For the first of these, the worker
16 obtains and carries a 1-liter sample containing 95% water and 5% sludge solids by volume, with
17 a sludge dry weight of about 0.075 kg (assuming sludge solids have a density of about 1.5 g/cm³).
18 Thus a sludge sample with unit activity concentration of 37 Bq/kg (1 pCi/g) will contain 2.8 Bq
19 (75 pCi) of activity, and is considered a point source in this assessment.

20 For sludge processing, the worker stands near a conveyer belt carrying 10 liters/meter of unit
21 concentration sludge at 20% solids. The source is thus considered a line source with 111 Bq/m
22 (3000 pCi/m).

23 For biosolids loading, the worker carries out tasks near a circular pile of de-watered sludge
24 (porosity 0.4 and dry bulk density 1520 kg/m³) that is 100 m² in area and 0.5 m in thickness.
25 Again, a unit activity concentration of 37 Bq/kg (1 pCi/g) is assumed.

7 Sludge that is composted ends up typically in the range of 40 to 60% solids, and is much like an organic topsoil. This material can dry out further, but when placed in piles the surface, it tends to seal over. The inner pile material retains much of its moisture, so that the entire pile does not turn to dust.

4 EXPOSURE SCENARIOS

1 This chapter describes in detail the exposure scenarios of the study. Each assessment starts with
2 the selection of a specific set of parameter values and distributions to be used as inputs to the
3 RESRAD family of codes. The RESRAD code employed for each scenario is listed in Chapter 2,
4 along with the individuals considered to be exposed. In what follows, a table is provided for
5 each of them, indicating the exposure pathways considered to be active. A second table
6 delineates those modeling parameters *that differ from the baseline values* listed in Appendix A.

7 A specific choice of modeling parameter values and distributions for a scenario reflects and
8 defines the characteristics of the site and of the exposed population. It also largely establishes
9 the degree of conservativeness of the calculation. For this study, an attempt was made to
10 construct scenarios to yield doses to "the average members of the critical group." Here, the
11 "critical group" for a scenario refers to a sub-population with relatively high exposure to sludge
12 through close proximity or through the management practices described in the scenario. The
13 "average member" of the critical group is then defined by the pathway and the rate of exposure to
14 sludge-related radionuclides, based on average, or typical, conditions for the group. That is, the
15 environmental conditions and the behavior, and thus the rate of exposure, of the average member
16 of the critical group are intended to be plausibly conservative, and not extreme-case.

17 As was noted earlier, most parameter values and distributions do not change from scenario to
18 scenario. A set of "baseline" parameter values and distributions has been defined, and these are
19 listed in Appendix A. The majority of these coincide with RESRAD default values, the
20 justification for which are explained in the RESRAD documentation. The relatively small
21 number of parameter values and distributions that are scenario-specific are explicitly listed and
22 discussed in each scenario description. For some of these, appropriate and credible references
23 led to the choice of particular parameter values or distributions; in other cases, the selection
24 resulted from discussions (sometimes lengthy) among the Work Group members and their
25 consultants. Since the scenarios have been devised to serve as generic sites rather than to
26 describe specific ones in detail, moreover, there are bound to be real situations to which they do
27 not apply. They are intended, however, to be as broadly representative as is reasonably
28 achievable.

29 4.1 ONSITE RESIDENT

30 In risk assessment, the resident farmer family is often modeled as a bounding case study. A
31 similar but much more common situation, however, is that of people who inhabit homes built on
32 land previously used for farming – new houses are often constructed on former farmlands near
33 urban areas. Because this is a common trend in the United States, this Onsite Resident is the first
34 and the most extensively explored scenario out of the seven considered.

35 In this scenario, the source farm-field was amended one or more times in the past with sewage
36 sludge fertilizer that may have contained radionuclides, as discussed in Chapter 3. A house was
37 completed on the land one year after the last deposition of sludge, and thereafter it is inhabited by
38 people who are not professional farmers. It is conservatively assumed that they produce

1 significant portions of their annual diet on-site in the same manner as the resident farmer.
2 Radionuclide transport did occur over the year(s) before the new residents came onsite, and
3 continues after they arrive.

4 The relevant transport and exposure pathways assumed for this scenario are summarized in
5 Table 4.1a. Family members are exposed directly to external gamma emissions from
6 sludge-containing soil. They inhale resuspended dust and outdoor radon and, since the home is
7 built on land where sludge has been applied in the past, indoor radon as well. Doses from indoor
8 radon can vary greatly depending on the construction of a building's foundation. For residential
9 homes, the three major foundation types for new construction are an enclosed crawl space, a slab,
10 and a basement. A simple slab-on-grade without excavation of the upper soil layer was modeled
11 in this assessment, since preliminary RESRAD calculations indicated that this allows more radon
12 diffusion into the house than the basement. The RESRAD code was not designed to evaluate an
13 enclosed crawl space foundation type, but it is plausible that radon concentrations might be
14 higher in such a situation because of a "chimney" effect. In real houses, of course, radon
15 concentration depend strongly on the specifics of the design and construction, but that level of
16 detail is neither practicable nor appropriate for the generic scenario modeled here.

17 With respect to the ingestion pathways, the residents drink well water, and grow vegetables
18 (50%), fruit (50%) and fodder, and raise a few animals for personal consumption (100% of meat
19 and milk), and they may inadvertently ingest small amounts of soil. It is assumed that 90% of the
20 drinking water for humans comes from a well located at the down-gradient edge of the source
21 field, and about 10% from uncontaminated sources (*e.g.*, from a nearby town's treated
22 waterworks) consumed while the resident is away from the property. Human ingestion of
23 contaminated surface water was considered to be unlikely, given the availability of well water,
24 but there may be exposure through fish caught from a local river or lake; fifty percent of the
25 annual diet of fish is from contaminated surface water. The food produced onsite is grown in soil
26 that has been treated with sludge and that is irrigated with groundwater and surface water that
27 contains radionuclides washed out of the sludge/soil mix. The soil ingestion pathway is
28 included, but a pica child who exhibits excessive hand-mouth activity or deliberate consumption
29 of soil is not considered. These ingestion assumptions are generally conservative.

30 Six sub-scenarios are used to investigate the dependence of calculated dose on the number of
31 years of application of sludge, Table 4.1b. The first sub-scenario performs a complete
32 probabilistic analysis for one year of application, making use of all the currently available
33 parameter distributions and sampling capability of RESRAD Version 6, apart from field size.
34 Sub-scenario two also considers only a single application, but it is fully deterministic; it serves
35 as a baseline for the deterministic computations for multiple years of application (as discussed in
36 Section 3.2.2) that follow. Sub-scenarios three through six use deterministic calculations to
37 examine the impacts of five, twenty, fifty, and one hundred years of accumulation of sludge
38 onsite, respectively. As discussed in connection with Equations 3.6, the factor F_n (the ratio of
39 the n-year deterministic to the 1-year deterministic doses) is used to scale the single-year
40 probabilistic results of sub-scenario 1 for multiple years of application.

1 The level of detail in Table 4.1b (the assumptions on site vs. town water, on well vs. surface
 2 water, etc.) appears to be much less than that in Table 4.1a only because nearly all the
 3 information in the latter is already incorporated into the set of baseline RESRAD parameter
 4 values for this study, as summarized in Appendix A.

5 **Table 4.1a Onsite Resident Scenario Pathways**

| Human Exposure | Environmental | Pathway Included? | Comments |
|--------------------------|------------------|-------------------|---|
| External radiation | Direct exposure | Yes | Agricultural field; soil / sludge mixture 15 cm deep. |
| Inhalation | Resuspended | Yes | Mass loading represents an average value; dust from top 15 cm (mixture region). |
| | Indoor | Yes | House sits on contaminated zone surface; diffusion in through slab foundation; radon also from water. |
| | Outdoor radon | Yes | Radium in contaminated soil. |
| Ingestion of water | Groundwater | Yes | 90% ingested water from onsite well, 10% from uncontaminated sources. |
| | Surface water | No | People with wells generally do not drink surface water. |
| Ingestion of plants | Irrigation water | Yes | 50% from well, 50% from surface waters. |
| | Dust Deposition | Yes | Plants contaminated through foliar deposition of dust. |
| | Root uptake | Yes | Plants contaminated through root uptake. |
| Ingestion of meat / milk | Livestock water | Yes | 50% from well, 50% from surface waters. |
| | Livestock soil | Yes | Soil consumption by livestock. |
| | Fodder | Yes | Root uptake of, and foliar deposition of, contaminated water. Water 50% from well, 50% from surface waters. |
| | Dust deposition | Yes | Foliar deposition of dust. |
| | Root uptake | Yes | Root uptake from contaminated soil. |
| Ingestion of fish | Surface | Yes | Consumption of fish from contaminated surface water. |
| Ingestion of soil | Surface soil | Yes | Dirt from hands, etc. Pica child <i>not</i> considered. |

Table 4.1b. Onsite Resident Scenario and Sub-Scenario Parameters and Distributions

| | Parameter | Value/Distribution | Comments |
|--|-----------------------|--|--|
| Sub-scenario 1 (Uncertainty) | | Appendix A Baseline distributions, values, except... | Probabilistic, except land area |
| 1 | Years of application | 1 | |
| Sub-scenarios 2 – 6 (Deterministic) | | <u>Appendix A Baseline</u> values, except... | Deterministic |
| All | Log or linear spacing | Linear | So as to obtain annual dose results for each year |
| All | No. of graphic points | 1024 | Maximum permitted by RESRAD. Data from graphical points (one at each year from 0 to 1023) are used to calculate scaling factors. |
| 2 | Years of application | 1 | Replace distributions with point values (see Sections 2.4.2, 3.2.2) |
| 3 | Years of application | 5 | " |
| 4 | Years of application | 20 | " |
| 5 | Years of application | 50 | " |
| 6 | Years of application | 100 | " |

4.2 RECREATIONAL USER ON RECLAIMED LAND SCENARIO

The Recreational User scenario takes place on a land reclamation site where there occurred a single large application of sludge which is incorporated into the soil to help reclaim an area disturbed severely by mining or excavation. It is a common practice, where possible, to attempt to incorporate the sludge and other soil additives, such as agricultural lime, manure, etc., into the surface material of the reclamation site by discing or other tillage practices. This helps to prepare the area to support the establishment of a sustainable vegetative cover. Typically, no separate cover is applied in such treatment.

It will take some time before trees and other plants establish themselves and animals come to inhabit the site. The present analysis assumes that three years after sludge application, when a

1 sustainable vegetative cover is in place (and after short-lived isotopes have largely decayed
2 away), the site is opened to the general public for hiking, camping, picnicking, boating, hunting,
3 fishing, and other residential uses. No residential homes are constructed, nor is there any
4 agriculture.

5 Of the various recreational users, the hunter-fisherman who consumes game and fish obtained
6 onsite is likely to be the most highly exposed. Recreational users are assumed to spend one week
7 per year outdoors in the area. (The doses from all exposure pathways except game meat
8 consumption can be scaled linearly to account for shorter, longer, or multiple visits.) Game such
9 as deer will eat plants that may have extracted radionuclides from the soil, and they will drink
10 potentially contaminated surface waters. A hunter kills a single deer (typically the legal limit);
11 he eats a portion of it over the course of the following year. Likewise, fish will take up
12 radionuclides that reach surface waters; but unlike the situation for deer meat, it is assumed that
13 nearly all fish caught are eaten onsite.

14 Also included in the modeling are external exposure, inhalation of contaminated dust, and soil
15 ingestion. The source and availability of water will vary from place to place. Some sites will
16 have wells for drinking water and washing, while at others, users may have to rely on surface
17 water. It is assumed here that people drink from a well, and wildlife drink surface water. The
18 exposure pathways are summarized in Table 4.2a, and parameter distributions and values specific
19 to this scenario (i.e., those that are not baseline) appear in Table 4.2b. Also not listed in
20 Table 4.2b are those values that explicitly apply to indoor activities, or to irrigation, or to the
21 consumption by humans of surface water, fruit, grain, leafy vegetables, or milk obtained onsite
22 (since these pathways are considered to be not in operation). In cases where a pathway has been
23 turned off in the model, some parameters have been left at their baseline values – which, of
24 course, has no effect on the dose calculation.

Table 4.2a Recreational User on Reclaimed Land Pathways

| Human Exposure | Environmental Pathway | | Pathway Included? | Comments |
|--------------------------|------------------------|------------------|-------------------|---|
| External radiation | Direct exposure | | Yes | |
| Inhalation | Resuspended dust | | Yes | |
| | Indoor radon | | No | |
| | Outdoor radon | | Yes | |
| Ingestion of water | Groundwater | | Yes | All well water |
| | Surface water | | No | |
| Ingestion of plants | Irrigation water | | No | No farming, irrigation. |
| | Dust deposition | | No | |
| | Root uptake | | No | |
| Ingestion of meat / milk | Livestock (game) water | | Yes | Deer drink surface water. |
| | Livestock (game) soil | | Yes | |
| | Fodder | Irrigation water | No | No irrigation. |
| | | Dust deposition | Yes | |
| | | Root uptake | Yes | Vegetation for deer grows in contaminated soil. |
| Ingestion of fish | Surface water | | Yes | |
| Ingestion of soil | Surface soil | | Yes | |

1 **Table 4.2b Recreational User Scenario Parameters and Distributions**

2

| Parameter | Value/Distributions | Comments |
|---|---------------------|---|
| 3 Livestock (i.e., deer) 4 water contamination 5 fraction | 1 | |
| 6 Plant food contamination 7 fraction | 0 | |
| 8 Meat (deer) 9 contamination fraction | 1 | |
| 10 Aquatic food 11 contaminated fraction | 1 | |
| 12 Livestock fodder intake 13 for meat (kg/d) | 2.7 kg/d | From Wildlife Exposure Factors Handbook (EPA 1993b) Allometric Equations for herbivore mammals for a 250 lb (~114 kg) deer (Whitetail deer from Nebraska Game and Parks Commission) |
| 14 Livestock water intake 15 for meat (L/d) | 7 L/d | From (EPA 1993b) Allometric Equations |
| 16 Livestock intake of soil 17 (kg/d) | 0.02 | Deer prefer leafy plants. Value obtained by scaling the Baseline rate of ingestion of grass by a cow. Assume all vegetation eaten onsite. |
| 18 Groundwater fraction for 19 livestock water | 0 | Deer drink only surface water. |
| 20 Storage time for meat (d) | 182.5 | Deer meat consumed over 365 d. |
| 21 Storage time for fish (d) | 0 | Fish eaten right away use. |
| 22 Meat transfer factor 23 (pCi/kg per pCi/d) | Baseline values | Use cattle values and distributions as was done in the 503 rule. |

24

4.3 NEARBY TOWN RESIDENT SCENARIO

The Nearby Town Resident scenario is designed to assess the doses to members of the public living in a town, the proximal edge (and critical group) of which is located about 800 m (one half mile) downstream (for both ground- and surface-water) and downwind from an agricultural field where sludge has been applied for one or more years. None of the receptor population resides on the site where sludge was applied, nor do the local people eat a significant amount of food grown there, so that all exposure pathways involve physical transport of radionuclides from the source field to the town or to neighboring fields.

Primary pathways include airborne transport of contaminated dust from the source field either to the town or to other fields, and runoff of contaminated soil into a lake or river that supplies water for the town and neighboring farms. Another possibly important pathway is leaching of radionuclides into the groundwater and into the surface water. Townspeople may inhale dust blown from the sludge-applied field, or be exposed to dust that has settled on the streets or other areas of the town, or drink contaminated water from local wells or from nearby surface water, or ingest plants grown in nearby fields that are contaminated by the airborne dust, etc. A body of surface water is available for fishing. It is located midway between the sludge-applied field and the receptor, and can be contaminated by groundwater flowing from the primary site.

All of these mechanisms involve dilution of the source material prior to exposure of the Nearby Town Residents or of nearby farms (where food is produced for local consumption), and it was expected that this scenario would yield dose values much lower than those of the Onsite Resident. The possibility of more than a few people being exposed, however, does add relevance to the case.

Exposure pathways for the Nearby Town scenario are described in Table 4.3a, and the non-baseline parameters in Table 4.3b.

1 **Table 4.3a Nearby Town Resident Pathways**

| 2 | Human Exposure | Environmental Pathway | Pathway Included? | Comments | |
|----|--------------------------|-----------------------|-------------------|--|---------------------------------------|
| 3 | External radiation | Direct exposure | Yes | Contamination of surface soil in town; dust deposited by airborne transport from the field | |
| 4 | | Suspended dust | Yes | Atmospheric transport from contaminated field. | |
| 5 | Inhalation | Indoor radon | No | Diffusion of radon into basements from surrounding soil; nearly all radon entering basements will be from native, local soil, not from sludge. | |
| 6 | | Outdoor radon | Yes | Air transport and radon emanation from deposition of contaminated dust. | |
| 7 | | Groundwater | No | Town uses treated and monitored water, so actual radionuclide content would not exceed MCLs. | |
| 8 | Ingestion of water | Surface water | No | Town uses treated and monitored water | |
| 9 | Ingestion of plants | Irrigation water | No | Town uses treated and monitored water | |
| 10 | | Dust deposition | Yes | | |
| | | Root uptake | Yes | Root uptake from soil contaminated by atmospheric transport | |
| 11 | Ingestion of meat / milk | Livestock water | No | Town uses treated and monitored water | |
| 12 | | Livestock soil | Yes | | |
| | | Fodder | Irrigation water | No | Town uses treated and monitored water |
| | | | Dust deposition | Yes | |
| | | | Root uptake | Yes | |
| 13 | Ingestion of fish | Surface water | Yes | | |
| 14 | Ingestion of soil | Surface soil | Yes | Atmospheric transport from contaminated agricultural field. | |

Table 4.3b Nearby Town Resident Scenario and Sub-Scenario Parameters and Distributions

| | Parameter | Value / Distribution | Comment |
|--|--|--|--|
| Sub-scenario 1 (Uncertainty) | | Appendix A baseline values and distributions, except... | |
| 1 | Years of application | 1 yr | |
| | Fraction of water from surface body | 0 | Household water and irrigation water are not contaminated. They are not from a local well or surface water body. |
| | – Household purposes | 0 | |
| | – Beef cattle | 0 | |
| | – Dairy cows | 0 | |
| | – Irrigation for fruit, grain, non-leafy vegetable field | 0 | |
| | – Irrigation for leafy vegetable field | 0 | |
| | – Irrigation for livestock pasture and silage field | 0 | |
| | – Irrigation for livestock grain field | 0 | |
| | Fraction of water from well | 0 | Household water and irrigation water are not contaminated. |
| | c/Q, all | see Table 3.2 | |
| Sub-scenarios 2 – 6 (Deterministic) | | Appendix A baseline and sub-scenario 1 values, except... | |
| all | Number of intermediate time points | 1024 | To obtain annual dose results for the considered time frame of 1000 years. |
| all | Times at which output is reported | 1023 | To obtain annual dose results for the considered time frame of 1000 years. |
| 2 | Years of application | 1 yr | |
| 3 | Years of application | 5 yr | |
| 4 | Years of application | 20 yrs | NA |
| 5 | Years of application | 50 yrs | NA |
| 6 | Years of application | 100 yrs | NA |

4.4 LANDFILL/SURFACE IMPOUNDMENT NEIGHBOR SCENARIO

In two sub-scenarios, people live in a house near (150 meters) the boundary of either a) a municipal solid waste (MSW) landfill, or b) a surface impoundment where sludge is buried. Source characteristics were discussed in Section 3.3.

While not professional farmers, the landfill neighbors do some gardening and raise a few animals for personal consumption. The landfill or impoundment is fenced in, and neither the neighbors nor any animals spend any time on it.⁸

Each of these sub-scenarios extends over three distinct time-periods, during which the site is: 1) being filled with sludge and waste; 2) being monitored after filling is complete (required to be 30 years under RCRA regulations); and 3) past the 30-year monitoring period.

1. The time of active landfill operation is relatively short. It is assumed that a liner prevents contaminants from leaching into the ground water (i.e., the leachate is captured, treated and released),⁹ and groundwater is monitored. The sludge is presumed to be moist, moreover, with little suspension of dust. And the fact that the sludge sits primarily below grade keeps the direct gamma exposure of any neighbors low.
2. Over the subsequent 30 years, the liner remains intact (or is repaired if leakage is detected), and an engineering barrier (i.e., an impermeable cover) prevents contaminant runoff into neighboring surface waters or airborne releases. Decay and ingrowth are accounted for in the model, but there are no active pathways by means of which radioactive material can expose people.
3. Only the third period need be analyzed in this scenario. For simplicity, it is assumed that the cover is a relatively impermeable clay and the liner is a compacted clay (i.e., drainage layers and geo-membranes are not used), with standard default properties.

In both sub-scenarios, the cover thickness and erosion rate have default values, so that cover breakthrough occurs halfway through the 1,000 year calculation period. The integrity of the cover and liner would determine the water infiltration rate to deeper soil, but no actual data are available to correlate the integrity condition with the infiltration rate. Previous data on RCRA D leak detection systems show an infiltration rate ranging from 0.004 to 16 cm/yr, with a typical value of 0.9 cm/yr. Preliminary analyses using the HELP model showed that the infiltration rate can range from 3.3 cm/yr for a conservative case to 22 cm/yr for a very worst case, so a value of 3.3 cm/yr was used for the deterministic calculations. For the uncertainty calculation, the

⁸ Someone building a residence directly on a landfill far in the future might well experience a higher dose than someone living near it, but many states have laws prohibiting such an intrusion; even without such institutional control, moreover, deeds should record that a landfill once occupied the site, making construction there unlikely. The landfill neighbor scenario would thus seem to be more plausible and realistic than that of the intruder.

⁹ Typical leakage rates through RCRA D landfills have been measured to be about 1 cm/y, which is considered negligible in the context of this generic assessment.

1 infiltration rate was assumed to have a uniform distribution with a range of from 3.3 cm/yr
2 to 22 cm/yr.

3 The value of the runoff coefficient, which determines the relative amount of precipitation that
4 flows off-site, was tailored to the selected infiltration rate, with a range of from 0.413 to 0.916
5 chosen. To avoid a situation in which the infiltration rate would be greater than the soil hydraulic
6 conductivity, the hydraulic conductivity of the liner was set equal to the infiltration rate value,
7 and was correlated with the runoff coefficient in the uncertainty calculation.

8 The other specific pathways and parameters, which are similar to those of the onsite resident
9 scenario, are shown in Tables 4.4a and 4.4b.

Table 4.4a Landfill Neighbor Pathways – Post-Monitoring Period

| Human Exposure | Environmental Pathway | | Pathway Included? | Comments |
|--------------------------|-----------------------|------------------|-------------------|--|
| External radiation | Direct exposure | | Yes | |
| Inhalation | Suspended dust | | Yes | Cover has been eroded / disturbed. |
| | Indoor radon | | No | House is not on sludge disposal site. |
| | Outdoor radon | | Yes | Cover has been eroded / disturbed. |
| Ingestion of water | Groundwater | | Yes | 90% ingested water from well. 10% from uncontaminated sources. |
| | Surface water | | No | |
| Ingestion of plants | Irrigation water | | Yes | 50% from well, 50% from surface waters. Foliar deposition of water. |
| | Dust deposition | | Yes | Mainly from air dispersion of the sludge material. |
| | Root uptake | | Yes | Soil becomes contaminated because of deposition of radionuclides resulting from air dispersion and irrigation. |
| Ingestion of meat / milk | Livestock water | | Yes | 50% from well, 50% from surface waters. |
| | Livestock soil | | Yes | |
| | Fodder | Irrigation water | Yes | 50% from well, 50% from surface waters. Root uptake. |
| | | Dust deposition | Yes | |
| | | Root uptake | Yes | |
| Ingestion of fish | Surface water | | Yes | Surface water becomes contaminated through runoff of radionuclides from the landfill. |
| Ingestion of soil | Surface soil | | Yes | |

1 **Table 4.4b Landfill Neighbor Scenario Parameter and Distributions – After Fill**
 2 **and Monitoring Period**

| 3 Parameter | 4 Value / Distribution | 5 Comments |
|---|--|---|
| | Appendix A baseline values and distributions, except... | |
| 6 Nuclide concentration (pCi/g) | 7 Decay/ingrowth for 30 years Initial activity: Sub-scenarios 1 & 2 = 0.025 pCi/g; sub-scenarios 3 & 4 = 1 pCi/g | 8 See Chapter 3 |
| 9 Primary Contamination Area Parameters | | |
| 10 Area of primary contamination (m ²) | 11 10000 | 12 About 2 acres (see EPA 1988b). |
| 13 Length of contamination parallel to aquifer flow (m) | 14 100 | 15 Square root of area. |
| 16 Depth of soil mixing layer (m) | 17 0.15 | 18 Default plowing depth |
| 19 Runoff coefficient | 0.916/Uniform(0.413, 0.916) | To get an infiltration rate ranging from 0.03 m/yr to 0.22 m/yr. |
| 20 Irrigation applied per year (m/y) | 0 | No irrigation on the landfill area. |
| Cover | | |
| Thickness (m) | 0.5 | Standard thickness for clay layer |
| Bulk density (g/cm ³) | 1.52 | |
| Total porosity | 0.427 | HELP model default (Schroeder et al 1994) |
| Soil erodibility factor | 0.3 | Default value of RESRAD-Offsite. Results in erosion rate of 0.001 m/yr. |

Table 4.4b Landfill Neighbor Scenario Parameter and Distributions – After Fill and Monitoring Period (continued)

| Parameter | Value / Distribution | Comments |
|---------------------------------------|--|--|
| Volumetric water content | 0.427 | Set to the total porosity value to obtain the desired infiltration rate. |
| Contaminated Zone | | |
| Thickness (m) | 2 | Total 20,000 m ³ of sludge or waste. |
| Total porosity | 0.671 for MSW landfill and 0.427 for surface impoundment | From Tables 3.2 for MSW landfill. For surface impoundment, the value corresponds to that of sewage sludge. |
| Dry bulk density (g/cm ³) | 1.18 for MSW landfill and 1.52 for surface impoundment | 1.18 is the average value of the range specified in Table 3.2. |
| Field capacity | 0.292 for MSW landfill and 0.2 for surface impoundment | From Table 3.2 for MSW landfill. 0.2 is RESRAD default value. |
| Hydraulic conductivity (m/yr) | 315 for MSW landfill; 9.974/{Bounded LogNormal (2.3, 2.11, 0.004, 9250)} for surface impoundment | From Table 3.2 for MSW landfill. Soil value for surface impoundment. |
| Unsaturated zone 1 (liner) | | |
| Thickness (m) | 0.5 | Standard thickness for clay layer |
| Hydraulic conductivity (cm/s) | 0.03 / {Uniform(0.03,0.22)} | Same as the infiltration rate. |
| Total Porosity | 0.427 | HELP model default (Schroeder et al 1994) |
| Air Transport Parameters | | |
| Ingrowth factor for Rn -222 progeny | 0.265 | |

Table 4.4b Landfill Neighbor Scenario Parameter and Distributions – After Fill and Monitoring Period (continued)

| Parameter | Value / Distribution | Comments |
|---|----------------------|--|
| c/Q, all | see Table 3.4 | Adjusted CAP88PC value for a wind speed of 4.24 m/s at 150m |
| Groundwater Transport Parameters | | |
| Distance from down-gradient edge of contamination to well in the direction parallel to aquifer flow (m) | 150 | Collocate the well with the receptor. |
| Distance from down-gradient edge of contamination to surface water body in the direction parallel to aquifer flow (m) | 150 | Collocate the surface water body with the receptor |
| External Radiation Shape and Area Factor | | |
| Off-site | | |
| Scale (m) | 600 | |
| Receptor location X (m) | 506 | Circular landfill, 56 m radius; receptor is 150 m from its edge. |
| Receptor location Y (m) | 300 | |

4.5 INCINERATOR NEIGHBOR SCENARIO

The Incinerator Neighbor scenario models the potential for exposure of a member of the public residing near a typical sewage sludge incineration facility. The incinerator burns de-watered sludge, and the resulting exhaust gas is released from the top of a stack as a plume, some of which settles onto the Neighbor's property. The exposed individuals reside on a small, farm located at the point of maximum average annual air radionuclide concentration of the plume at ground level. The farm already existed when the incinerator facility was constructed, so exposure begins immediately after the POTW begins burning sludge. The incinerator will operate at nearly 100% capacity for 50 years, after which it is shut down and decommissioned. Since the residual ash from the process has no impact on the critical population group, it is not considered here. Table 4.5a summarizes the applicable pathways. Residual exposure and dose from plant operations are modeled out to 1,000 years.

1 The Incinerator Neighbor receives dose from external exposure, inhalation and ingestion.
 2 External exposure occurs from submersion in the plume, and from radiation emitted by nuclides
 3 that have been deposited on the ground. Inhalation of activity in the plume also leads to dose.
 4 Ingestion exposure comes from drinking contaminated water, eating plant foods raised by the
 5 Incinerator Neighbor that have activity either on their surface or taken up through the roots, or by
 6 eating meat or drinking milk from livestock that have ingested contaminated feed or water. The
 7 parameters used in RESRAD-OFFSITE for this scenario are identical to those defined in the
 8 Nearby Town Resident scenario, with the exception of some those listed in Table 4.5b.

9 **Table 4.5a Incinerator Neighbor Pathways**

| Exposure Pathway | Environmental Pathway | Pathway Included? | Comments | |
|--------------------------|-----------------------|-------------------|---|--|
| External radiation | Direct exposure | Yes | Plume submersion and groundshine. | |
| Inhalation | Plume inhalation | Yes | Exposed individual placed in the sector with highest concentration. | |
| | Indoor radon | No | | |
| | Outdoor radon | Yes | In plume, and emanating from deposited radionuclides | |
| Ingestion of water | Groundwater | No | | |
| | Surface water | No | | |
| Ingestion of plants | Irrigation water | No | | |
| | Dust deposition | Yes | | |
| | Root uptake | Yes | Surface deposition of transported nuclides. | |
| Ingestion of meat / milk | Livestock water | No | | |
| | Livestock soil | Yes | | |
| | Fodder | Irrigation water | No | |
| | | Dust deposition | Yes | |
| Root uptake | | Yes | | |
| Ingestion of fish | Surface Water | No | | |
| Ingestion of soil | Surface soil | Yes | Deposition of transported effluent. | |

Table 4.5b Incinerator Neighbor Scenario Parameters and Distributions

| Parameter | Value / Distributions | Comments |
|--|--|---|
| Dispersion Calculation in CAP88-PC | | |
| Lid Height (m) | 1,000 | |
| Stack Height (m) | 13 | From Easterly (Ohio) incinerator; typical of older incinerators with stack height less than the 65 ft. 'good engineering practice' height from the 503 rule risk assessment |
| Stack Diameter (m) | 1 | Easterly incinerator |
| Stack Exit Velocity (m/sec) | 1 | Easterly incinerator |
| Radiation Dose Calculation in RESRAD-Offsite | Appendix A baseline values and distributions, except ... | |
| Annual release rate of radionuclide from the incinerator (pCi /yr) | For each radionuclide of concern | |
| Sediment delivery ratio | 0 | No primary soil contamination source, therefore, no contaminant delivery to surface water. |
| c/Q, all | see Table 3.6 | |
| Fraction of water from surface body Household purposes | 0 | Household water and irrigation water are not contaminated because there is no primary soil contamination source. |
| – Beef cattle | 0 | |
| – Dairy cows | 0 | |
| – Irrigation for fruit, grain, non-leafy vegetable field | 0 | |
| – Irrigation for leafy vegetable field | 0 | |
| – Irrigation for livestock pasture and silage field | 0 | |
| – Irrigation for livestock grain field | 0 | |
| Fraction of water from well | 0 | Household water and irrigation water are not contaminated because there is no primary soil contamination source. |

1 **Table 4.5b Incinerator Neighbor Scenario Parameters and Distributions**
 2 **(continued)**

| 3 Parameter | Value / Distributions | Comments |
|--|------------------------------|--|
| 4 Distance from down gradient edge of 5 contamination to | | The value does not affect the dose results. However, to reduce the calculation time, a value of 0 was specified. |
| 6 - Well in the direction parallel to 7 aquifer flow (m) | 0 | |
| 8 - Surface water body in the direction 9 parallel to aquifer flow (m) | 0 | |
| 10 Distance from center of contamination 11 to well in the direction perpendicular 12 to aquifer flow (m) | 0 | The value does not affect the dose results. However, to reduce the calculation time, a value of 0 was specified. |
| 13 Fraction of time spent off-site, within 14 the range of radiation emanating from 15 primary contamination | | No primary contamination source. |
| 16 - Indoors | 0 | |
| 17 - Outdoors | 0 | |

18 **4.6 SLUDGE APPLICATION WORKER SCENARIO**

20 A sludge application worker engaged in the agricultural application of sludge to fields typically
 21 drives or works on a truck, tractor, or other vehicle that dispenses liquid, dewatered, or dried
 22 sludge at a fairly constant rate. Radiation exposures from the application of sludge would be
 23 primarily by way of external exposure and dust inhalation. External exposure is calculated both
 24 for the sludge being applied at the time as well as sludge applied from previous applications (5,
 25 20, 50, and 100 years). Since individuals working with sewage sludge are known to practice
 26 reasonable hygiene, inadvertent hand-to-mouth transfer or other ingestion of sludge is not
 27 considered here. Table 4.6a summarizes the exposure pathways considered. The driver is
 28 assumed to be situated above the ground on the truck, which provides some shielding.

29 Dewatered sludge cake, which is applied as a fertilizer or soil amendment, is typically 10 to
 30 20 percent solids, so there is little dust loading (Metro 2000). Sludge may also be applied in
 31 liquid or semi-liquid form, where dust generation would be even less. If the sludge is heat dried
 32 or mixed with other materials and composted, however, the resulting moisture content can be
 33 low. Since differences in the inhalation of dust is the dominant issue here, the scenario will
 34 consider the limiting case of the application of dry sludge to be more conservative.

35 Table 4.6b presents the non-baseline parameter values.

1 **Table 4.6a Agricultural Application Worker Pathways**

| 2 Exposure Pathway | 3 Environmental Pathway | | 4 Pathway Included? | 5 Comments |
|-----------------------------|--------------------------------|------------------|----------------------------|--------------------------------------|
| 6 External radiation | Direct exposure | | Yes | |
| 7 Inhalation | Resuspended dust | | Yes | |
| | Indoor radon | | No | |
| | Outdoor radon | | Yes | |
| 8 Ingestion of water | Groundwater | | No | |
| | Surface water | | No | |
| 9 Ingestion of plants | Irrigation water | | No | |
| | Dust deposition | | No | |
| | Root uptake | | No | |
| 10 Ingestion of meat / milk | Livestock water | | No | |
| | Livestock soil | | No | |
| | Fodder | Irrigation water | No | |
| | | Dust deposition | No | |
| Root uptake | | No | | |
| 11 Ingestion of fish | Surface Water | | No | |
| 12 Ingestion of soil | Surface soil | | No | Assume industrial hygiene practices. |

Table 4.6b Agricultural Application Worker Scenario Parameters and Distributions

| Scenario 6 sub-scenario | Parameter | Value / Distribution | Comments |
|-----------------------------------|---|---|---|
| Sub-scenario 1 (Uncertainty) | | Appendix A baseline values, distribution except... | |
| 1 | Years of application | 1 yr | |
| | Times for Calculation (yr) | 1 | Worker is only present during the application of sludge |
| | Cover (shielding) thickness (m) | 0.003 | Based on observed sludge application equipment |
| | Cover (shielding) density | 7.87 | density of steel |
| | Cover (shielding) erosion | 0 | No erosion of the shielding |
| | Receptor distance from the ground, m | 1 | |
| | Inhalation rate (m ³ /y) | 14,600, Triangular (4750, 7300, 28900) | Inhalation rate distribution for adult male for typical outdoor activity levels from NRC (2000b) (NUREG/CR-6697). |
| | Mass loading for inhalation (g/m ³) | 3×10 ⁻⁴ , Uniform (1×10 ⁻⁴ , 5×10 ⁻⁴) | Values are for average conditions outdoor during gardening from NRC (1992b) (NUREG/CR-5512, Volume 1) |
| | Exposure Duration (y) | 1 | Worker is only present during the application of sludge |
| | Indoor time fraction | 0 | Worker is engaged in application of sludge at the field |
| | Outdoor time fraction | 0.23 | Based on the assumption that the application worker spends 8 h/d for 250 d/y in the field. |
| Sub-scenarios 2-6 (Deterministic) | | Appendix A baseline and Sub-scenario 1 values, except... | Not Applicable |
| All | Log / linear spacing | Linear | To obtain annual dose results for each year |
| | Number of graphic points | 1024 | To obtain the largest number of annual doses in a single run |

Table 4.6b Agricultural Application Worker Scenario Parameters and Distributions (continued)

| Scenario 6 sub-scenario | Parameter | Value / Distribution | Comments |
|-------------------------|----------------------|----------------------|----------|
| 2 | Years of application | 1 | NA |
| 3 | Years of application | 5 | NA |
| 4 | Years of application | 20 | NA |
| 5 | Years of application | 50 | NA |
| 6 | Years of application | 100 | NA |

4.7 PUBLICLY OWNED TREATMENT WORKS WORKER SCENARIO

The purpose of this scenario is to consider potential radiation exposures of POTW workers. As should be apparent from the above, the operation of any one POTW involves a range of tasks, in addition to which there is a high degree of variability among POTWs in sludge handling processes. Our scenarios cannot encompass the entire scale of potential exposure situations, but it appears that there are three tasks that are representative and/or involve relatively high exposures to the sludge. These are: i) sludge sampling and sample transport to the lab for analysis; ii) sludge processing; and iii) biosolids loading. For all three of these tasks, exposures are due primarily to direct gamma exposure and radon (if radon precursors are present). For the third sub-scenario, inhalation is considered a possible exposure pathway as well. Because the biological hazard of the sludge is high, workers generally practice good industrial hygiene, so that inadvertent sludge ingestion, in particular, is omitted from the analysis.

4.7.1 SLUDGE SAMPLING

Once the raw sludge is separated from the treated wastewater effluent, it is sampled periodically. Samples may also be taken from digesters, dewatering devices, mixers, storage tanks, trucks, and from other processes that are used to treat, condition or transport the sludge. If automated equipment for this sampling process is not employed, then once a shift or so, an operator must manually collect sludge samples (typically about 1 liter) for analysis. The solids content is about 3 to 6 percent at this point. The worker carries the sample to the analytical laboratory, and may personally test it for percent total solids and volatile organics. The total duration of the procedure is about 5 minutes, during all of which time the operator is in close contact with sludge. Table 4.7a indicates the pathways that are active and included..

During the sampling process, a worker could be exposed to external radiation. Owing to the considerable biological hazard of the material, however, workers generally practice a high degree of industrial hygiene during this operation, and it appears that other potential exposure pathways will not be significant on a routine basis. (If an accident such as the splashing of waste onto an operator occurs, of course, inhalation, dermal, and other exposure pathways may be of

1 importance. But such accident conditions are rare, and they are not considered further in this
2 report.) It is assumed that a 1-liter sample containing 5% by volume solids is a point source held
3 for 5 minutes at waist level and at a distance of 0.5 m. The activity in the sample was derived in
4 Chapter 3. Self-shielding by the sample container and water are neglected.

5 Exposures calculated from this scenario are expected to be somewhat conservative, since the
6 actual sampling procedure includes some time during which the sample is being centrifuged and
7 otherwise manipulated, so that additional shielding and distance apply. Preliminary investigation
8 revealed that the scenario leads to small doses, so probabilistic analyses have not been
9 performed.

10 The parameters used with RESRAD-BUILD are presented in Table 4.7b. The doses calculated
11 are for one working shift.

12 **4.7.2 SLUDGE PROCESSING WITHIN PUBLICLY OWNED** 13 **TREATMENT WORKS**

14 This sub-scenario considers a situation in which an operator's workspace is located adjacent to a
15 conveyer belt transporting sludge cake, Table 4.7a. The cake is typically about 20% solids, so
16 the air dust loading around the conveyer is assumed to be very low, but there is a potential of
17 receiving a dose from external exposure.

18 The relevant parameters appear in Table 4.7b. The conveyer is represented by a line source (see
19 Chapter 3 for additional source details). The operator is located 3 m from the belt, which would
20 be a minimum distance for significant amounts of time near a mechanical operation with no
21 noise abatement.

22 Dose per hour adjacent to the conveyer belt is computed. The scenario is conservative but, again,
23 because of the low exposures, no probabilistic analysis is needed.

24 **4.7.3 BIOSOLIDS LOADING/STORAGE**

25 This sub-scenario is more likely to lead to both external and inhalation exposures. The worker
26 spends his time next to a pile of dewatered sludge (roughly 100 square meters in area). The
27 operations involve loading sludge at a POTW for transport offsite (into bags, trucks, or other).
28 The worker may be in an area of some dust loading, but it is controlled (e.g., through wetting
29 down or use of respirator) so as to not violate OSHA regulations. Exposures in this situation will
30 be from (1) external exposure from the sludge pile; (2) external exposure from immersion in a
31 cloud of airborne dust or vapors, and (3) inhalation of contaminated dust.

32 RESRAD-BUILD is used to model the exposures for this scenario. Table 4.7b lists those
33 parameters that differ from the baseline values. See Chapter 3 for source details. It is
34 conservatively assumed that the worker stands at the edge of the slab source for 2,000 hours per
35 year. No shielding is included in the calculation.

1 The airborne dust loading in the warehouse is conservatively assumed to be at the level of the
 2 OSHA standard for respirable, nuisance dust, 29 CFR 1910 Subpart Z, Table Z-1 (Limits for
 3 Contaminants in Air), namely 5 mg/m³.

4 It is difficult to assess the range of working conditions and practices for this scenario. The
 5 conditions have been chosen to represent a situation as observed at one real POTW, but those at
 6 other POTWs are likely to differ significantly from these, owing to the various possible uses for
 7 the sludge and the varied methods for processing it.

8 **Table 4.7a All POTW Worker Pathways**

| Exposure Pathway | Environmental Pathway | Pathway Included? | Comments | |
|--------------------------|------------------------|-------------------|--|--|
| External radiation | Direct exposure | Yes | All cases | |
| | Submersion | Yes | Immersion in cloud of dust, only for biosolids loading | |
| Inhalation | Resuspended dust | Yes | Only for biosolids loading | |
| | Indoor radon | Yes | Only for transport and biosolids loading | |
| | Outdoor radon | No | | |
| Ingestion of water | Groundwater | No | | |
| | Surface water (runoff) | No | | |
| Ingestion of plants | Irrigation water | No | | |
| | Dust deposition | No | | |
| | Root uptake | No | | |
| Ingestion of meat / milk | Livestock water | No | | |
| | Livestock soil | No | | |
| | Fodder | Irrigation water | No | |
| | | Dust deposition | No | |
| Root uptake | | No | | |
| Ingestion of fish | Surface Water | No | | |
| Ingestion of soil | Surface soil | No | Assumes industrial hygiene practices eliminate ingestion | |

Table 4.7b General POTW Worker Sub-Scenario Parameters and Distributions

| Sub-Scenario | Parameter | Value / Distribution | Comments |
|--|---|---------------------------------------|---|
| 1 - Sludge sampling (Deterministic) | | Appendix A baseline values, except... | |
| | Exposure Duration (d) | 1 | |
| | Indoor Fraction | 3.47×10^{-3} | To get a total exposure time of 5 minutes |
| | Max. No. of Points for Time Integration | 1 | Instantaneous dose is calculated |
| | Source Type | Point | |
| | Activity Concentration, pCi | 75 | |
| | Air Release Fraction | 0 | To suppress all air dependent pathways |
| | Receptor Location | (0,0,0.5) | Receptor at a distance of 0.5 m from the source |
| 2 - Processing (Deterministic) | | Appendix A baseline values, except... | |
| | Exposure Duration (d) | 1 | Scenario definition |
| | Indoor Fraction | 4.17×10^{-2} | To get a total exposure time of a hour |
| | Max. No. of Points for Time Integration | 1 | Instantaneous dose is calculated |
| | Source Type | Line | |
| | Source Direction | X | |
| | Source Length (m) | 50 | |
| | Activity Concentration, pCi/m | 3,000 | Scenario definition |
| | Air Release Fraction | 0 or 0.357 | Zero, to suppress all air dependent pathways for all radionuclides except for radon precursors, where air release fraction of 0.357 is used |
| | Removable Fraction | 0.1 | |
| | Radon Release Fraction | 0.1 | |

Table 4.7b General POTW Worker Sub-Scenario Parameters and Distributions (continued)

| Sub-Scenario | Parameter | Value / Distribution | Comments |
|---------------------------------------|--------------------|--|---|
| | Source Lifetime, d | 10,000 | |
| | Receptor Location | (0,0,3) | Receptor at a distance of 3 m from the source |
| 3 - Biosolids loading (Probabilistic) | | Appendix A baseline distributions, values, except... | |
| | Indoor Fraction | 0.228 | To get a total exposure time of 2,000 hours in one year |
| 4 - Biosolids loading (Deterministic) | | Appendix A baseline values, except... | |
| | Indoor Fraction | 0.228 | To get a total exposure time of 2,000 hours in one year |

5 SENSITIVITY, AND UNCERTAINTY AND VARIABILITY

5.1 SENSITIVITY

A number of sensitivity analyses were performed to ensure that the source analysis methods in this study are robust. These rely on previous sensitivity analyses carried out on the RESRAD family of codes. In particular, the recent NRC documents NUREG/CR-6676 and NUREG/CR-6697 list and categorize the various parameters used in RESRAD and RESRAD-BUILD, and rank the degree of influence of each on calculation results (NRC 2000a,b). These documents also developed distributions for high ranking parameters, and these were used in the present analysis.

Of particular interest are the assumptions employed in implementing the multiple-years of application source term. Sensitivity analyses on these assumptions (e.g., parameters such as erosion rate and water table drop rate set to zero) indicated that the results are not significantly affected.

5.2 SCENARIO UNCERTAINTY AND VARIABILITY

5.2.1 EXPOSURE ENVIRONMENT

The range of exposure groups and situations developed for this analysis was felt, by the SSS, to be typical and 'reasonable.' There may exist, however, certain allowed combinations of parameters that lead to radiation exposures that are greater or less than those calculated here. In exploring this variability, the ISCORS SSS noted that the POTW worker scenarios, for example, display a broad array of site configurations and operations across the country. The SSS calculated the DSRs for Ra-226 and Th-228 in the POTW Loading subscenario with the site-specific parameters for a particular POTW; the results were within the range of the DSRs probabilistic calculations, with the Ra-226 DSR at about the 40th percentile level, and the Th-228 DSR at the 5th percentile. Thus, the calculation suggests that the use of the 95th percentile DSR would be conservative for this individual POTW, but that the probability distributions capture a plausible range of scenario variability.

5.2.2 EXPOSED POPULATIONS: CHILDREN/INFANTS

The effect of variability in the age of the exposed populations is not fully addressed in this analysis. This is partially due to the choice (described in Chapter 1) to use dose coefficients based on the methods of ICRP 26 and ICRP 30, as contained in Federal Guidance Reports 11 and 12 (EPA 1988a, 1993a). A *qualitative* understanding of the relative impacts on infants and children can be derived from Report No. 129 of the National Council on Radiation Protection and Measurements (NCRP 1999), however, which derives ratios for the dose coefficients as well as intake factors for children (10 yr old) versus adults, and for infants versus adults. For the radionuclides and dominant pathways of interest, the ratios are in almost all cases less than a factor of 2. This is small compared to the parameter uncertainty/variability calculated using

1 Monte Carlo methods (see below) as well as compared to the source variability seen in the
 2 NRC/EPA national survey of radioactivity in sewage sludge and ash.

3 5.3 PARAMETER UNCERTAINTY AND VARIABILITY

4 The main means of incorporating uncertainty and variability into the computations was through
 5 the use of distributions for certain input parameters. Table 5.1 summarizes uncertainties and/or
 6 variability characterized by distributions for selected parameters. Additional detail is contained
 7 in NRC (2000b). In many cases, the use of a distribution reflects both uncertainty and variability.

8 **Table 5.1 Parameters and their Uncertainties and Variability***

| 9 Parameter | Uncertainty Characterized by Distribution | Variability Characterized by Distribution |
|---|---|--|
| 10 <i>Hydrogeological parameters</i> | | |
| 11 Distribution Coefficients | The possibility of rapid transport due to fracture flow and/or colloidal transport. | Variability of published measured or estimated values. |
| 12 Total and Effective 13 Porosities | — | Variability of published measured or estimated values based on national databases. |
| 14 Hydraulic Conductivities | The possibility of rapid transport due to fracture flow and/or colloidal transport. | Variability of published measured or estimated values based on national databases. |
| 15 Soil b parameter | — | Variability of published measured or estimated values. |
| 16 Hydraulic Gradient | — | Variability of published measured or estimated values. |
| 17 Unsaturated Zone 18 Thickness | — | Variability across continental U.S. |
| 19 Well pump intake depth | Uncertainty in actual intake depths | Variability in aquifer thicknesses |
| 20 Depth of Soil Mixing 21 Layer | — | Variability in natural (wind, precipitation) and man-made processes (tillage). |

Table 5.1 Parameters and their Uncertainties and Variability* (continued)

| Parameter | Uncertainty Characterized by Distribution | Variability Characterized by Distribution |
|--|--|--|
| <i>Human Intake Parameters</i> | | |
| Inhalation Rate | — | Variability in adults due to differences in long-term patterns of time and activity. |
| Soil Ingestion Rate | Uncertainty in adults due to limited data. | Variability in adults. Distribution includes mean rate for children. |
| Drinking Water Ingestion Rate | — | Variability in adults. |
| Milk Consumption Rate | Uncertainty due to limited data and changes over time. | Variability across adults and children. |
| <i>Crops and Livestock Parameters</i> | | |
| Plant, Meat, Milk, and Fish Transfer factors | Uncertainty in the transfer factor method. | Variability among different sites and foodstuffs. |
| Depth of roots | — | Variability amongst different plant types and growing conditions |
| <i>Building Characteristics parameters</i> | | |
| Indoor dust filtration factor | — | Variability amongst different buildings, climates, and seasons. |
| External Gamma Shielding Factor | — | Variability amongst different home constructions |
| <i>Other parameters</i> | | |
| Resuspension Rate | Uncertainty due to limited data. | Variability amongst different sites. |
| Shielding Density | — | Variability amongst different substances. |
| Note: | | |
| * Additional detail on these parameters and others can be found in Yu et al. 2000. | | |

1 The results of the parameter uncertainty/variability analysis using the probabilistic RESRAD
2 codes are summarized in Table 5.2. The tabulated values of the ratio of the 95% to the 5% DSR,
3 in particular, characterize the range of uncertainty and variability in the DSRs, and reflect the
4 choice of parameter distributions chosen.

5 Another sources of parameter uncertainty and variability is that the inhalation dose coefficients
6 from FGR 11 (EPA 1988a) have different values for different clearance rates (typically days,
7 weeks, or years). Because of the generic nature of this assessment, no assumptions were made
8 about the distributions of sizes and clearance rates of suspended particles from sewage sludge,
9 but rather the largest inhalation dose coefficient was chosen.

10 Many parameters in this assessment may be correlated, and the analysis includes correlation
11 coefficients that can be well characterized and justified for a generic site¹⁰. For instance, the
12 partition coefficients of U-234, U-235, and U-238 are set to be correlated because the transport
13 characteristics are isotope-independent. Some correlations, such as that between the total and the
14 effective porosities, are discussed in NRC (2000a).

15

10 Additional correlations may need to be considered for specific sites.

1 **Table 5.2 Parameter Uncertainty/Variability Results**

2

3

4

| Ratio of 95% DSR to 5% DSR | | | | | | | | |
|----------------------------|-----------------|-------------------|-------------|------------------------|--|----------------------|---------------------------|-----------------------|
| Radio-nuclide | Onsite Resident | Recreational User | Nearby Town | Landfil (MSW) Neighbor | Landfil (Surface Impoundment) Neighbor | Incinerator Neighbor | Sludge Application Worker | POTW Worker (loading) |
| Ac-227 | 2.9 | 1.2 | 6.2 | 114.7 | 53.6 | 2.0 | 4.5 | 4.8 |
| Am-241 | 5.6 | 1.9 | 6.4 | 185.1 | 90.9 | 2.0 | 8.7 | 14.8 |
| Be-7 | 2.2 | 1.0 | 7.3 | 1.0 | 1.0 | 3.0 | 1.1 | 1.0 |
| C-14 | 76.1 | 557.7 | 2.0 | 1.0 | 4.2E+12 | 2.1 | 4.7 | 1.3 |
| Ce-141 | 2.2 | 1.0 | 4.2 | 1.0 | 1.0 | 1.7 | 1.0 | 1.0 |
| Co-57 | 2.3 | 1.1 | 12.7 | 1.0 | 1.0 | 5.4 | 1.1 | 1.0 |
| Co-60 | 2.3 | 1.1 | 9.6 | 1.1E+03 | 404.8 | 3.8 | 1.2 | 1.0 |
| Cr-51 | 2.2 | 1.1 | 9.0 | 1.0 | 1.0 | 4.4 | 1.1 | 1.0 |
| Cs-134 | 2.3 | 1.1 | 18.7 | 1.0 | 1.0 | 4.6 | 1.1 | 1.0 |
| Cs-137 | 2.7 | 1.1 | 14.9 | 110.4 | 63.2 | 5.2 | 1.1 | 1.0 |
| Eu-154 | 2.2 | 1.1 | 8.2 | 412.2 | 95.9 | 2.6 | 1.1 | 1.0 |
| Fe-59 | 2.2 | 1.1 | 9.0 | 1.0 | 1.0 | 4.3 | 1.1 | 1.0 |
| H-3 | 8.9 | 11.8 | 3.9 | 1.0 | 8.2E+29 | 2.1 | 5.2 | 18.8 |
| I-125 | 12.8 | 5.5 | 8.6 | 1.0 | 1.0 | 6.0 | 1.8 | 1.0 |
| I-131 | 2.5 | 1.1 | 8.6 | 1.0 | 1.0 | 6.0 | 1.1 | 1.0 |
| In-111 | 2.2 | 1.0 | 7.7 | 1.0 | 1.0 | 5.1 | 1.0 | 1.0 |
| K-40 | 2.2 | 1.2 | 8.55 | 1.2E+08 | 2.1E+07 | 4.7 | 1.2 | 1.0 |
| La-138 | 8.0 | 4.1 | 14.7 | 4.1E+32 | 6.1E+33 | 5.4 | 5.7 | 1.0 |
| Np-237 | 74.9 | 841.9 | 6.8 | 4.8E+08 | 2.8E+08 | 2.0 | 3.0 | 213.3 |
| Pa-231 | 22.1 | 55.4 | 17.7 | 3.3E+04 | 5.0E+03 | 2.0 | 19.6 | 9.6 |
| Pb-210 | 9.9 | 8.2 | 6.1 | 81.4 | 77.2 | 1.9 | 5.2 | 6.4 |
| Po-210 | 20.2 | 14.3 | 4.8 | 1.0 | 1.0 | 2.5 | 12.2 | 99.1 |
| Pu-238 | 7.0 | 3.0 | 6.1 | 11.9 | 1.1 | 2.0 | 12.6 | 187.5 |
| Pu-239 | 6.8 | 3.2 | 5.8 | 11.6 | 12.5 | 2.0 | 12.7 | 251.9 |
| Ra-226 | 1.2 | 1.1 | 1.0 | 1.5 | 1.3 | 3.0 | 1.0 | 17.4 |
| Ra-228 | 2.4 | 1.1 | 1.1 | 11.1 | 12.1 | 2.1 | 1.1 | 1.0 |
| Sm-153 | 2.1 | 1.0 | 6.4 | 1.0 | 1.0 | 3.8 | 1.0 | 1.0 |
| Sr-89 | 28.2 | 8.3 | 5.0 | 1.0 | 1.0 | 2.7 | 1.2 | 1.0 |
| Sr-90 | 35.9 | 27.9 | 15.3 | 1.2E+07 | 5.8E+06 | 9.0 | 1.6 | 1.1 |
| Th-228 | 2.0 | 1.1 | 1.0 | 1.0 | 1.0 | 2.0 | 1.1 | 12.7 |
| Th-229 | 2.2 | 1.1 | 6.0 | 35.7 | 25.3 | 2.0 | 2.6 | 2.6 |
| Th-230 | 62.6 | 46.3 | 29.5 | 4.2 | 3.5 | 2.1 | 26.3 | 142.6 |
| Th-232 | 3.9 | 2.1 | 3.0 | 5.2 | 3.1 | 2.0 | 2.6 | 219.4 |
| Tl-201 | 2.2 | 1.0 | 16.2 | 1.0 | 1.0 | 11.6 | 1.0 | 1.0 |
| Tl-202 | 2.2 | 1.1 | 16.6 | 1.0 | 1.0 | 9.3 | 1.1 | 1.0 |
| U-233 | 18.9 | 340.9 | 7.7 | 114.4 | 104.9 | 2.0 | 18.6 | 88.3 |
| U-234 | 19.2 | 299.1 | 6.2 | 28.7 | 23.8 | 2.0 | 13.2 | 131.0 |
| U-235 | 2.9 | 4.9 | 6.8 | 84.8 | 224.0 | 2.0 | 2.1 | 1.2 |
| U-238 | 4.7 | 15.5 | 6.2 | 8.8E+03 | 3.7E+04 | 2.0 | 2.7 | 2.0 |
| Xe-131m | 2.3 | 1.3 | 1.0 | 1.0 | 1.0 | 1.0 | 1.3 | 1.0 |
| Zn-65 | 6.2 | 1.8 | 12.0 | 1.0 | 1.0 | 7.5 | 1.6 | 1.0 |

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5.4 MODEL UNCERTAINTY

Chapters 1 and 2 included discussion of the limitations of the generic modeling performed here. This section describes uncertainties from the use of the RESRAD computer codes.

5.4.1 TREATMENT OF SURFACE WATER

Surface waters range from ponds maintained by groundwater and local runoff to long, rapidly flowing rivers fed by vast watersheds. RESRAD and RESRAD-OFFSITE do not make that distinction, but rather focus on the amount of dilution of the contaminated water and sediment that reach the surface water. RESRAD uses only the watershed area in calculating a dilution factor relative to the aquifer. RESRAD-OFFSITE also considers runoff, and requires other variables, such as the residence time, the water body volume, the distance from the river to the contaminated zone, the sediment delivery ratio, and depth relative to the ground water table.

The methodology developed to address multiple years of application requires that surface water be contaminated only by means of ground water, *i.e.*, not by runoff from a field upon which sludge has been applied (this is to ensure mass balance over multiple applications). Also, the rate of erosion of surface soil is set to zero in the calculation of leaching of radionuclides downward from the source level, and the depth of the water table is held fixed over time. The relatively conservative RESRAD default watershed area was used adopted to compensate somewhat for the uncertainties introduced by these assumptions,

5.4.2 OFFSITE EXPOSURES

A basic assumption of the offsite analyses is that contaminated dust is blown from the source to the receptor and other neighboring fields, but that further transport is governed by local conditions. In reality, transport is determined largely by the details of the balance between the amount of wind-blown dust settling *and staying* on a town or neighboring fields, on the one hand, and the amount that is blown or washed away. In other words, is the amount of contaminated dust that is blown into the town equal to or less than that which is blown away, or is there a residual that remains in the town and could be a source of exposure?

Even a relatively simple calculation of this balance requires detailed knowledge of the joint frequency-of-occurrence spectrum of the puffs of wind of various magnitudes that sweep over the source site and then over the receptor, the size distribution of dust particles both places, temporal patterns of precipitation, and numerous other factors for which it would be difficult to make defensible modeling assumptions and approximations. In view of the great uncertainty and variability in these factors, this analysis assumes (as does most other air transport and dose modeling) that little activity is removed from the contaminated top layer of soil by erosion, weathering, or leaching. Deposited material acts, rather, like a new, thin-layer addition to the contaminated zone source available for leaching, and for uptake via the pathway models for ingestion, inhalation, external, *etc.*

5.4.3 INFILTRATION RATE FOR LANDFILLS/SURFACE IMPOUNDMENTS

It is assumed that after the 30 year monitoring period, infiltration through a landfill or surface impoundment can be handled with a simple soil model. In particular, the default infiltration rate assumed in RESRAD is about 50 cm/y. Since it is not obvious that this provides an adequate representation of landfill performance, the Hydrologic Evaluation of Landfill Performance (HELP) code was also applied to the scenario. The HELP model performs a detailed water balance calculation accounting for many more processes than the RESRAD code. (Schroeder et al 1994)

The HELP model found that for a typical municipal solid waste landfill, the leakage rates (infiltration through the bottom layer) is negligible (much less than 1 cm/y). For a "worst case" scenario under modern-day practices, the HELP model calculated an infiltration rate of 3.3 cm/y out of 107 cm/y of precipitation, with leachate at about 46 cm/year. For a "worst case" scenario that assumes a high rate of liner defects in the range of those found at very old facilities, the HELP model calculated an infiltration rate of 22 cm/y (again out of 107 cm/y of precipitation), with leachate at about 25 cm/y. Unfortunately, there is very little data on the long-term performance of cover/liner systems.

Based on these calculations, the probabilistic calculations in this assessment assume an infiltration rate that is distributed between 0.03 m/yr and 0.22 m/yr. This is considered reasonably conservative, especially given the 1000 year modeling framework, but not extreme in light of the uncertainties. However, the uncertainty in the value remains significant, and may exceed the range used in the calculation.

6 SUMMARY OF DOSE-TO-SOURCE RATIOS

6.1 INTRODUCTION

This Chapter presents an overview of the results of the probabilistic DSR calculations. The detailed results are tabulated in Appendix E.

As discussed in Section 2.4.4, the probabilistic version of RESRAD runs J realizations, and generates J curves of dose as a function time, $dsr_j(t), j = 1 \dots J$, for every scenario and for every radionuclide (set at unit specific activity in dry sludge.) Each $dsr_j(t)$ has a maximum value, called DSR_j ,

$$DSR_j = \text{Max}[dsr_j(t)] , \quad (6.1)$$

and the set of these maximum values, $\{DSR_j\}$, itself comprises a distribution. It is the 95-percentile values from this distribution that populate the DSR tables below; other percentile values are contained in Appendix E. It is a standard practice to consider a relatively conservative percentile value when an assessment is generic and not site-specific (in a site-specific assessment, it may be appropriate to use a measure of central tendency). The major pathway(s) is(are) also reported.

In addition, if a radionuclide has more than 10% of its dose through the indoor radon pathway, then an "*" is marked in the "Critical Pathway(s)" column. The indoor radon pathway breakouts with radon and non-radon components are listed in separate tables. These tables present the non-radon DSR in mrem/year per pCi/g, and the indoor radon DSRs in three different units: mrem/year per pCi/g, Working Levels per pCi/g, and pCi/liter of the appropriate radon daughter per pCi/g. The latter two are actually "concentration to source ratios," since Working Levels and pCi/liter are both concentration units.

6.2 LAND APPLICATION SCENARIOS

The following Tables give the 95% DSRs for the land application scenarios, as well as the multiple year scaling factors, where appropriate. Several general characteristics are of note. The Onsite Resident calculations had the highest DSRs for most of the radionuclides, in particular when multiple years of application were considered. The radionuclides with the highest calculated DSRs are Np-237 and Ra-226.

In a few cases (C-14, Np-237, U-233, U-234, and U-238), the Recreational User scenario had larger DSRs than the other land application scenarios under the assumption of a single application. This is largely due to the ten times larger source term in the Recreational scenario. In no cases were the Recreational User DSRs the largest when multiple years of application were considered in the other scenarios. In the case of certain radionuclides with very short half-lives (I-131, In-111, Sm-153, Tl-201, and Tl-202), the Nearby Town scenario gave the highest DSRs because of the rapid exposure through the air transport pathway. However, these DSRs were all

1 very small (less than 0.001 mrem/yr per pCi/g). Indoor radon was only a significant component
 2 of the dose for the Onsite Resident with Ra-226 and Th-228. In the case of Ra-226, radon was
 3 the dominant pathway.

4 **Table 6.1 Onsite Resident Scenario Total DSR Results**

| Radio-nuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factors | | | | |
|---------------|--------------------|--------------------------|-----------------|----------|----------|----------|----------|
| | | | 1 | 5 | 20 | 50 | 100 |
| Ac-227 | 1.06e-02 | External | 9.67e-01 | 4.53e+00 | 1.44e+01 | 2.39e+01 | 2.85e+01 |
| Am-241 | 1.43e-03 | Plant and Soil Ingestion | 9.98e-01 | 4.96e+00 | 1.95e+01 | 4.70e+01 | 8.86e+01 |
| Be-7 | 1.63e-04 | External | 8.61e-03 | 8.68e-03 | 8.68e-03 | 8.68e-03 | 8.68e-03 |
| C-14 | 2.42e-02 | Meat and Plant Ingestion | 1.00e+00 | 5.00e+00 | 2.00e+01 | 4.99e+01 | 9.95e+01 |
| Ce-141 | 1.19e-04 | External | 4.13e-04 | 4.13e-04 | 4.13e-04 | 4.13e-04 | 4.13e-04 |
| Co-57 | 1.03e-03 | External | 3.91e-01 | 6.35e-01 | 6.41e-01 | 6.41e-01 | 6.41e-01 |
| Co-60 | 4.06e-02 | External | 8.72e-01 | 3.38e+00 | 6.38e+00 | 6.82e+00 | 6.82e+00 |
| Cr-51 | 5.26e-05 | External | 1.06e-04 | 1.06e-04 | 1.06e-04 | 1.06e-04 | 1.06e-04 |
| Cs-134 | 2.63e-02 | External | 7.13e-01 | 2.02e+00 | 2.48e+00 | 2.48e+00 | 2.48e+00 |
| Cs-137 | 1.35e-02 | External | 9.74e-01 | 4.63e+00 | 1.54e+01 | 2.77e+01 | 3.53e+01 |
| Eu-154 | 1.88e-02 | External | 9.23e-01 | 3.96e+00 | 9.56e+00 | 1.17e+01 | 1.20e+01 |
| Fe-59 | 3.43e-03 | External | 3.38e-03 | 3.39e-03 | 3.39e-03 | 3.39e-03 | 3.39e-03 |
| H-3 | 1.20e-05 | Water | 1.00e+00 | 4.51e+00 | 1.29e+01 | 1.41e+01 | 1.41e+01 |
| I-125 | 6.09e-04 | Meat | 1.16e-02 | 1.17e-02 | 1.17e-02 | 1.17e-02 | 1.17e-02 |
| I-131 | 2.79e-04 | External | 1.73e-14 | 1.73e-14 | 1.73e-14 | 1.73e-14 | 1.73e-14 |
| In-111 | 1.18e-04 | External | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 |
| K-40 | 2.34e-03 | External | 8.05e-01 | 2.73e+00 | 4.07e+00 | 4.13e+00 | 4.13e+00 |
| La-138 | 1.78e-02 | External | 7.91e-01 | 2.59e+00 | 3.69e+00 | 3.73e+00 | 3.73e+00 |
| Np-237 | 2.42e-01 | Fish | 1.00e+00 | 5.00e+00 | 2.00e+01 | 5.00e+01 | 1.00e+02 |

Table 6.1 Onsite Resident Scenario Total DSR Results (continued)

| | Radio-nuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factors | | | | |
|----|---------------|--------------------|------------------------------|-----------------|----------|----------|----------|----------|
| | | | | 1 | 5 | 20 | 50 | 100 |
| 1 | Pa-231 | 4.75e-02 | Plant Ingestion and External | 1.00e+00 | 5.00e+00 | 2.00e+01 | 4.94e+01 | 9.59e+01 |
| 2 | Pb-210 | 1.88e-02 | Meat | 1.00e+00 | 4.83e+00 | 1.56e+01 | 2.65e+01 | 3.19e+01 |
| 3 | Po-210 | 6.13e-03 | Meat | 1.59e-01 | 1.90e-01 | 1.90e-01 | 1.90e-01 | 1.90e-01 |
| 4 | Pu-238 | 1.23e-03 | Plant and Soil Ingestion | 9.91e-01 | 4.86e+00 | 1.82e+01 | 3.99e+01 | 6.51e+01 |
| 5 | Pu-239 | 1.35e-03 | Plant and Soil Ingestion | 9.99e-01 | 4.98e+00 | 1.97e+01 | 4.84e+01 | 9.36e+01 |
| 6 | Ra-226 | 1.94e-01 | Radon * | 1.00e+00 | 5.00e+00 | 2.00e+01 | 4.98e+01 | 9.83e+01 |
| 7 | Ra-228 | 3.55e-02 | External | 1.00e+00 | 4.82e+00 | 1.16e+01 | 1.30e+01 | 1.30e+01 |
| 8 | Sm-153 | 9.93e-06 | External | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 |
| 9 | Sr-89 | 4.11e-04 | Meat and Plant Ingestion | 6.43e-03 | 6.47e-03 | 6.47e-03 | 6.47e-03 | 6.47e-03 |
| 10 | Sr-90 | 3.23e-02 | Meat and Plant Ingestion | 9.40e-01 | 4.17e+00 | 1.11e+01 | 1.49e+01 | 1.56e+01 |
| 11 | Th-228 | 2.36e-02 | External * | 6.96e-01 | 1.92e+00 | 2.29e+00 | 2.29e+00 | 2.29e+00 |
| 12 | Th-229 | 5.71e-03 | External | 1.00e+00 | 5.00e+00 | 1.99e+01 | 4.96e+01 | 9.85e+01 |
| 13 | Th-230 | 6.24e-02 | Radon | 1.00e+00 | 5.01e+00 | 2.01e+01 | 5.06e+01 | 1.03e+02 |
| 14 | Th-232 | 5.28e-02 | External | 1.00e+00 | 5.00e+00 | 2.00e+01 | 4.99e+01 | 9.94e+01 |
| 15 | Tl-201 | 1.88e-05 | External | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 |
| 16 | Tl-202 | 3.45e-04 | External | 1.00e-09 | 1.00e-09 | 1.00e-09 | 1.00e-09 | 1.00e-09 |
| 17 | U-233 | 1.09e-03 | Meat and Plant Ingestion | 9.93e-01 | 4.89e+00 | 1.86e+01 | 4.20e+01 | 7.25e+01 |

Table 6.1 Onsite Resident Scenario Total DSR Results (continued)

| Radio-nuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factors | | | | |
|---------------|--------------------|--------------------------|-----------------|----------|----------|----------|----------|
| | | | 1 | 5 | 20 | 50 | 100 |
| U-234 | 1.02e-03 | Meat and Plant Ingestion | 9.90e-01 | 4.86e+00 | 1.81e+01 | 3.95e+01 | 6.42e+01 |
| U-235 | 2.53e-03 | External | 9.90e-01 | 4.86e+00 | 1.81e+01 | 3.95e+01 | 6.39e+01 |
| U-238 | 1.00e-03 | External | 9.90e-01 | 4.86e+00 | 1.81e+01 | 3.94e+01 | 6.35e+01 |
| Xe-131m | 2.53e-06 | External | 7.86e-13 | 7.86e-13 | 7.86e-13 | 7.86e-13 | 7.86e-13 |
| Zn-65 | 2.07e-02 | External | 3.54e-01 | 5.44e-01 | 5.47e-01 | 5.47e-01 | 5.47e-01 |

Table 6.2 Onsite Resident Scenario Indoor Radon DSR Results

| Radio-nuclide | 95% Peak Non-Rn DSR | 95% Peak Indoor Rn-only DSR | | |
|---------------|---------------------|-----------------------------|----------|-----------|
| | | TEDE | WL | pCi/L |
| Ra-226 | 4.91e-02 | 1.51e-01 | 6.01e-06 | 8.72e-04 |
| Th-228 | 2.14e-02 | 2.01e-03 | 4.83e-07 | 0.0000208 |

Note:

The scaling factors in Table 6.1 should be used to correct for the waiting time and multiple years of application.

Table 6.3 Recreational User Scenario Total DSR Results

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factor |
|--------------|--------------------|-----------------------|-----------------------|
| | | | 3 year waiting period |
| Ac-227 | 1.91e-03 | External | 9.04e-01 |
| Am-241 | 8.73e-05 | External | 9.94e-01 |
| Be-7 | 4.58e-05 | External | 6.44e-07 |
| C-14 | 9.76e-02 | Fish | 1.00e+00 |
| Ce-141 | 3.33e-05 | External | 7.09e-11 |
| Co-57 | 2.76e-04 | External | 5.99e-02 |
| Co-60 | 1.10e-02 | External | 6.64e-01 |
| Cr-51 | 1.49e-05 | External | 1.21e-12 |
| Cs-134 | 6.40e-03 | External | 3.63e-01 |
| Cs-137 | 2.86e-03 | External | 9.29e-01 |
| Eu-154 | 5.36e-03 | External | 7.87e-01 |
| Fe-59 | 9.67e-04 | External | 3.87e-08 |
| H-3 | 4.51e-06 | Meat, Water, and Fish | 8.62e-01 |
| I-125 | 3.31e-05 | Meat | 1.99e-06 |
| I-131 | 6.23e-05 | External | 0.00e+00 |
| In-111 | 3.30e-05 | External | 0.00e+00 |
| K-40 | 7.17e-04 | External | 6.20e-01 |
| La-138 | 5.60e-03 | External | 5.91e-01 |
| Np-237 | 6.07e-01 | Fish | 8.57e-01 |
| Pa-231 | 1.03e-02 | External | 1.00e+00 |
| Pb-210 | 6.29e-04 | Meat | 9.77e-01 |
| Po-210 | 3.89e-04 | Meat | 4.09e-03 |
| Pu-238 | 3.28e-05 | Meat and Inhalation | 9.74e-01 |
| Pu-239 | 3.98e-05 | Meat and Inhalation | 9.98e-01 |
| Ra-226 | 8.54e-03 | External | 1.00e+00 |
| Ra-228 | 7.33e-03 | External | 1.00e+00 |
| Sm-153 | 2.77e-06 | External | 0.00e+00 |
| Sr-89 | 1.50e-05 | Meat and External | 2.74e-07 |
| Sr-90 | 1.45e-03 | Meat | 8.68e-01 |
| Th-228 | 6.48e-03 | External | 3.38e-01 |
| Th-229 | 1.40e-03 | External | 1.00e+00 |

Table 6.3 Recreational User Scenario Total DSR Results (continued)

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factor |
|--------------|--------------------|---------------------|-----------------------|
| | | | 3 year waiting period |
| Th-230 | 2.95e-03 | External | 1.00e+00 |
| Th-232 | 1.22e-02 | External | 1.00e+00 |
| Tl-201 | 5.01e-06 | External | 0.00e+00 |
| Tl-202 | 9.54e-05 | External | 1.02e-27 |
| U-233 | 1.96e-03 | Fish | 1.00e+00 |
| U-234 | 1.34e-03 | Meat and Inhalation | 9.80e-01 |
| U-235 | 2.15e-03 | External | 9.79e-01 |
| U-238 | 1.23e-03 | External | 9.81e-01 |
| Xe-131m | 8.19e-07 | External | 0.00e+00 |
| Zn-65 | 2.35e-03 | External | 4.44e-02 |

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1 **Table 6.4 Nearby Town Scenario Total DSR Results**

| Radio-nuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factors | | | | |
|---------------|--------------------|-----------------------------|-----------------|----------|----------|----------|----------|
| | | | 1 | 5 | 20 | 50 | 100 |
| Ac-227 | 5.94e-05 | Inhalation | 1.00e+00 | 4.68e+00 | 1.49e+01 | 2.51e+01 | 3.00e+01 |
| Am-241 | 4.22e-06 | Inhalation | 1.00e+00 | 4.98e+00 | 1.95e+01 | 4.71e+01 | 8.89e+01 |
| Be-7 | 6.43e-12 | Inhalation | 1.00e+00 | 1.36e+00 | 1.36e+00 | 1.36e+00 | 1.36e+00 |
| C-14 | 5.22e-07 | Inhalation | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| Ce-141 | 7.12e-11 | Inhalation | 1.00e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 |
| Co-57 | 2.98e-10 | Meat Ingestion | 1.00e+00 | 2.74e+00 | 2.84e+00 | 2.84e+00 | 2.84e+00 |
| Co-60 | 1.36e-08 | External | 1.00e+00 | 4.91e+00 | 1.53e+01 | 1.93e+01 | 1.94e+01 |
| Cr-51 | 1.80e-11 | Meat Ingestion | 1.00e+00 | 1.03e+00 | 1.03e+00 | 1.03e+00 | 1.03e+00 |
| Cs-134 | 2.84e-08 | Meat Ingestion | 1.00e+00 | 3.67e+00 | 5.23e+00 | 5.25e+00 | 5.25e+00 |
| Cs-137 | 4.28e-08 | Meat Ingestion and External | 1.00e+00 | 5.00e+00 | 1.98e+01 | 4.65e+01 | 7.64e+01 |
| Eu-154 | 7.50e-09 | External | 1.00e+00 | 4.97e+00 | 1.80e+01 | 3.03e+01 | 3.28e+01 |
| Fe-59 | 7.44e-10 | Meat Ingestion | 1.00e+00 | 1.07e+00 | 1.07e+00 | 1.07e+00 | 1.07e+00 |
| H-3 | 5.32e-07 | Inhalation | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| I-125 | 1.55e-08 | Meat Ingestion | 1.00e+00 | 1.05e+00 | 1.05e+00 | 1.05e+00 | 1.05e+00 |
| I-131 | 2.12e-08 | Meat Ingestion | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| In-111 | 4.54e-11 | Plant and Meat Ingestion | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| K-40 | 4.94e-10 | External | 1.00e+00 | 4.86e+00 | 1.48e+01 | 1.88e+01 | 1.90e+01 |
| La-138 | 2.69e-08 | Inhalation and External | 1.00e+00 | 3.95e+00 | 8.23e+00 | 9.12e+00 | 9.15e+00 |
| Np-237 | 5.00e-06 | Inhalation | 1.00e+00 | 4.36e+00 | 1.14e+01 | 1.47e+01 | 1.52e+01 |
| Pa-231 | 5.30e-05 | Inhalation | 1.00e+00 | 5.00e+00 | 2.00e+01 | 4.95e+01 | 9.60e+01 |
| Pb-210 | 4.04e-07 | Inhalation | 1.00e+00 | 4.83e+00 | 1.59e+01 | 2.75e+01 | 3.38e+01 |
| Po-210 | 9.68e-08 | Inhalation | 1.00e+00 | 1.35e+00 | 1.35e+00 | 1.35e+00 | 1.35e+00 |
| Pu-238 | 3.62e-06 | Inhalation | 1.00e+00 | 4.91e+00 | 1.84e+01 | 4.02e+01 | 6.59e+01 |
| Pu-239 | 3.95e-06 | Inhalation | 1.00e+00 | 4.99e+00 | 1.98e+01 | 4.84e+01 | 9.38e+01 |

Table 6.4 Nearby Town Scenario Total DSR Results (continued)

| | Radio-nuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factors | | | | |
|----|---------------|--------------------|-------------------------------|-----------------|----------|----------|----------|----------|
| | | | | 1 | 5 | 20 | 50 | 100 |
| 1 | Ra-226 | 1.19e-04 | Radon (outdoor) | 1.00e+00 | 4.99e+00 | 1.99e+01 | 4.91e+01 | 9.64e+01 |
| 2 | Ra-228 | 1.96e-04 | Radon (outdoor) | 1.00e+00 | 4.82e+00 | 1.25e+01 | 1.43e+01 | 1.43e+01 |
| 3 | Sm-153 | 7.39e-11 | Plant and Meat Ingestion | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| 4 | Sr-89 | 5.70e-10 | Inhalation and Meat Ingestion | 1.00e+00 | 1.03e+00 | 1.03e+00 | 1.03e+00 | 1.03e+00 |
| 5 | Sr-90 | 5.76e-08 | Meat Ingestion | 1.00e+00 | 4.98e+00 | 1.91e+01 | 3.75e+01 | 4.58e+01 |
| 6 | Th-228 | 3.41e-04 | Radon (outdoor) | 1.00e+00 | 2.76e+00 | 3.29e+00 | 3.29e+00 | 3.29e+00 |
| 7 | Th-229 | 1.92e-05 | Inhalation | 1.00e+00 | 5.00e+00 | 1.99e+01 | 4.97e+01 | 9.86e+01 |
| 8 | Th-230 | 4.30e-05 | Radon (outdoor) | 1.00e+00 | 5.00e+00 | 1.99e+01 | 4.94e+01 | 9.75e+01 |
| 9 | Th-232 | 3.51e-04 | Radon (outdoor) | 1.00e+00 | 5.00e+00 | 2.00e+01 | 4.98e+01 | 9.93e+01 |
| 10 | Tl-201 | 4.49e-11 | Meat Ingestion | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| 11 | Tl-202 | 2.19e-10 | Meat Ingestion | 1.00e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 |
| 12 | U-233 | 1.50e-06 | Inhalation | 1.00e+00 | 4.92e+00 | 1.85e+01 | 4.13e+01 | 6.97e+01 |
| 13 | U-234 | 1.15e-06 | Inhalation | 1.00e+00 | 4.90e+00 | 1.83e+01 | 3.98e+01 | 6.45e+01 |
| 14 | U-235 | 1.19e-06 | Inhalation | 1.00e+00 | 4.91e+00 | 1.84e+01 | 4.06e+01 | 6.76e+01 |
| 15 | U-238 | 1.04e-06 | Inhalation | 1.00e+00 | 4.90e+00 | 1.83e+01 | 3.98e+01 | 6.44e+01 |
| 16 | Xe-131m | 0.00e+00 | Inhalation | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| 17 | Zn-65 | 5.64e-09 | Meat Ingestion | 1.00e+00 | 2.43e+00 | 2.48e+00 | 2.48e+00 | 2.48e+00 |
| 18 | | | | | | | | |

6.3 LANDFILL NEIGHBOR SCENARIO

The following Tables give the 95% DSRs for the landfill neighbor scenarios. Several general characteristics are of note. The Surface Impoundment calculations had higher DSRs than the Municipal Solid Waste sub-scenario, as expected by the higher volume of sludge in the surface impoundment. The radionuclides with the highest calculated DSRs are Np-237 and Th-232.

For several radionuclides, indoor radon was a significant fraction of the dose, and indoor radon and non-radon components were calculated and are presented in a separate table.

Table 6.5 Landfill Neighbor Scenario (Municipal Solid Waste) Total DSR Results

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|--------------|--------------------|---------------------|
| Ac-227 | 4.77e-11 | Inhalation |
| Am-241 | 3.72e-05 | Inhalation |
| Be-7 | 0.00e+00 | N/A |
| C-14 | 4.81e-05 | Inhalation |
| Ce-141 | 0.00e+00 | N/A |
| Co-57 | 0.00e+00 | N/A |
| Co-60 | 2.95e-30 | Fish |
| Cr-51 | 0.00e+00 | N/A |
| Cs-134 | 0.00e+00 | N/A |
| Cs-137 | 2.76e-10 | Fish |
| Eu-154 | 2.70e-22 | Fish |
| Fe-59 | 0.00e+00 | N/A |
| H-3 | 3.01e-07 | Inhalation |
| I-125 | 0.00e+00 | N/A |
| I-131 | 0.00e+00 | N/A |
| In-111 | 0.00e+00 | N/A |
| K-40 | 9.19e-06 | External |
| La-138 | 7.72e-04 | Inhalation |
| Np-237 | 1.37e-01 | Fish and Inhalation |
| Pa-231 | 2.44e-04 | Inhalation |
| Pb-210 | 2.54e-10 | Fish |
| Po-210 | 0.00e+00 | N/A |
| Pu-238 | 5.10e-07 | Fish and Inhalation |
| Pu-239 | 5.58e-05 | Fish and Inhalation |

Table 6.5 Landfill Neighbor Scenario (Municipal Solid Waste) Total DSR Results (continued)

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|--------------|--------------------|------------------------|
| Ra-226 | 1.95e-03 | Radon * |
| Ra-228 | 5.93e-27 | Fish |
| Sm-153 | 0.00e+00 | N/A |
| Sr-89 | 0.00e+00 | N/A |
| Sr-90 | 3.06e-11 | Fish |
| Th-228 | 0.00e+00 | N/A |
| Th-229 | 2.25e-04 | Fish and Inhalation |
| Th-230 | 8.95e-04 | Radon * |
| Th-232 | 7.93e-03 | Radon * |
| Tl-201 | 0.00e+00 | N/A |
| Tl-202 | 0.00e+00 | N/A |
| U-233 | 2.46e-05 | Fish and Inhalation |
| U-234 | 7.32e-06 | Radon and Inhalation * |
| U-235 | 8.23e-06 | Inhalation |
| U-238 | 3.71e-06 | Inhalation |
| Xe-131m | 0.00e+00 | N/A |
| Zn-65 | 0.00e+00 | N/A |

Table 6.6 Landfill Neighbor Scenario (MSW) Indoor Radon DSR Results

| Radio-nuclide | 95% Peak Non-Rn DSR | 95% Peak Indoor Rn-only DSR | | |
|---------------|---------------------|-----------------------------|----------|----------|
| | | TEDE | WL | pCi/L |
| Ra-226 | 7.50e-04 | 3.76e-03 | 1.48e-07 | 1.93e-05 |
| Th-230 | 3.67e-04 | 1.59e-03 | 6.25e-08 | 8.14e-06 |
| Th-232 | 2.41e-04 | 3.26e-03 | 6.47e-07 | 3.64e-06 |
| U-234 | 4.61e-06 | 8.06e-06 | 3.15e-10 | 4.11e-08 |

Table 6.7 Landfill Neighbor Scenario (Surface Impoundment) Total DSR Results

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|--------------|--------------------|------------------------------|
| Ac-227 | 2.48e-09 | Inhalation |
| Am-241 | 1.90e-03 | Fish |
| Be-7 | 0.00e+00 | N/A |
| C-14 | 6.02e-03 | Inhalation |
| Ce-141 | 0.00e+00 | N/A |
| Co-57 | 0.00e+00 | N/A |
| Co-60 | 1.68e-28 | Fish |
| Cr-51 | 0.00e+00 | N/A |
| Cs-134 | 0.00e+00 | N/A |
| Cs-137 | 1.39e-08 | Fish |
| Eu-154 | 1.42e-20 | Fish |
| Fe-59 | 0.00e+00 | N/A |
| H-3 | 1.66e-05 | Inhalation |
| I-125 | 0.00e+00 | N/A |
| I-131 | 0.00e+00 | N/A |
| In-111 | 0.00e+00 | N/A |
| K-40 | 4.26e-04 | External |
| La-138 | 4.45e-02 | Inhalation |
| Np-237 | 1.18e+01 | Water and Plant (Irrigation) |
| Pa-231 | 1.04e-02 | Inhalation |
| Pb-210 | 1.52e-08 | Fish |
| Po-210 | 0.00e+00 | N/A |
| Pu-238 | 2.52e-06 | Fish and Inhalation |
| Pu-239 | 2.37e-03 | Fish and Inhalation |
| Ra-226 | 8.88e-02 | Radon * |
| Ra-228 | 3.24e-25 | Fish |
| Sm-153 | 0.00e+00 | N/A |
| Sr-89 | 0.00e+00 | N/A |
| Sr-90 | 1.58e-09 | Fish |
| Th-228 | 0.00e+00 | N/A |
| Th-229 | 9.45e-03 | Fish and Inhalation |
| Th-230 | 4.32e-02 | Radon * |

Table 6.7 Landfill Neighbor Scenario (Surface Impoundment) Total DSR Results (continued)

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|--------------|--------------------|---------------------|
| Th-232 | 4.06e-01 | Radon * |
| Tl-201 | 0.00e+00 | N/A |
| Tl-202 | 0.00e+00 | N/A |
| U-233 | 9.33e-04 | Fish and Inhalation |
| U-234 | 3.41e-04 | Radon * |
| U-235 | 3.36e-04 | Inhalation |
| U-238 | 1.38e-04 | Inhalation |
| Xe-131m | 0.00e+00 | N/A |
| Zn-65 | 0.00e+00 | N/A |

Table 6.8 Landfill Neighbor Scenario (Surface Impoundment) Indoor Radon DSR Results

| Radio-nuclide | 95% Peak Non-Rn DSR | 95% Peak Indoor Rn-only DSR | | |
|---------------|---------------------|-----------------------------|----------|----------|
| | | TEDE | WL | pCi/L |
| Ra-226 | 2.66e-02 | 1.93e-01 | 7.57e-06 | 9.85e-04 |
| Th-230 | 1.41e-02 | 8.47e-02 | 3.32e-06 | 4.32e-04 |
| Th-232 | 1.00e-02 | 1.68e-01 | 3.33e-05 | 1.87e-04 |
| U-234 | 1.99e-04 | 4.28e-04 | 1.68e-08 | 2.19e-06 |

6.4 INCINERATOR NEIGHBOR SCENARIO

The following Table gives the 95% DSRs for the incinerator neighbor scenario. These values have been "decay corrected" to translated instantaneous dose rates to annual doses. The highest DSRs for the incinerator neighbor scenario were Ac-227 and the long-lived radionuclides Pa-231, Th-229, and Th-232.

Table 6.9 Incinerator Neighbor Scenario Total DSR Results

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|---------------------|---------------------------|---------------------------------|
| Ac-227 | 1.18e+01 | Inhalation |
| Am-241 | 7.99e-01 | Inhalation |
| Be-7 | 1.09e-06 | External |
| C-14 | 3.99e-07 | Inhalation |
| Ce-141 | 3.02e-06 | Inhalation |
| Co-57 | 1.02e-04 | Meat Ingestion |
| Co-60 | 7.97e-03 | External |
| Cr-51 | 8.78e-07 | Meat Ingestion |
| Cs-134 | 6.69e-03 | Meat Ingestion |
| Cs-137 | 1.43e-02 | Meat Ingestion and External |
| Eu-154 | 4.34e-03 | External |
| Fe-59 | 3.54e-04 | Meat Ingestion |
| H-3 | 3.17e-06 | Inhalation |
| I-125 | 6.99e-02 | Meat Ingestion |
| I-131 | 1.31e-02 | Meat Ingestion |
| In-111 | 2.42e-07 | Plant and Meat Ingestion |
| K-40 | 4.81e-04 | External |
| La-138 | 1.06e-02 | Inhalation and External |
| Np-237 | 9.93e-01 | Inhalation |
| Pa-231 | 2.35e+00 | Inhalation |
| Pb-210 | 4.74e-02 | Inhalation and Plant Ingestion |
| Po-210 | 1.64e-02 | Inhalation |
| Pu-238 | 7.04e-01 | Inhalation |
| Pu-239 | 7.74e-01 | Inhalation |
| Ra-226 | 8.80e-02 | Inhalation, External, and Plant |
| Ra-228 | 2.53e-02 | Inhalation |
| Sm-153 | 2.03e-07 | Plant and Meat Ingestion |
| Sr-89 | 4.70e-05 | Inhalation and Meat Ingestion |
| Sr-90 | 3.86e-02 | Meat Ingestion |
| Th-228 | 5.23e-01 | Inhalation |
| Th-229 | 3.87e+00 | Inhalation |
| Th-230 | 5.85e-01 | Inhalation |
| Th-232 | 2.97e+00 | Inhalation |

Table 6.9 Incinerator Neighbor Scenario Total DSR Results (continued)

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|--------------|--------------------|---------------------|
| Tl-201 | 2.31e-07 | Meat Ingestion |
| Tl-202 | 4.74e-06 | Meat Ingestion |
| U-233 | 2.43e-01 | Inhalation |
| U-234 | 2.37e-01 | Inhalation |
| U-235 | 2.22e-01 | Inhalation |
| U-238 | 2.12e-01 | Inhalation |
| Xe-131m | 0.00e+00 | Inhalation |
| Zn-65 | 2.28e-03 | Meat Ingestion |

6.5 OCCUPATIONAL SCENARIOS

6.5.1 SLUDGE APPLICATION WORKER

For the Sludge Application Worker scenario, the highest DSRs were due to Ac-227, Co-60, Ra-226, and Th-232. For multiple years of application, Th-232 has the highest DSR because of the importance of daughter ingrowth.

Table 6.10 Sludge Application Worker Scenario Total DSR Results

| Radio-nuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factors | | | | |
|---------------|--------------------|---------------------|-----------------|----------|----------|----------|----------|
| | | | 1 | 5 | 20 | 50 | 100 |
| Ac-227 | 7.62e-03 | Inhalation | 1.00e+00 | 4.68e+00 | 1.48e+01 | 2.47e+01 | 2.94e+01 |
| Am-241 | 4.42e-04 | Inhalation | 1.00e+00 | 4.98e+00 | 1.95e+01 | 4.71e+01 | 8.88e+01 |
| Be-7 | 4.00e-05 | External | 1.00e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 |
| C-14 | 1.71e-07 | Inhalation | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| Ce-141 | 2.60e-05 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| Co-57 | 2.05e-04 | External | 1.00e+00 | 1.63e+00 | 1.64e+00 | 1.64e+00 | 1.64e+00 |
| Co-60 | 9.87e-03 | External | 1.00e+00 | 3.88e+00 | 7.32e+00 | 7.82e+00 | 7.82e+00 |
| Cr-51 | 1.27e-05 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| Cs-134 | 5.35e-03 | External | 1.00e+00 | 2.84e+00 | 3.47e+00 | 3.48e+00 | 3.48e+00 |
| Cs-137 | 2.25e-03 | External | 1.00e+00 | 4.75e+00 | 1.58e+01 | 2.84e+01 | 3.62e+01 |
| Eu-154 | 4.73e-03 | External | 1.00e+00 | 4.29e+00 | 1.04e+01 | 1.27e+01 | 1.30e+01 |
| Fe-59 | 8.81e-04 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| H-3 | 3.36e-07 | Inhalation | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |

Table 6.10 Sludge Application Worker Scenario Total DSR Results (continued)

| Radio-nuclide | 95% Peak Total DSR | Critical Pathway(s) | Scaling Factors | | | | |
|---------------|--------------------|---------------------|-----------------|----------|----------|----------|----------|
| | | | 1 | 5 | 20 | 50 | 100 |
| I-125 | 2.05e-07 | External | 1.00e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 |
| I-131 | 4.90e-05 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| In-111 | 2.73e-05 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| K-40 | 6.51e-04 | External | 1.00e+00 | 3.39e+00 | 5.06e+00 | 5.13e+00 | 5.13e+00 |
| La-138 | 5.08e-03 | External | 1.00e+00 | 3.28e+00 | 4.67e+00 | 4.71e+00 | 4.71e+00 |
| Np-237 | 1.17e-03 | External | 1.00e+00 | 4.35e+00 | 1.10e+01 | 1.40e+01 | 1.44e+01 |
| Pa-231 | 6.41e-03 | Inhalation | 1.00e+00 | 6.72e+00 | 4.73e+01 | 1.78e+02 | 4.30e+02 |
| Pb-210 | 2.34e-05 | Inhalation | 1.00e+00 | 5.26e+00 | 1.73e+01 | 2.94e+01 | 3.55e+01 |
| Po-210 | 4.16e-06 | Inhalation | 1.00e+00 | 1.19e+00 | 1.19e+00 | 1.19e+00 | 1.19e+00 |
| Pu-238 | 3.75e-04 | Inhalation | 1.00e+00 | 4.91e+00 | 1.84e+01 | 4.03e+01 | 6.57e+01 |
| Pu-239 | 4.16e-04 | Inhalation | 1.00e+00 | 4.99e+00 | 1.98e+01 | 4.84e+01 | 9.37e+01 |
| Ra-226 | 7.41e-03 | External | 1.00e+00 | 4.99e+00 | 1.99e+01 | 4.91e+01 | 9.63e+01 |
| Ra-228 | 6.74e-03 | External | 1.00e+00 | 6.25e+00 | 1.67e+01 | 1.88e+01 | 1.89e+01 |
| Sm-153 | 1.78e-06 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| Sr-89 | 1.15e-06 | External | 1.00e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 | 1.01e+00 |
| Sr-90 | 1.67e-05 | External | 1.00e+00 | 4.43e+00 | 1.18e+01 | 1.58e+01 | 1.65e+01 |
| Th-228 | 6.23e-03 | External | 1.00e+00 | 2.75e+00 | 3.29e+00 | 3.29e+00 | 3.29e+00 |
| Th-229 | 3.15e-03 | External | 1.00e+00 | 5.00e+00 | 1.99e+01 | 4.96e+01 | 9.85e+01 |
| Th-230 | 2.63e-03 | External | 1.00e+00 | 5.30e+00 | 2.57e+01 | 8.61e+01 | 2.43e+02 |
| Th-232 | 1.25e-02 | External | 1.00e+00 | 1.41e+01 | 1.63e+02 | 5.81e+02 | 1.29e+03 |
| Tl-201 | 3.28e-06 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| Tl-202 | 8.03e-05 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| U-233 | 1.99e-04 | Inhalation | 1.00e+00 | 4.94e+00 | 1.89e+01 | 4.37e+01 | 7.78e+01 |
| U-234 | 1.23e-04 | Inhalation | 1.00e+00 | 4.90e+00 | 1.83e+01 | 3.98e+01 | 6.43e+01 |
| U-235 | 6.08e-04 | External | 1.00e+00 | 4.90e+00 | 1.83e+01 | 3.98e+01 | 6.45e+01 |
| U-238 | 1.94e-04 | External | 1.00e+00 | 4.90e+00 | 1.82e+01 | 3.97e+01 | 6.41e+01 |
| Xe-131m | 4.35e-07 | External | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 | 1.00e+00 |
| Zn-65 | 1.52e-03 | External | 1.00e+00 | 1.54e+00 | 1.55e+00 | 1.55e+00 | 1.55e+00 |

1 **6.5.2 PUBLICLY OWNED TREATMENT WORKS WORKER**
 2 **SCENARIOS**

3 For the POTW Worker Scenarios, the Loading sub-scenario had the highest DSRs, and the
 4 radionuclides Ra-226 and Th-228 had by far the highest DSRs in that sub-scenario. In the case
 5 of the Sampling Worker, even if samples were taken every hour for 2000 hours a year, the DSRs
 6 would be significantly smaller than those for the Loading sub-scenario. Similarly, even in the
 7 case where the Transport Worker is in proximity to sewage sludge for 2000 hours a year, the
 8 Loading sub-scenario would have the highest DSRs. Indoor radon contributed a significant
 9 portion of the dose for Ra-226 and Th-228 in the Transport and Loading sub-scenarios. For these
 10 scenarios, radon doses are also presented separately.

11 **Table 6.11 POTW Sampling Worker Scenario Total DSR Results**

| Radionuclide | Peak Total DSR | Radionuclide | Peak Total DSR |
|--------------|----------------|--------------|----------------|
| Ac-227 | 3.80e-09 | Po-210 | 8.60e-14 |
| Am-241 | 4.05e-10 | Pu-238 | 2.63e-11 |
| Be-7 | 5.08e-10 | Pu-239 | 1.08e-11 |
| C-14 | 6.03e-10 | Ra-226 | 1.61e-08 |
| Ce-141 | 7.54e-10 | Ra-228 | 9.19e-09 |
| Co-57 | 1.17e-09 | Sm-153 | 6.84e-10 |
| Co-60 | 2.39e-08 | Sr-89 | 8.45e-13 |
| Cr-51 | 3.23e-10 | Sr-90 | 2.47e-14 |
| Cs-134 | 1.59e-08 | Th-228 | 1.38e-08 |
| Cs-137 | 5.79e-09 | Th-229 | 3.42e-09 |
| Eu-154 | 1.21e-08 | Th-230 | 1.88e-11 |
| Fe-59 | 1.14e-08 | Th-232 | 1.68e-11 |
| H-3 | 0.00e+00 | Tl-201 | 9.30e-10 |
| I-125 | 7.63e-10 | Tl-202 | 4.78e-09 |
| I-131 | 3.87e-09 | U-233 | 1.74e-11 |
| In-111 | 4.13e-09 | U-234 | 2.16e-11 |
| K-40 | 1.45e-09 | U-235 | 1.82e-09 |
| La-138 | 1.18e-08 | U-238 | 2.54e-10 |
| Np-237 | 2.49e-09 | Xe-131m | 2.82e-10 |
| Pa-231 | 5.61e-10 | Zn-65 | 5.68e-09 |
| Pb-210 | 5.62e-11 | | |

34 Notes:

35 Only External pathway was evaluated in this sub-scenario. In addition, only deterministic calculations were
 36 performed.

Table 6.12 POTW Intra-POTW Transport Worker Scenario Total DSR Results

| Radionuclide | Peak Total DSR | Critical Pathway(s) |
|--------------|----------------|----------------------|
| Am-241 | 3.84e-08 | External |
| Be-7 | 5.72e-08 | External |
| C-14 | 7.13e-08 | External |
| Ce-141 | 8.57e-08 | External |
| Co-57 | 1.30e-07 | External |
| Co-60 | 2.71e-06 | External |
| Cr-51 | 3.57e-08 | External |
| Cs-134 | 1.80e-06 | External |
| Cs-137 | 6.54e-07 | External |
| Eu-154 | 1.38e-06 | External |
| Fe-59 | 1.30e-06 | External |
| H-3 | 0.00e+00 | External |
| I-125 | 8.15e-08 | External |
| I-131 | 4.35e-07 | External |
| In-111 | 4.59e-07 | External |
| K-40 | 1.65e-07 | External |
| La-138 | 1.34e-06 | External |
| Np-237 | 2.67e-07 | External |
| Pa-231 | 5.34e-08 | External |
| Pb-210 | 3.78e-09 | External |
| Po-210 | 9.73e-12 | External |
| Pu-238 | 1.61e-09 | External |
| Pu-239 | 6.61e-10 | External |
| Ra-226 | 3.29e-06 | External and Radon * |
| Ra-228 | 1.04e-06 | External |
| Sm-153 | 7.92e-08 | External |
| Sr-89 | 9.57e-11 | External |
| Sr-90 | 1.50e-12 | External |
| Th-228 | 6.74e-05 | External * |
| Th-229 | 3.76e-07 | External |
| Th-230 | 1.15e-09 | External |
| Th-232 | 9.37e-10 | External |

Table 6.12 POTW Intra-POTW Transport Worker Scenario Total DSR Results (continued)

| Radionuclide | Peak Total DSR | Critical Pathway(s) |
|--|----------------|---------------------|
| Tl-201 | 1.04e-07 | External |
| Tl-202 | 5.39e-07 | External |
| U-233 | 1.17e-09 | External |
| U-234 | 1.30e-09 | External |
| U-235 | 1.91e-07 | External |
| U-238 | 2.69e-08 | External |
| Xe-131m | 3.08e-08 | External |
| Zn-65 | 6.43e-07 | External |
| Note: Only deterministic calculations were performed for this sub-scenario. | | |

Table 6.13 POTW Intra-POTW Transport Worker Scenario Indoor Radon DSR Results

| Radionuclide | Peak Non-Rn DSR | Peak Indoor Rn-only DSR | | |
|--|-----------------|-------------------------|----------|----------|
| | | TEDE | WL | pCi/L |
| Ra-226 | 1.83e-06 | 1.46e-06 | 3.30e-07 | 2.00e-04 |
| Th-228 | 1.57e-06 | 6.58e-05 | 7.63e-05 | 3.87e-02 |
| Note: Only deterministic calculations were performed for this sub-scenario. | | | | |

Table 6.14 POTW Biosolids Loading Worker Scenario Total DSR Results

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|--------------|--------------------|-------------------------|
| Am-241 | 4.69e-02 | Inhalation |
| Be-7 | 2.45e-02 | External |
| C-14 | 1.12e-06 | External |
| Ce-141 | 2.50e-02 | External |
| Co-57 | 3.84e-02 | External |
| Co-60 | 1.40e+00 | External |
| Cr-51 | 1.48e-02 | External |
| Cs-134 | 8.13e-01 | External |
| Cs-137 | 2.92e-01 | External |
| Eu-154 | 6.63e-01 | External |
| Fe-59 | 6.62e-01 | External |
| H-3 | 2.65e-03 | Inhalation |
| I-125 | 1.20e-03 | External |
| I-131 | 1.84e-01 | External |
| In-111 | 1.61e-01 | External |
| K-40 | 9.05e-02 | External |
| La-138 | 6.91e-01 | External |
| Np-237 | 5.78e-02 | Inhalation |
| Pa-231 | 1.61e-01 | Inhalation and External |
| Pb-210 | 2.66e-03 | Inhalation and External |
| Po-210 | 8.69e-04 | Inhalation |
| Pu-238 | 3.60e-02 | Inhalation |
| Pu-239 | 4.76e-02 | Inhalation |
| Ra-226 | 2.28e+01 | Radon * |
| Ra-228 | 5.18e-01 | External |
| Sm-153 | 1.16e-02 | External |
| Sr-89 | 7.90e-04 | External |
| Sr-90 | 2.09e-03 | External |
| Th-228 | 8.30e+01 | Radon * |
| Th-229 | 3.48e-01 | External |
| Th-230 | 3.35e-02 | Inhalation |
| Th-232 | 1.67e-01 | Inhalation |

**Table 6.14 POTW Biosolids Loading Worker Scenario Total DSR
Results (continued)**

| Radionuclide | 95% Peak Total DSR | Critical Pathway(s) |
|--------------|--------------------|---------------------|
| Tl-201 | 2.02e-02 | External |
| Tl-202 | 2.10e-01 | External |
| U-233 | 1.51e-02 | Inhalation |
| U-234 | 1.23e-02 | Inhalation |
| U-235 | 7.35e-02 | External |
| U-238 | 2.26e-02 | External |
| Xe-131m | 1.75e-03 | External |
| Zn-65 | 3.20e-01 | External |

**Table 6.15 POTW Biosolids Loading Worker Scenario Indoor Radon DSR
Results**

| Radio-nuclide | 95% Peak Non-Rn DSR | 95% Peak Indoor Rn-only DSR | | |
|---------------|---------------------|-----------------------------|----------|----------|
| | | TEDE | WL | pCi/L |
| Ra-226 | 9.67e-01 | 2.18e+01 | 2.44e-03 | 1.48e+00 |
| Th-228 | 9.09e-01 | 8.21e+01 | 4.74e-02 | 2.42e+01 |

7 RADIATION DOSES CORRESPONDING TO THE RESULTS OF THE ISCORS PUBLICLY OWNED TREATMENT WORKS SURVEY

7.1 RADIATION DOSES CORRESPONDING TO SURVEY SAMPLE ACTIVITIES

Given a measured activity in a sludge or ash sample taken from a real POTW, the Dose-to-Source Ratios (DSRs) calculated in Chapter 6 can be used to estimate the corresponding dose that potentially would be imparted to members of the critical population group for any of the seven hypothetical scenarios that have been constructed.

For a given sample that yields the set of measured activities, $\{A_r\}$, with the radionuclides parameterized by r , and in considering scenario s , one can approximate the *total peak dose* as

$$D_s = \sum_r A_r \times \text{DSR}_{rs}, \quad (7.1)$$

where $\{\text{DSR}_{rs}\}$ are the 95-th percentile Dose-to-Source Ratios for these radionuclides and for scenario s . Equation (7.1) would be strictly valid only if the dose peaks for all the radionuclides occurred at the same time, which they do not – so it may somewhat slightly overestimate the total dose; but it is commonly the case that one or a few radionuclides dominate the estimated total dose, so deviations from the equation are likely not to be significant.

With the procedure of Equation (7.1) and the selection of the 95% DSRs, and for each scenario, a total (all radionuclides) dose was calculated for every sludge and ash sample¹¹ from the ISCORS national survey (REF). With N survey samples, the N values of dose found for each scenario defines a distribution, and it is the median (50%) and 95% values of these distributions of calculated doses that are presented in Table 7.1, and are presented with and without any significant indoor Radon component. The separate calculations of doses and concentrations with indoor Radon only are presented in Table 7.2.

The estimated doses included in this Report apply only to the critical population group related to each scenario. While coarse upper-bound calculations for general populations may be feasible, more realistic estimates would require careful assessments of demographic and other issues, such as the rates at which farmlands are being developed and town borders are expanding. There has been no attempt here to undertake such a study, however, nor to compute any population doses.

¹¹ For all the scenarios but the landfill neighbor, the sewage sludge samples from the survey are used for the source term. For the landfill neighbor scenario, two different source terms are used: The municipal solid waste (MSW) sub-scenario uses both sewage sludge and ash samples, since municipal solid waste landfills tend to contain both materials; the source term for the surface impoundment sub-scenario, by contrast, considers only sludge samples.

Table 7.1 Calculated Total Peak Dose from Survey Samples: Summary Results With and Without Indoor Radon Contribution

| Scenario | Sub-Scenario | Median sample | | 95% sample | | Dominant Radionuclide(s) [pathways] |
|---|------------------------|---------------|-------------|------------|-------------|-------------------------------------|
| | | TEDE | TEDE w/o Rn | TEDE | TEDE w/o Rn | |
| S1 - Onsite Resident | 1 yr of appl. | 0.5 | 0.2 | 3 | 1 | Ra-226 [indoor radon] |
| | 5 | 2.5 | 1 | 14 | 4.9 | Ra-226 [indoor radon] |
| | 20 | 9.2 | 3.4 | 55 | 16 | Ra-226 [indoor radon] |
| | 50 | 22 | 7.2 | 130 | 37 | Ra-226 [indoor radon] |
| | 100 | 42 | 13 | 260 | 69 | Ra-226 [indoor radon] |
| S2 - Recreational | N/A | 0.04 | -- | 0.22 | -- | Ra-226 [external] |
| S3 - Nearby Town | 1 yr of appl. | 6.4e-04 | -- | 3.2e-03 | -- | Ra-226 [outdoor radon] |
| | 5 | 2.8e-03 | -- | 0.014 | -- | Ra-226 [outdoor radon] |
| | 20 | 8.5e-03 | -- | 0.045 | -- | Ra-226 [outdoor radon] |
| | 50 | 0.017 | -- | 0.094 | -- | Ra-226 [outdoor radon] |
| | 100 | 0.029 | -- | 0.17 | -- | Ra-226 [outdoor radon] |
| S4 - Landfill | MSW - Sludge | 4.6e-03 | 1.6e-03 | 0.027 | 0.01 | Ra-226 [indoor radon] |
| | MSW - Ash | 0.014 | 3.1e-03 | 0.041 | 0.014 | Ra-226 [indoor radon] |
| | Impoundment | 0.21 | 0.062 | 1.2 | 0.36 | Ra-226 [indoor radon] |
| S5 - Incinerator | N/A | 1.2 | -- | 7.7 | -- | multiple [multiple] |
| S6 - Sludge Application Worker | 1 yr of appl. | 0.032 | -- | 0.15 | -- | Ra-226 [external] |
| | 5 | 0.16 | -- | 0.77 | -- | Ra-226 [external] |
| | 20 | 0.57 | -- | 3 | -- | Ra-226 [external] |
| | 50 | 1.3 | -- | 7.4 | -- | Ra-226 [external] |
| | 100 | 2.3 | -- | 15 | -- | Ra-226 [external] |
| S7 - POTW Workers | Sampling (mrem/sample) | 9.6e-08 | -- | 4.9e-07 | -- | Ra-226 [external] |
| | Transport (mrem/hr) | 4.6e-05 | 1.1e-05 | 1.9e-04 | 5.6e-05 | Th-228 [indoor radon, external] |
| | Loading | 98 | 5.3 | 420 | 26 | Ra-226, Th-228 |
| Notes: | | | | | | |
| All values rounded to two significant figures. 95% DSRs are used in all total peak dose calculations. A "--" denotes that indoor radon was not separately calculated. | | | | | | |

Table 7.2 Calculated Total Peak Radon Doses and Concentrations from Survey Samples

| Scenario | Sub-Scenario | Median sample | | | | 95% sample | | | |
|----------------------|---------------|---------------|------------|--------------|--------------|--------------|------------|--------------|--------------|
| | | TEDE Rn only | WL Rn only | pCi/L Rn-222 | pCi/L Rn-220 | TEDE Rn only | WL Rn only | pCi/L Rn-222 | pCi/L Rn-220 |
| S1 - Onsite Resident | 1 yr of appl. | 0.3 | 1.3e-05 | 1.7e-03 | 8.3e-08 | 2 | 7.9e-05 | 0.011 | 4.0e-07 |
| | 5 | 1.5 | 6.2e-05 | 8.7e-03 | 2.3e-07 | 9.8 | 3.9e-04 | 0.057 | 1.1e-06 |
| | 20 | 6 | 2.4e-04 | 0.035 | 2.7e-07 | 39 | 1.6e-03 | 0.23 | 1.3e-06 |
| | 50 | 15 | 6.0e-04 | 0.087 | 2.7e-07 | 98 | 3.9e-03 | 0.56 | 1.3e-06 |
| | 100 | 30 | 1.2e-03 | 0.17 | 2.7e-07 | 193 | 7.7e-03 | 1.1 | 1.3e-06 |
| S4 - Landfill | MSW - Sludge | 9.1e-03 | 3.4e-07 | 3.9e-05 | 0 | 0.057 | 2.1e-06 | 2.6e-04 | 1.5e-06 |
| | MSW - Ash | 0.018 | 1.0e-06 | 7.2e-05 | 1.8e-06 | 0.078 | 3.1e-06 | 3.5e-04 | 3.4e-06 |
| | Impoundment | 0.47 | 2.5e-05 | 2.0e-03 | 0 | 2.9 | 1.5e-04 | 0.013 | 7.5e-05 |
| S7 - POTW Workers | Transport | 3.4e-05 | 3.4e-05 | 4.0e-04 | 0.017 | 1.5e-04 | 1.6e-04 | 2.6e-03 | 0.081 |
| | Loading | 92 | 0.028 | 3 | 10 | 390 | 0.12 | 19 | 51 |

7.2 CALCULATED DOSES FOR LAND APPLICATION SCENARIOS

As is evident from Table 7.1, the only non-worker scenario of any potential concern is the onsite resident. The primary contributing radionuclides here are from NORM sources, and the critical pathway is indoor radon from Ra-226. Radon and its daughters are responsible for 65% – 75% of the calculated doses, and gamma ray exposure from radium for another 20%. The Radon-specific calculations are in Table 7.2.

The parameter values selected for the calculation tend in general to be somewhat conservative. The air exchange rate is taken to be relatively low, for example, especially in view of the fact that many houses in high-radon areas have radon mitigation systems in place. The foundation slab for the onsite resident's house was laid down directly on the soil surface with no excavation; in practice, soils are usually removed down to the natural and undisturbed level, and any significant excavation of the ground surface prior to building the house foundation (whether a slab or a basement) will largely eliminate the radon dose. On the other hand, construction of an unventilated crawl space foundation could lead to an *increased* radon dose. In general, however, the calculated doses probably overestimate the actual radon doses in most residences.

For some long-lived radionuclides (in particular, radium-226), doses scale more or less linearly with number of applications. This should be borne in mind especially when interpreting the doses to the on-site resident for 100, or even 50, applications; these two sub-scenarios were included in the modeling for consistency with the technical support for the 40 CFR 503 rule, and to examine trends in the calculations. No data has been found to support the proposition that sludge might, or might not, be applied over such long periods at a significant number of farms.

Short lived radioisotopes such as iodine-131 are generally not of concern, by contrast, even when animals graze and people consume the resulting milk. Most sludge is classified as Class B, in

1 accord with 40 CFR 503, and therefore required to have 30 day waiting period prior to sale and
2 application; only rarely is sludge treated to destroy pathogens and released as Class A sludge
3 without a waiting period.

4 **7.3 CALCULATED DOSES FOR LANDFILL/IMPOUNDMENT** 5 **NEIGHBOR SCENARIO**

6 As expected, the calculated doses from the Surface Impoundment subscenario was greater than
7 those from the Municipal Solid Waste landfill. The dominant radionuclide was Ra-226, and the
8 dominant pathway the radon pathway in all cases. However, the doses even at the 95th percentile
9 sample level were small, with the largest being about 1.5 mrem/year.

10 **7.4 CALCULATED DOSES FOR PUBLICLY OWNED TREATMENT** 11 **WORKS INCINERATOR NEIGHBOR SCENARIO**

12 The doses from the incinerator neighbor were not dominated by any one radionuclide. The
13 radionuclides Ac-227, I-125, I-131, Pb-210, Ra-226, Th-228, Th-232, U-234, and U-238
14 commonly contributed to the total doses. The dominant pathways tended to be inhalation and
15 meat consumption. At the 95th percentile sample level, the doses were less than 10 mrem/yr.

16 **7.5 CALCULATED DOSES FOR PUBLICLY OWNED TREATMENT** 17 **WORKS SLUDGE/ASH MANAGEMENT SCENARIOS**

18 There is considerable variability in POTW facility design, operation and sludge management, as
19 discussed in Chapter 4, and this is reflected in the selection of parameter distributions.

20 The critical worker scenario is that of the POTW Loading Worker. NORM is again the primary
21 source, and indoor radon is dominant, with Rn-220 and Rn-222 and their daughters responsible
22 for 94% of the total calculated dose. Table 7.1 includes the total dose with and without the
23 indoor Radon pathway. Table 7.2 presents the results with only radon pathway.

24 As with the Onsite Resident, however, the radon dose for this sub-scenario is highly dependent
25 on the particular characteristics of the POTW site, in this case the room where sludge is being
26 managed (*e.g.*, dried, packaged, and loaded). A sensitivity analysis with building parameter
27 values determined for two real POTWs yielded doses from the radon pathway that were generally
28 lower than those calculated from the default probability distributions. Parameters that were
29 particularly sensitive included the bulk density and volume of the sludge, and the volume and air
30 exchange rate of the room.

31 Because of the site-specific nature of POTW operations, below are provided fitting functions for
32 calculating DSRs based on the above four site-specific parameters. These may be helpful for
33 *rough* estimates potential doses at particular POTWs. However, it should be emphasized that
34 more detailed site-specific assessments may be necessary for additional accuracy.

1 The following two expressions are for the DSRs for Ra-226 and Th-228 (in mrem/yr per pCi/g)
2 in terms of these four parameters alone and with all others held constant.¹²

3
$$DSR_{Ra-226} \gg 1 + 83.1 r_{sludge} V_{sludge} / [(0.008 + \lambda_x)(2.69 h_{room}^{-0.13} + \lambda_x) V_{room}] , \quad (7.2)$$

4
5
$$DSR_{Th-228} \gg 0.9 + 5290 r_{sludge} A_{sludge} / [(45 + \lambda_x)(1.25 h_{room}^{-0.77} + \lambda_x) V_{room}] . \quad (7.3)$$

6
7 These expressions reproduce RESRAD-BUILD runs to within about 10%.¹³ The first term in
8 each equation represents external exposure, and the second is for indoor radon exposure. λ_x is the
9 room air exchange rate in exchanges per hour; r_{sludge} the bulk density of the sludge in grams per
10 cubic cm; V_{sludge} the total volume of sludge in the room in cubic meters; V_{room} the total volume of
11 the room in cubic meters; h_{room} the height of the room in meters; and A_{sludge} the surface area of the
12 pile of sludge in the room in square meters. The derivation of these fitting formulae, and
13 additional discussion and motivation for their functional form, are contained in Appendix D.

14 7.6 UNCERTAINTY AND VARIABILITY IN CALCULATED DOSES

15 It should be borne in mind that there are uncertainties and variabilities in the DSRs, arising in the
16 construction of the hypothetical scenarios, in the selection of the modeling parameter values and
17 distribution, and in the model itself. There are also, of course, errors in the measured survey
18 activities used in the source terms. Of these, only the parameter uncertainty and variability and
19 the source variability are well quantified.

20 Table 7.3 summarizes the relative importance of parameter uncertainty/variability and source
21 variability (which greatly exceeds source uncertainty) with respect to the calculated doses. As
22 with Table 5-2, it presents the ratio of the 95-th percentile DSR to the 5% DSR. In the case of
23 parameter uncertainty/variability, the 95% sample dose was calculated using both 95% and 5%
24 DSRs, and this ratio captures the dose range due to changes in model parameters. In the case of
25 source uncertainty, the ratio was taken between the 95% sample dose and 5% sample dose, for a
26 fixed 95% DSR, thereby measuring the dose range due to different sludge and ash sample
27 sources. Clearly, the source variability is a significantly greater cause of variance than the
28 parameter uncertainty. Only in the cases of the POTW loading scenario are the magnitudes of
29 parameter uncertainty and variability (for Ra-226 and Th-228) and the source variability
30 comparable. In all other cases, the source variability is greater by a factor of at least 10.

12 It is assumed that even as the area of the sludge pile increases, the worker stands at its edge. The radon contribution to the Th-228 dose depends only on the area of the pile and not the volume because the Rn-220 half-life is so short (< 1 minute) that it can escape into the air via diffusion only when produced from Th-228 parents near the surface of the pile. Rn-222 from Ra-226 has a much longer half-life (almost 4 days), and can escape from any point inside a reasonably sized pile.

13 For instance, for $\lambda_x = 4$ per hour, $r_{sludge} = 1$ g/cm³, $A_{sludge} = 6900$ m², $V_{sludge} = 13,800$ m³, $V_{room} = 72,000$ m³, the worker standing at the edge of a circular pile, and 1 pCi/g each of Ra-226 and Th-228 in the sludge, RESRAD-BUILD gives a total dose of 5.1 mrem/yr, whereas the approximate expression above gives 4.5 mrem/yr, a difference of only 12%.

Table 7.3 Source Variability and Parameter Variability and Uncertainty in Calculated Survey Sample Doses

| Scenario | Subscenario | Source Variability: Ratio of 95% survey dose to 5% survey dose, both using 95% DSRs | Parameter Uncertainty & Variability: Ratio of 95% survey dose using 95% DSRs to 95% survey dose using 5% DSRs |
|---------------------------|------------------------|--|--|
| Onsite Resident | 1 yr of appl. | 43 | 1.3 |
| | 5 | 46 | 1.3 |
| | 20 | 58 | 1.2 |
| | 50 | 87 | 1.2 |
| | 100 | 100 | 1.2 |
| Recreational User | N/A | 31 | 1.5 |
| Residents of Nearby Town | 1 yr of appl. | 21 | 1.08 |
| | 5 | 25 | 1.09 |
| | 20 | 32 | 1.08 |
| | 50 | 40 | 1.03 |
| | 100 | 59 | 1.04 |
| Landfill Neighbor | MSW (Sludge) | 130 | 1.6 |
| | MSW (Ash) | 10 | 1.7 |
| | Impoundment | 130 | 1.4 |
| POTW Incinerator Neighbor | 50 Year Operation Life | 36 | 2.3 |

Table 7.3 Source Variability and Parameter Variability and Uncertainty in Calculated Survey Sample Doses (continued)

| Scenario | Subscenario | Source Variability: Ratio of 95% survey dose to 5% survey dose, both using 95% DSRs | Parameter Uncertainty & Variability: Ratio of 95% survey dose using 95% DSRs to 95% survey dose using 5% DSRs |
|---------------------------|---------------|--|--|
| Sludge Application Worker | 1 yr of appl. | 22 | 1.09 |
| | 5 | 24 | 1.07 |
| | 20 | 36 | 1.2 |
| | 50 | 60 | 1.3 |
| | 100 | 94 | 1.3 |
| POTW Workers | Sampling | 22 | - |
| | Transport | 14 | - |
| | Loading | 21 | 12 |

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8 CONCLUSION

1 This Report describes computations undertaken to assess the potential radiation exposures
2 associated with the handling, beneficial use, and disposal of sewage sludge that contains certain
3 naturally-occurring and/or man-made radioactive materials. The primary objective of this Dose
4 Modeling exercise is to provide perspective on the levels of radionuclides detected in the
5 ISCORS POTW Survey, taking into account typical sludge management practices.

6 The computations have been undertaken using probabilistic versions of three members of a
7 widely employed family of environmental transport codes: RESRAD, RESRAD-OFFSITE, and
8 RESRAD BUILD. The principal outputs are the tables of Dose-to-Source Ratios (DSR) for the
9 relevant radionuclides, under seven hypothetical sludge management scenarios, and the
10 associated tables of multiplicative factors that correct for multiple years of sludge application.
11 The ninety-fifth-percentile DSR value, for a particular radionuclide and scenario, relates the
12 ninety-fifth-percentile level of dose, as determined in a Monte Carlo computation, to an average
13 member of the critical population group that would result from the presence of unit activity
14 concentration in sludge – that is, for 37 Bq per kilogram (1 pCi per gram) of dry sludge.

15 As expected, the DSR values range widely within each scenario, for the various radionuclides,
16 and there is significant variance among the scenarios. These differences, however, are
17 meaningful only when considered in the context of the concentrations in sludge actually found in
18 the POTW Survey. Chapter 7 of this Dose Report combines the DSRs computed here with the
19 Survey measurements, and makes it clear that while some scenarios and radionuclides give rise
20 to very low doses, there are other radionuclide-scenario combinations that may be of concern. In
21 particular, the calculated ninety-fifth-percentile sample dose for the Onsite Resident (with 50 or
22 100 years of prior sludge application), and that for POTW Workers involved in sludge loading,
23 exceed 1 mSv/yr (100 mrem/yr)¹⁴. Doses to the POTW incinerator neighbor (after 50 years of
24 incineration) and the sludge application worker (after 50 years of field application), on the other
25 hand, were below 0.1 mSv/yr (10 mrem/year), and those to the recreational user, residents of a
26 nearby town, and neighbors of a landfill were all of little consequence.

27 The basic conclusions of this report are as follows:

- 28 • None of the non-POTW scenarios show a significant current widespread threat to public
29 health. For instance, the scenarios with the largest potential critical groups — the Nearby
30 Town and the Incinerator — show relatively small estimated doses.
- 31 • If agricultural land application is carried out for a long time into the future, then the potential
32 exists for future radiation exposure primarily due to Radon. This is illustrated in the 50 and
33 100 year application sub-scenarios of the Onsite Resident.

14 The current limit of total radiation exposure to the individual members of the general public from all controllable sources, as recommended by the International Commission on Radiological Protection as well as the National Council on Radiation Protection and Measurements, is 1 mSv/year (100 mrem/year).

- 1 • In specific cases of very high levels of radioactive materials (e.g., levels above the 95%), there
2 is the potential for localized radiation exposure.
- 3 • Within the POTW, little exposure is expected for sampling and transport. Only when workers
4 are in the same room with large quantities of sludge (e.g., for storage or loading) is there the
5 potential for significant exposure, predominantly due to Radon. In this case, the degree of
6 exposure is likely to depend highly on the configuration of the POTW in terms of room sizes,
7 ventilation, etc.

8 The doses computed for the On-Site Resident and the POTW Worker are notable; but several
9 important factors account for these elevated values, suggesting that typical exposures would not
10 necessarily approach such levels:

- 11 • The exposure scenarios are somewhat conservative; in addition, the doses mentioned above
12 are upper-end percentile values.
- 13 • The doses for the Onsite Resident for 50 or 100 years of annual application would be
14 significant – but very few farms in the country, so far, have used sewage sludge for even
15 20 years.
- 16 • High doses are generally attributable to the indoor radon pathway. For the Onsite Resident,
17 the 95-percentile sample doses tend to be a factor of 6.5 higher than the corresponding median
18 (50-percentile) sample doses, regardless of the number of years of application, simply because
19 of the difference in the concentration of radium in the sludge (13 pCi/gm vs. 2 pCi/gm). Both
20 for the Onsite Resident and the POTW Worker, exposures can be decreased radically through
21 the use of readily available radon testing and mitigation technologies.

22 The ISCORS Sewage Sludge Subcommittee has determined that the results of this analysis,
23 based on actual sludge and ash samples and the RESRAD model, are of acceptable quality for the
24 stated purposes of this project. While it would always be advantageous to look at other
25 scenarios, if resources allowed, the seven that have been developed for this analysis represent the
26 range of current practices for managing sewage sludge and ash, and the major possible routes of
27 exposure to them.

28 The RESRAD family of codes has been employed in a variety of regulatory analyses of
29 environmental radiation exposures, and is continually being developed and improved to enhance
30 its applicability to a broader range of situations. Although it is widely accepted, and has been
31 field tested and validated for many applications, validation of the results of this analysis would
32 enhance their value to a decision-maker. If the approach described in this Report is employed in
33 the analysis of a specific site, one or more of the scenarios developed herein may provide useful
34 guides. However, some site-specific conditions are likely to differ substantially from those
35 assumed for these scenarios, and may require using different parameter values and distributions.

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Appendix A
Baseline Parameter Values and
Distributions

1 **A.1 Introduction**

2 This appendix contains the "baseline" parameter values and distributions used in the RESRAD
3 calculations. The tables are divided into two sections. The first section is baseline values and
4 distributions that are used by multiple RESRAD codes, such as partition coefficients (K_d). The
5 second section contains the values and distributions for the RESRAD codes RESRAD 6.0,
6 RESRAD OFFSITE, and RESRAD-BUILD 3.0.

7 In performing the deterministic computations, it is necessary to replace distributions with a single
8 value. This assessment chose to use a central tendency of the distribution. In particular the
9 geometric mean is employed for parameters with a lognormal or log-uniform distribution, and the
10 arithmetic mean for all others.¹ Mean values were determined with the Mathematica software,
11 and are listed in the tables along with the distributions themselves. While it is recognized that no
12 measure of central tendency is ideal, there are several reasons for adopting the distribution mean.
13 Our stated objective is to model the "average member" of the critical group; using the median
14 would imply a 50 percentile member of the group, not the average member. Also, it was found
15 that the mean led to doses that were near to the mean of the probabilistic doses, where the two
16 could be compared. It should be borne in mind, in any case, that deterministic calculations are
17 used only for sensitivity analyses and for scaling the effects of multiple years of application, and
18 not in the computation of absolute values of the sludge dose-to-source ratios.

19 **A.2 Parameters Used in Multiple Codes**

20 Note: The parameters m and s for the log-normal distribution are defined as follows. If x is
21 log-normally distributed, then this means that the natural logarithm of x , $\ln(x)$, has a normal
22 distribution with mean of $\ln(x) = m$, and the standard deviation of $\ln(x) = s$.

1 In most cases, the scaling factors for multi-year applications were virtually the same whether parameter
distributions were replaced with their means or their medians. In the few cases where there was a significant
difference, the use of mean parameters gave a larger scaling factor, which would lead to more conservative
results.

1 **Table A.1 Baseline Values and Distributions for the K_d Parameter**

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| Element of Interest | RESRAD 6.0 Default Value | Baseline Value as Geometric Mean of the Distribution | Distribution from INUREG/CR-6697 | | |
|---------------------|--------------------------|--|---|----------|-------------|
| | | | Truncated Lognormal-n Distribution Parameters | | |
| | | | μ | σ | $\exp(\mu)$ |
| Ac | 20 | 825 | 6.72 | 3.22 | 825 |
| Am | 20 | 1445 | 7.28 | 3.15 | 1445 |
| Ba | 50 | 560 | 6.33 | 3.22 | 560 |
| Be | 929 | 929 | 6.84 | 3.22 | 929 |
| Bi | 0 | 105 | 4.65 | 3.22 | 105 |
| C | 0 | 11 | 2.40 | 3.22 | 11 |
| Ce | 1000 | 1998 | 7.6 | 2.08 | 1998 |
| Co | 1000 | 235 | 5.46 | 2.53 | 235 |
| Cr | 103 | 103 | 4.63 | 2.76 | 103 |
| Cs | 1000 | 446 | 6.10 | 2.33 | 446 |
| Eu | 825* | 825 | 6.72 | 3.22 | 825 |
| Fe | 1000 | 209 | 5.34 | 2.67 | 209 |
| H | 0 | 0.06 | -2.81 | .5 | .06 |
| I | 0.1 | 4.6 | 1.52 | 2.19 | 4.6 |
| In | 158 | 158 | 5.07 | 3.22 | 158 |
| K | 5.5 | 5.5 | 1.7 | 0.49 | 5.5 |
| La | 4.98 | 4.98 | 1.61 | 3.22 | 4.98 |
| Np | 257* | 17 | 2.84 | 2.25 | 17 |
| Pa | 50 | 380 | 5.94 | 3.22 | 380 |
| Pb | 100 | 2392 | 7.78 | 2.76 | 2392 |
| Po | 10 | 181 | 5.20 | 1.68 | 181 |
| Pu | 2000 | 953 | 6.86 | 1.89 | 953 |
| Ra | 70 | 3533 | 8.17 | 1.70 | 3533 |
| Sm | 825* | 825 | 6.72 | 3.22 | 825 |
| Sr | 30 | 32 | 3.45 | 2.12 | 32 |
| Th | 60,000 | 5884 | 8.68 | 3.62 | 5884 |
| Tl | 0 | 71 | 4.26 | 3.22 | 71 |
| U | 50 | 126 | 4.84 | 3.13 | 126 |
| Zn | 0 | 1075 | 6.98 | 4.44 | 1075 |

33 * Value calculated by RESRAD using a correlation with the plant transfer factor.

34 ** Distribution is truncated at a lower quantile of 0.001 and an upper quantile of 0.999.

1 **Table A.2 Baseline Values and Distributions for the Plant Transfer Factor**

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| Element of Interest | RESRAD 6.0 Default Value | Baseline Value as Geometric Mean of the Distribution | Distribution from NUREG/CR-6697 | | |
|---------------------|--------------------------|--|--|----------|----------------------|
| | | | Truncated Lognormal-n Distribution Parameters: | | |
| | | | μ | σ | $\exp(\mu)$ |
| Ac | 2.5×10^{-3} | 1.0×10^{-3} | -6.91 | 1.1 | 1.0×10^{-3} |
| Am | 1.0×10^{-3} | 1.0×10^{-3} | -6.91 | 0.9 | 1.0×10^{-3} |
| Ba | 5.0×10^{-3} | 1.0×10^{-2} | -4.61 | 1.1 | 1.0×10^{-2} |
| Be | 4.0×10^{-3} | 4.0×10^{-3} | -5.52 | 1.1 | 4.0×10^{-3} |
| Bi | 1.0×10^{-1} | 1.0×10^{-1} | -2.30 | 1.1 | 1.0×10^{-1} |
| C | 5.5 | 7.0×10^{-1} | -0.36 | 0.9 | 7.0×10^{-1} |
| Ce | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 1.0 | 2.0×10^{-3} |
| Co | 8.0×10^{-2} | 8.0×10^{-2} | -2.53 | 0.9 | 8.0×10^{-2} |
| Cr | 2.5×10^{-4} | 1.0×10^{-2} | -4.61 | 1.0 | 1.0×10^{-2} |
| Cs | 4.0×10^{-2} | 4.0×10^{-2} | -3.22 | 1.0 | 4.0×10^{-2} |
| Eu | 2.5×10^{-3} | 2.0×10^{-3} | -6.21 | 1.1 | 2.0×10^{-3} |
| Fe | 1.0×10^{-3} | 1.0×10^{-3} | -6.91 | 0.9 | 1.0×10^{-3} |
| H | 4.8 | 4.8 | 1.57 | 1.1 | 4.8 |
| I | 2.0×10^{-2} | 2.0×10^{-2} | -3.91 | 0.9 | 2.0×10^{-2} |
| In | 3.0×10^{-3} | 3.0×10^{-3} | -5.81 | 1.1 | 3.0×10^{-3} |
| K | 3.0×10^{-1} | 3.0×10^{-1} | -1.20 | 1.1 | 3.0×10^{-1} |
| La | 2.5×10^{-3} | 2.0×10^{-3} | -6.21 | 0.9 | 2.0×10^{-3} |
| Np | 2.0×10^{-2} | 2.0×10^{-2} | -3.91 | 0.9 | 2.0×10^{-2} |
| Pa | 1.0×10^{-2} | 1.0×10^{-2} | -4.61 | 1.1 | 1.0×10^{-2} |
| Pb | 1.0×10^{-2} | 4.0×10^{-3} | -5.52 | 0.9 | 4.0×10^{-3} |
| Po | 1.0×10^{-3} | 1.0×10^{-3} | -6.9 | 0.9 | 1.0×10^{-3} |
| Pu | 1.0×10^{-3} | 1.0×10^{-3} | -6.91 | 0.9 | 1.0×10^{-3} |
| Ra | 4.0×10^{-2} | 4.0×10^{-2} | -3.22 | 0.9 | 4.0×10^{-2} |
| Sm | 2.5×10^{-3} | 2.0×10^{-3} | -6.21 | 1.1 | 2.0×10^{-3} |
| Sr | 3.0×10^{-1} | 3.0×10^{-1} | -1.20 | 1.0 | 3.0×10^{-1} |
| Th | 1.0×10^{-3} | 1.0×10^{-3} | -6.91 | 0.9 | 1.0×10^{-3} |
| Tl | 2.0×10^{-1} | 2.0×10^{-1} | -1.61 | 1.1 | 2.0×10^{-1} |
| U | 2.5×10^{-3} | 2.0×10^{-3} | -6.21 | 0.9 | 2.0×10^{-3} |
| Zn | 4.0×10^{-1} | 4.0×10^{-1} | -0.92 | 0.9 | 4.0×10^{-1} |

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* Distribution is truncated at a lower quantile of 0.001 and an upper quantile of 0.999.

1 **Table A.3 Baseline Values and Distribution for the Meat Transfer Factor**

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| Element of Interest | RESRAD 6.0 Default Value | Baseline Value as Geometric Mean of the Distribution | Distribution from NUREG/CR-6697 | | |
|---------------------|--------------------------|--|---|----------|----------------------|
| | | | Truncated Lognormal Distribution Parameters | | |
| | | | μ | σ | $\exp(\mu)$ |
| Ac | 2.0×10^{-5} | 2.0×10^{-5} | -10.82 | 1.0 | 2.0×10^{-5} |
| Am | 5.0×10^{-5} | 5.0×10^{-5} | -9.90 | 0.2 | 5.0×10^{-5} |
| Ba | 2.0×10^{-4} | 2.0×10^{-4} | -8.52 | 0.9 | 2.0×10^{-4} |
| Be | 1.0×10^{-3} | 5.0×10^{-3} | -5.30 | 1.0 | 5.0×10^{-3} |
| Bi | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 1.0 | 2.0×10^{-3} |
| C | 3.1×10^{-2} | 3.0×10^{-2} | -3.47 | 1.0 | 3.0×10^{-2} |
| Ce | 2.0×10^{-5} | 2.0×10^{-5} | -10.82 | 0.9 | 2.0×10^{-5} |
| Co | 2.0×10^{-2} | 3.0×10^{-2} | -3.51 | 1.0 | 3.0×10^{-2} |
| Cr | 9.0×10^{-3} | 3.0×10^{-2} | -3.51 | 0.4 | 3.0×10^{-2} |
| Cs | 3.0×10^{-2} | 5.0×10^{-2} | -3.00 | 0.4 | 5.0×10^{-2} |
| Eu | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 1.0 | 2.0×10^{-3} |
| Fe | 2.0×10^{-2} | 3.0×10^{-2} | -3.51 | 0.4 | 3.0×10^{-2} |
| H | 1.2×10^{-2} | 1.2×10^{-2} | -4.42 | 1.0 | 1.2×10^{-2} |
| I | 7.0×10^{-3} | 4.0×10^{-2} | -3.22 | 0.4 | 4.0×10^{-2} |
| In | 4.0×10^{-3} | 4.0×10^{-3} | -5.52 | 1.0 | 4.0×10^{-3} |
| K | 2.0×10^{-2} | 2.0×10^{-2} | -3.91 | 0.2 | 2.0×10^{-2} |
| La | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 1.0 | 2.0×10^{-3} |
| Np | 1.0×10^{-3} | 1.0×10^{-3} | -6.91 | 0.7 | 1.0×10^{-3} |
| Pa | 5.0×10^{-3} | 5.0×10^{-6} | -12.21 | 1.0 | 5.0×10^{-6} |
| Pb | 8.0×10^{-4} | 8.0×10^{-4} | -7.13 | 0.7 | 8.0×10^{-4} |
| Po | 5.0×10^{-3} | 5.0×10^{-3} | -5.30 | 0.7 | 5.0×10^{-3} |
| Pu | 1.0×10^{-4} | 1.0×10^{-4} | -9.21 | 0.2 | 1.0×10^{-4} |
| Ra | 1.0×10^{-3} | 1.0×10^{-3} | -6.91 | 0.7 | 1.0×10^{-3} |
| Sm | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 1.0 | 2.0×10^{-3} |
| Sr | 8.0×10^{-3} | 1.0×10^{-2} | -4.61 | 0.4 | 1.0×10^{-2} |
| Th | 1.0×10^{-4} | 1.0×10^{-4} | -9.21 | 1.0 | 1.0×10^{-4} |
| Tl | 2.0×10^{-2} | 2.0×10^{-2} | -3.91 | 1.0 | 2.0×10^{-2} |
| U | 3.4×10^{-4} | 8.0×10^{-4} | -7.13 | 0.7 | 8.0×10^{-4} |
| Zn | 1.0×10^{-1} | 1.0×10^{-1} | -2.30 | 0.3 | 1.0×10^{-1} |

33 * Distribution is truncated at a lower quantile of 0.001 and an upper quantile of 0.999.

1 **Table A.4 Baseline Values and Distributions for the Milk Transfer Factor**

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| Element of Interest | RESRAD 6.0 Default Value | Baseline Value as Geometric Mean of the Distribution | Distribution from NUREG/CR-6697 | | |
|---------------------|--------------------------|--|---|----------|----------------------|
| | | | Truncated Lognormal-n Distribution Parameters | | |
| | | | μ | σ | $\exp(\mu)$ |
| Ac | 2.0×10^{-5} | 2.0×10^{-6} | -13.12 | 0.9 | 2.0×10^{-6} |
| Am | 2.0×10^{-6} | 2.0×10^{-6} | -13.12 | 0.7 | 2.0×10^{-6} |
| Ba | 5.0×10^{-4} | 5.0×10^{-4} | -7.60 | 0.7 | 5.0×10^{-4} |
| Be | 2.0×10^{-6} | 2.0×10^{-6} | -13.12 | 0.9 | 2.0×10^{-6} |
| Bi | 5.0×10^{-4} | 1.0×10^{-3} | -6.91 | 0.9 | 1.0×10^{-3} |
| C | 1.2×10^{-2} | 1.2×10^{-2} | -4.4 | 0.9 | 1.2×10^{-2} |
| Ce | 3.0×10^{-5} | 3.0×10^{-5} | -10.41 | 0.7 | 3.0×10^{-5} |
| Co | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 0.7 | 2.0×10^{-3} |
| Cr | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 0.7 | 2.0×10^{-3} |
| Cs | 8.0×10^{-3} | 1.0×10^{-2} | -4.61 | 0.5 | 1.0×10^{-2} |
| Eu | 2.0×10^{-5} | 6.0×10^{-5} | -9.72 | 0.9 | 6.0×10^{-5} |
| Fe | 3.0×10^{-4} | 3.0×10^{-4} | -8.11 | 0.7 | 3.0×10^{-4} |
| H | 1.0×10^{-2} | 1.0×10^{-2} | -4.6 | 0.9 | 1.0×10^{-2} |
| I | 1.0×10^{-2} | 1.0×10^{-2} | -4.61 | 0.5 | 1.0×10^{-2} |
| In | 2.0×10^{-4} | 2.0×10^{-4} | -8.52 | 0.9 | 2.0×10^{-4} |
| K | 7.0×10^{-3} | 7.0×10^{-3} | -4.96 | 0.5 | 7.0×10^{-3} |
| La | 2.0×10^{-5} | 6.0×10^{-5} | -9.72 | 0.9 | 6.0×10^{-5} |
| Np | 5.0×10^{-6} | 1.0×10^{-5} | -11.51 | 0.7 | 1.0×10^{-5} |
| Pa | 5.0×10^{-6} | 5.0×10^{-6} | -12.21 | 0.9 | 5.0×10^{-6} |
| Pb | 3.0×10^{-4} | 3.0×10^{-4} | -8.11 | 0.9 | 3.0×10^{-4} |
| Po | 3.4×10^{-4} | 4.0×10^{-4} | -7.82 | 0.7 | 4.0×10^{-4} |
| Pu | 1.0×10^{-6} | 1.0×10^{-6} | -13.82 | 0.5 | 1.0×10^{-6} |
| Ra | 1.0×10^{-3} | 1.0×10^{-3} | -6.91 | 0.5 | 1.0×10^{-3} |
| Sm | 2.0×10^{-5} | 6.0×10^{-5} | -9.72 | 0.9 | 6.0×10^{-5} |
| Sr | 2.0×10^{-3} | 2.0×10^{-3} | -6.21 | 0.5 | 2.0×10^{-3} |
| Th | 5.0×10^{-6} | 5.0×10^{-6} | -12.21 | 0.9 | 5.0×10^{-6} |
| Tl | 3.0×10^{-3} | 3.0×10^{-3} | -5.81 | 0.9 | 3.0×10^{-3} |
| U | 6.0×10^{-4} | 4.0×10^{-4} | -7.82 | 0.6 | 4.0×10^{-4} |
| Zn | 1.0×10^{-2} | 1.0×10^{-2} | -4.61 | 0.9 | 1.0×10^{-2} |

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* Distribution is truncated at a lower quantile of 0.001 and an upper quantile of 0.999.

1 **Table A.5 Baseline Values and Distributions for the Aquatic Food (Fish)**
 2 **Transfer Factor**

| Element of Interest | RESRAD 6.0 Default Value | Baseline Value as Geometric Mean of the Distribution | Distribution from NUREG/CR-6697 | | |
|---------------------|--------------------------|--|-----------------------------------|----------|-------------|
| | | | Lognormal Distribution Parameters | | |
| | | | μ | σ | $\exp(\mu)$ |
| Ac | 15 | 15 | 2.7 | 1.1 | 15 |
| Am | 30 | 30 | 3.4 | 1.1 | 30 |
| Ba | 4.0 | 4.0 | 1.4 | 1.1 | 4.0 |
| Be | 100 | 100 | 4.6 | 1.1 | 100 |
| Bi | 15 | 15 | 2.7 | 1.1 | 15 |
| C | 50000 | 49000 | 10.8 | 1.1 | 49000 |
| Ce | 30 | 30 | 3.4 | 1.1 | 30 |
| Co | 300 | 300 | 5.7 | 1.1 | 300 |
| Cr | 200 | 200 | 5.3 | 1.1 | 200 |
| Cs | 2000 | 2000 | 7.6 | 0.7 | 2000 |
| Eu | 50 | 50 | 3.9 | 1.1 | 50 |
| Fe | 200 | 200 | 5.3 | 1.1 | 200 |
| H | 1 | 1 | 0 | 0.1 | 1 |
| I | 40 | 40 | 3.7 | 1.1 | 40 |
| In | 10000 | 10000 | 9.2 | 1.1 | 10000 |
| K | 1000 | 1000 | 6.9 | 1.1 | 1000 |
| La | 30 | 30 | 3.4 | 1.1 | 30 |
| Np | 30 | 30 | 3.4 | 1.1 | 30 |
| Pa | 10 | 10 | 2.3 | 1.1 | 10 |
| Pb | 300 | 300 | 5.7 | 1.1 | 300 |
| Po | 100 | 100 | 4.6 | 1.1 | 100 |
| Pu | 30 | 30 | 3.4 | 1.1 | 30 |
| Ra | 50 | 50 | 3.9 | 1.1 | 50 |
| Sm | 25 | 25 | 3.2 | 1.1 | 25 |
| Sr | 60 | 60 | 4.1 | 1.1 | 60 |
| Th | 100 | 100 | 4.6 | 1.1 | 100 |
| Tl | 10,000 | 10,000 | 9.2 | 1.1 | 10,000 |
| U | 10 | 10 | 2.3 | 1.1 | 10 |
| Zn | 1000 | 1000 | 6.9 | 1.1 | 1000 |

1 **A.3 Code-Specific Parameters**

2 **Table A.6 Probability Distribution Notations Used in Baseline Parameter Tables**

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| Notation | Type of Distribution |
|---------------------------------------|----------------------|
| TruncN(μ , σ , a, b) | Truncated Normal |
| TruncLogN(μ , σ , a, b) | Truncated Lognormal |
| BoundedLogN(μ , σ , a, b) | Bounded Lognormal |
| Uniform(a, b) | Uniform |
| LogU(a, b) | Loguniform |
| Triangular(a, c, b) | Triangular |
| Continuous Linear | Empirical |
| Continuous Log | Empirical |

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12 The following notation is used in the baseline tables:

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14 * Mean value of the distribution.

15 ** Geometric mean value of the distribution.

16 *** Not an input parameter in RESRAD.

17 () RESRAD or RESRAD-Offsite default value not used as baseline value.

18 N/A Not applicable.

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Table A.7 RESRAD Baseline Parameter Values and Distributions

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions (Baseline Distributions (if other than NUREG/CR-6697)) | Comments for Baseline Values/Distributions |
|--|------------------------------|--|---|--|
| Title | | | | |
| Title | | Scenario dependent | | Scenario Definition |
| Dose Factor Library | Default File | | | RESRAD Default Library |
| Cut-off Half Life (180 d or 30 d) | (180 d) | 30 d | | |
| Graphics Parameters | | | | |
| Number of Points (32, 64, 128, 256, 512, 1024) | 32 | | | |
| Linear Spacing/Log Spacing | Log Spacing | | | |
| Time Integration Parameters | | | | |
| Maximum No of Points for Dose | 17 | | | |
| Maximum No of Points for Risk | (257) | 1 | | Radiation dose instead of cancer risk is concerned in the analyses. Using a smaller integration point will shorten the calculation time. |
| User Preferences | | | | |
| Use Line Draw Character (yes/no) | yes | | | |
| Find Peak Pathway Dose (yes/no) | yes | | | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|---|------------------------------|--|---|--|
| Save All Files After Each Run (yes/no) | no | yes | | |
| Time Integrated Probabilistic Risk (yes/no) | no | | | |
| Calculation Times | | | | |
| Basic Radiation Dose Limit (mrem/year) | 25 | | | |
| Times for Calculation (years) | (1000) | 1023 | | Values used to obtain dose results for each year. |
| Source | | | | |
| Nuclide Concentration (pCi/g) | (100) | 0.0044 | | Scenario definition. Corresponds to a soil density of 1.52 g/cm ³ . |
| Contaminated Zone Parameters | | | | |
| Area of Contaminated Zone (m ²) | (10000) | 404685 | | Scenario definition (1acre = 4046 square meter). |
| Thickness of Contaminated Zone (m) | (2) | 0.15 | | Scenario definition (15 cm depth of contamination) |
| Length Parallel to Aquifer Flow (m) | (100) | 636 | | Scenario definition (square root of the area). |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|-----------------------|---|--|---|
| Cover & Contaminated Zone Hydrological Data | | | | |
| Cover Depth (m) | 0 | | | Scenario Definition (No cover layer assumed) |
| Density of Cover Material (g/cm ³) | 1.5 | | | Not required when cover depth equals zero. |
| Cover Erosion Rate (m/y) | 0.001 | | | Not required when cover depth equals zero. |
| Density of Contaminated Zone (g/cm ³) | (1.5) | 1.52* | | |
| Contaminated Zone Erosion Rate (m/y) | (0.001) | 0 | | 0 was used in dose analysis to get conservative results. |
| Contaminated Zone Total Porosity | (0.4) | 0.426 | | Values was calculated using density of the contaminated zone. |
| Contaminated Zone Field Capacity | 0.2 | | | |
| Contaminated Zone Hydraulic Conductivity (m/y) | (10) | 9.974** | BoundedLogN(2.3, 2.11, 0.004, 9250) | |
| Contaminated Zone b Parameter | (5.3) | 2.895** | BoundedLogN(1.06, 0.66, 0.5, 30) | |
| Humidity in Air (g/m ³) | (8) | 7.243** | TruncLogN(1.98, 0.334, 0.001, 0.999) | |
| Evapotranspiration Coefficient | (0.5) | 0.625* | Uniform(0.5, 0.75) | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|------------------------------|--|---|---|
| Wind Speed (m/s) | (2) | 4.242** | BoundedLogN(1.445, 0.2419, 1.4, 13) | |
| Precipitation (m/y) | 1.0 | | | |
| Irrigation (m/y) | 0.2 | | | |
| Irrigation mode (Overhead/Ditch) | Overhead | | | |
| Runoff Coefficient | (0.2) | 0.45* | Uniform(0.1, 0.8) | |
| Watershed Area for Nearby Stream or Pond (m ²) | 1000000 | | | |
| Accuracy for Water/Soil Computation | 0.001 | | | |
| Saturated Zone Hydrological Data | | | | |
| Density (g/cm ³) | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Effective Porosity | (0.2) | 0.355* | TruncN(0.355, 0.0906, 0.001, 0.999) | |
| Total Porosity | (0.4) | 0.425* | TruncN(0.425, 0.0867, 0.001, 0.999) | |
| Field Capacity | 0.2 | | | |
| Hydraulic Conductivity (m/y) | (100) | 9.974** | BoundedLogN(2.3, 2.11, 0.004, 9250) | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|---|-----------------------|---|--|---|
| b Parameter | (5.3) | | | Not required when the water table drop rate was set to 0. |
| Hydraulic Gradient | (0.02) | 0.00604** | BoundedLogN(-5.11, 1.77, 7e-5, 0.5) | |
| Water Table Drop Rate (m/y) | (0.001) | 0 | | 0 was used to get conservative dose results. |
| Well Pump Intake Depth (m below water table) | (10) | 15.33* | Triangular(6, 10, 30) | |
| Model for Water Transportation (Nondispersion/Mass-Balance) | Nondispersion | | | |
| Well Pumping Rate (m ³ /y) | 250 | | | |
| Unsaturated Zone Parameters | | | | |
| Thickness (m) | (4) | 9.895** | BoundedLogN(2.2926, 1.276, 0.18, 320) | |
| Density (g/cm ³) | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Effective Porosity | (0.2) | 0.355* | TruncN(0.355, 0.0906, 0.001, 0.999) | |
| Total Porosity | (0.4) | 0.425* | TruncN(0.425, 0.0867, 0.001, 0.999) | |
| Field Capacity | 0.2 | | | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|-----------------------|---|--|--|
| Hydraulic Conductivity (m/y) | (10) | 9.974** | BoundedLogN(2.3, 2.11, 0.004, 9250) | |
| b Parameter | (5.3) | 2.895** | BoundedLogN(1.06, 0.66, 0.5, 30) | |
| Occupancy, Inhalation and External Gamma Data | | | | |
| Inhalation Rate (m ³ /y) | (8400) | 8627* | Triangular(4380, 8400, 13100) | |
| Mass Loading for Inhalation (g/m ³) | (0.001) | 2.45E-05* | Continuous Linear | |
| Exposure Duration (y) | 30 | | | |
| Indoor Dust Filtration Factor | (0.4) | 0.55* | Uniform(0.15, 0.95) | |
| External Gamma Shielding Factor | (0.7) | 0.27** | BoundedLogN(-1.3, 0.59, 0.044, 1) | |
| Indoor Time Fraction | (0.5) | 0.651* | | |
| Outdoor Time Fraction | 0.25 | | | |
| Shape of Contaminated Zone (circular/noncircular) | circular | | | |
| Ingestion Pathway Dietary Data | | | | |
| Fruit, Vegetable and Grain Consumption (kg/y) | (160) | 210.33* | Triangular(135, 178, 318) | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|------------------------------------|-----------------------|---|--|---|
| Leafy Vegetable Consumption (kg/y) | (14) | 22.667* | No distribution / Triangular (13, 25, 30) | Baseline distribution derived from EPA 1997 using methodology of NUREG/CR-6697. |
| Milk (L/y) | (92) | 120.67* | Triangular(60, 102, 200) | |
| Meat and Poultry (kg/y) | (63) | 222.1* | No distribution / Triangular(5.0, 72.6, 588.7) | Baseline distribution derived from EPA 1997 using methodology of NUREG/CR-6697. |
| Fish (kg/y) | (5.4) | 155.6* | No distribution / Triangular(2.0, 56.3, 408.5) | Baseline distribution derived from EPA 1997 using methodology of NUREG/CR-6697. |
| Other Sea Food (kg/y) | (0.9) | 0 | | No ocean fish. |
| Soil Ingestion (g/y) | (36.5) | 18.27* | Triangular(0, 18.3, 36.5) | |
| Drinking Water Intake (L/y) | (510) | 409.5** | TruncLogN(6.015, 0.489, 0.001, 0.999) | |
| Contaminated Fractions | | | | |
| Drinking Water | (1) | 0.9 | | Scenario definition. |
| Household Water | 1 | | | |
| Livestock water | 1 | | | |
| Irrigation water | 1 | | | |
| Aquatic food | (0.5) | 0.463* | Triangular(0, 0.39, 1) | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions/ Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|-----------------------|---|---|--|
| Plant food | -1 | | | Calculated by RESRAD from area factor |
| Meat | -1 | | | Calculated by RESRAD from area factor |
| Milk | -1 | | | Calculated by RESRAD from area factor |
| Ingestion Pathway, Non-dietary Data | | | | |
| Livestock fodder intake for meat (kg/d) | 68 | | | |
| Livestock fodder intake for milk (kg/d) | 55 | | | |
| Livestock water intake for meat (L/d) | 50 | | | |
| Livestock water intake for milk (L/d) | 160 | | | |
| Livestock intake of soil (kg/d) | 0.5 | | | |
| Mass loading for foliar deposition (g/m ²) | 0.0001 | | | |
| Depth of soil mixing layer (m) | (0.15) | 0.25* | Triangular(0.0, 0.15, 0.6) | |
| Depth of roots (m) | (0.9) | 2.15* | Uniform(0.3, 4.0) | |
| Groundwater Fractional Usage | | | | |
| Drinking Water | 1 | | | |

Table A.7... RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|-----------------------|---|--|--|
| Household Water | 1 | | | |
| Livestock water | (1) | 0.5 | | To consider potential surface water contamination as well. |
| Irrigation water | (1) | 0.5 | | To consider potential surface water contamination as well. |
| Non-leafy Plant Factors | | | | |
| Wet Weight Crop Yield (kg/m ²) | (0.7) | 1.75** | TruncLogN(0.56, 0.48, 0.001, 0.999) | |
| Length of Growing Season (y) | 0.17 | | | |
| Translocation Factor | 0.1 | | | |
| Weathering Removal Constant (1/y) | (20) | 35.70* | Triangular(5.1, 18, 84) | |
| Wet Foliar Interception Fraction | 0.25 | | | |
| Dry Foliar Interception Fraction | 0.25 | | | |
| Leafy Plant Factors | | | | |
| Wet Weight Crop Yield (kg/m ²) | 1.5 | | | |
| Length of Growing Season (y) | 0.25 | | | |
| Translocation Factor | 1 | | | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|---|-----------------------|---|--|--|
| Wet Foliar Interception Fraction | (0.25) | 0.560* | Triangular(0.06, 0.67, 0.95) | |
| Dry Foliar Interception Fraction | 0.25 | | | |
| Fodder Plant Factors | | | | |
| Wet Weight Crop Yield (kg/m ²) | 1.1 | | | |
| Length of Growing Season (y) | 0.08 | | | |
| Translocation Factor | 1 | | | |
| Wet Foliar Interception Fraction | 0.25 | | | |
| Dry Foliar Interception Fraction | 0.25 | | | |
| Radon Data | | | | |
| Cover Total Porosity | 0.4 | N/A | | No cover. |
| Cover Volumetric Water Content | 0.05 | N/A | | No cover. |
| Cover Radon Diffusion Coefficient (m ² /s) | 2 x 10 ⁻⁶ | N/A | | No cover. |
| Bldg Foundation Thickness (m) | 0.15 | | | |
| Bldg Foundation Density (g/cm ³) | 2.4 | | | |
| Bldg Foundation Total Porosity | 0.1 | | | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|---|------------------------------|--|---|---|
| Bldg Foundation Volumetric Water Content | 0.03 | | | |
| Bldg Foundation Radon Diffusion Coefficient (m ² /s) | 3 x 10 ⁻⁷ | | | |
| Contaminated Radon Diffusion Coefficient (m ² /s) | 2 x 10 ⁻⁶ | | | |
| Radon Vertical Dimension of Mixing (m) | 2 | | | |
| Building Air Exchange Rate (1/hr) | 0.5 | | | |
| Building Room Height (m) | 2.5 | | | |
| Building Indoor Area Factor | 0 | | | Value calculated by the code. |
| Foundation Depth Below Ground Surface (m) | -1 | | | Value calculated by the code. |
| Rn-222 Emanation Coefficient | 0.25 | | | |
| Rn-220 Emanation Coefficient | 0.15 | | | |
| Storage Times Before Use Data | | | | |
| Fruits, Non-leafy Vegetables and Grain (d) | 14 | | | |
| Leafy Vegetables (d) | 1 | | | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|------------------------------|--|---|---|
| Milk (d) | 1 | | | |
| Meat (d) | 20 | | | |
| Fish (d) | 7 | | | |
| Crustacea and Mollusks (d) | 7 | | | |
| Well Water (d) | 1 | | | |
| Surface Water (d) | 1 | | | |
| Livestock Fodder (d) | 45 | | | |
| Carbon-14 Data | | | | |
| C-12 Concentration in Local Water | 0.00002 | | | |
| C-12 Concentration in Contaminated Soil | 0.03 | | | |
| Fraction of Vegetation Carbon Adsorbed from Soil | 0.02 | | | |
| Fraction of Vegetation Carbon Adsorbed from Air | 0.98 | | | |
| Thickness of Evasion Layer of C-14 in Soil | 0.3 | 0.367* | Triangular(0.2, 0.3, 0.6) | |
| C-14 Evasion Flux Rate from Soil | 0.0000007 | | | |

Table A.7 RESRAD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions/, Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|-----------------------|---|--|--|
| C-12 Evasion Flux Rate from Soil | 1E-10 | | | |
| Grain Fraction in Livestock Feed (Balance is Hay/Fodder) for Beef Cattle | 0.8 | | | |
| Grain Fraction in Livestock Feed (Balance is Hay/Fodder) for Milk Cow | 0.2 | | | |
| DCF Correction Factor for Gaseous Forms of C-14 | 88.94 | | | |

Table A.8 RESRAD Baseline Parameter Correlations for Probabilistic Analyses

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|--|--|-------------------------|---|
| Unsaturated Zone Soil Density | Unsaturated Zone Total Porosity | -0.99 | The two parameters are strongly negatively correlated. |
| Saturated Zone Soil Density | Saturated Zone Total Porosity | -0.99 | The two parameters are strongly negatively correlated. |
| Unsaturated Zone Total Porosity | Unsaturated Zone Effective Porosity | 0.96 | A correlation of 0.96 provides satisfactory pairing of sampling data. |
| Saturated Zone Total Porosity | Saturated Zone Effective Porosity | 0.96 | A correlation of 0.96 provides satisfactory pairing of sampling data. |
| Unsaturated Zone Soil Density | Unsaturated Zone Effective Porosity | -0.96 | The two parameters are strongly negatively correlated. |
| Saturated Zone Soil Density | Saturated Zone Effective Porosity | -0.96 | The two parameters are strongly negatively correlated. |
| K _d of U-238 in Contaminated Zone | K _d of U-234 in Contaminated Zone | 0.99 | To ensure the same K _d value was used by different isotopes of the same element. |
| K _d of U-238 in Unsaturated Zone | K _d of U-234 in Unsaturated Zone | 0.99 | Same as above. |
| K _d of U-238 in Saturated Zone | K _d of U-234 in Saturated Zone | 0.99 | Same as above. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|---|---|
| Title | | | | | |
| Title | | | Scenario dependent | | Scenario definition |
| Intermediate time points | | | | | |
| Number of points (32, 64, 128, 256, 512, 1024, 2048, 4096) | | (128) | 32 | | |
| Linear spacing/Log Spacing | | linear | | | |
| Minimum time increment | v | 1 | | | |
| Dose factor library | | (DOSFAC.BIN) | DOSFAC6.BIN | | To consider short-lived radionuclides. |
| Cut-off half life (180 days, 30 days, 6 hours) | | (180 days) | 6 hours | | To include shorter-lived radionuclides in the analysis. |
| Display update (0.25, 0.5, 1, 2, 4, 8, 16 sec) | v | 1 | | | |
| Use line draw character | | Yes | | | |
| First Inputs | | | | | |
| Basic radiation dose limit (mrem/yr) | | (30) | 25 | | |
| Exposure duration (yr) | | 30 | | | |
| Number of unsaturated zone | | 1 | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|--|---|--|--|
| Source | | | | | |
| Nuclide concentration (pCi/g) | | | 0.0044 | | Scenario definition. Corresponds to a soil density of 1.52 g/cm ³ . |
| Source Release | | | | | |
| Release to groundwater, leach rate (1/yr) | | 0 | | | |
| Distribution Coefficients (ml/g) | | | | | |
| Contaminated zone | | Nuclide dependent (see Table A.1 Baseline Values and Distributions for the K _d Parameter) | Geometric mean of distribution (see Table A.1 Baseline Values and Distributions for the K _d Parameter) | Nuclide dependent (see Table A.1 Baseline Values and Distributions for the K _d Parameter) | |
| Unsaturated zone | | Same as above | Same as above | Same as above | |
| Saturated zone | | Same as above | Same as above | Same as above | |
| Sediment in surface water body | v | Same as above | Same as above | Same as above | |
| Fruit, grain, non-leafy fields | v | Same as above | Same as above | Same as above | |
| Leafy vegetable fields | v | Same as above | Same as above | Same as above | |
| Pasture, silage growing areas | v | Same as above | Same as above | Same as above | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|---|--|---|--|
| Livestock feed grain fields | v | Same as above | Same as above | Same as above | |
| Transfer Factors | | | | | |
| Soil to plant transfer factor [(pCi/kg)/(pCi/kg)] | | | | | RESRAD-Offsite considers different plant types and accepts different transfer factors, whereas RESRAD accepts only one transfer factor that is used for all plant types. |
| Fruit, grain, non-leafy vegetables | v | Nuclide dependent (see Table A.2 Baseline Values and Distributions for the Plant Transfer Factor) | Geometric mean of distribution (see Table A.2 Baseline Values and Distributions for the Plant Transfer Factor) | Nuclide dependent (see Table A.2 Baseline Values and Distributions for the Plant Transfer Factor) | |
| Leafy vegetables | v | Same as above | Same as above | Same as above | |
| Pasture, silage | v | Same as above | Same as above | Same as above | |
| Livestock feed grain | v | Same as above | Same as above | Same as above | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|--|---|--|----------|
| Intake to animal product transfer factor | | | | | |
| Meat [(pCi/kg)/(pCi/d)] | | Nuclide dependent (see Table A.3 Baseline Values and Distributions for the Meat Transfer Factor) | Geometric mean of distribution (see Table A.3 Baseline Values and Distributions for the Meat Transfer Factor) | Nuclide dependent (see Table A.3 Baseline Values and Distributions for the Meat Transfer Factor) | |
| Milk [(pCi/L)/(pCi/d)] | | Nuclide dependent (see Table A.4 Baseline Values and Distributions for the Milk Transfer Factor) | Geometric mean of distribution (see Table A.4 Baseline Values and Distributions for the Milk Transfer Factor) | Nuclide dependent (see Table A.4 Baseline Values and Distributions for the Milk Transfer Factor) | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|---------------------------------|---|--|---|----------|
| Water to aquatic food transfer factor Fish [(pCi/kg)/(pCi/L)] | | Nuclide dependent [see Table A.5 Baseline Values and Distributions for the Aquatic Food (Fish) Transfer Factor] | Geometric mean of distribution [see Table A.5 Baseline Values and Distributions for the Aquatic Food (Fish) Transfer Factor] | Nuclide dependent [see Table A.5 Baseline Values and Distributions for the Aquatic Food (Fish) Transfer Factor] | |
| Crustacea [(pCi/kg)/(pCi/L)] | | Nuclide dependent | Not used | Nuclide dependent / Not used | |
| Reporting Times | | | | | |
| Times at which output is reported (yr) | | 1, 3, 6, 12, 30, 75, 175, 420, 970 | | | |
| Storage Times | | | | | |
| Surface water (d) | | 1 | | | |
| Well water (d) | | 1 | | | |
| Fruits, grain, and non-leafy vegetables (d) | | 14 | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|--|---|
| Leafy vegetables (d) | | 1 | | | |
| Pasture and silage (d) | v | 1 | | | Livestock fodder in RESRAD is divided into two categories in RESRAD-Offsite: (1) pasture and silage, and (2) grain. |
| Livestock feed grain (d) | v | 45 | | | Livestock fodder is divided into two categories in RESRAD-Offsite: (1) pasture and silage, and (2) grain. |
| Meat (d) | | 20 | | | |
| Milk (d) | | 1 | | | |
| Fish (d) | | 7 | | | |
| Crustacea and mollusks (d) | | 7 | | | |
| Site Properties | | | | | |
| Precipitation (m/yr) | | 1 | | | |
| Wind speed (m/s) | | (2) | 4.242** | BoundedLogN(1.44 5, 0.2419, 1.4, 13) | |
| Primary Contamination Area Parameters | | | | | |
| Contaminated zone and cover | | | | | |
| Area of primary contamination (m ²) | | (10000) | 404685 (100 acres) | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|--|--|---|
| Length of contamination parallel to aquifer flow (m) | | (100) | 636 (equivalent to the square root of area). | | |
| Depth of soil mixing layer (m) | | (0.15) | 0.25* | Triangular (0.0, 0.15, 0.6) | |
| Deposition velocity of dust (m/s) | v | (0.01) | 0.002 | | Value decided based on the screening calculation for air transport in the earlier version of the Scenarios chapter. |
| Irrigation applied per year (m/y) | | 0.2 | | | |
| Evapotranspiration coefficient | | (0.5) | 0.625* | Uniform(0.5, 0.75) | |
| Runoff coefficient | | (0.2) | 0.45* | Uniform(0.1, 0.8) | |
| Rainfall erosion index | v | 200 | | | The parameter is used to calculate the erosion rate. |
| Slope-length-steepness factor | v | 1 | | | The parameter is used to calculate the erosion rate. |
| Cropping management factor | v | 0.11 | | | The parameter is used to calculate the erosion rate. |
| Conservation practice factor | v | 1 | | | The parameter is used to calculate the erosion rate. |
| Contaminated zone | | | | | |
| Thickness (m) | | (2) | 0.15 | | Plowing depth. |

Table A.9 - RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---------------------------------------|-------------------------------------|-------------------------------|---|--|---|
| Total porosity | | (0.4) | 0.426 | | Value calculated using the dry bulk density. |
| Erosion rate (m/y) | | (0.0009856) | 0 | Continuous Log / No distribution was specified in dose analyses | The parameter value is calculated by RESRAD-Offsite using other input parameters. By specifying a 0 erodibility factor, the calculated value is 0, which was used in dose analysis to get conservative results. This parameter is an input parameter in RESRAD, the default value is 0.001. |
| Dry bulk density (g/cm ³) | | (1.5) | 1.52* | | |
| Soil erodibility factor (tons/acre) | v | (0.3) | 0 | | A value of 0 was used to get 0 erosion rate. The parameter is used to calculate the erosion rate. |
| Field capacity | | (0.3) | 0.2 | | Value was decided to keep consistence with the RESRAD baseline value. |
| Soil b parameter | | (5.3) | 2.895** | BoundedLogN(1.06, 0.66, 0.5, 30) | |
| Hydraulic conductivity (m/y) | | (10) | 9.974** | BoundedLogN(2.3, 2.11, 0.004, 9250) | |
| Clean Cover | | | | | |
| Thickness (m) | | 0 | | | No cover material. |
| Total porosity | | (0.4) | Not used | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---------------------------------------|-------------------------------------|-------------------------------|---|--|--|
| Erosion rate (m/y) | | (0.0009856) | Not used | | No cover material. The parameter value is calculated by RESRAD-Offsite using other input parameters. |
| Dry bulk density (g/cm ³) | | (1.5) | Not used | TruncN(1.52, 0.230, 0.001, 0.999) / not used | No cover material. |
| Soil erodibility factor (tons/acre) | v | (0.3) | Not used | | No cover material. The parameter is used to calculate the erosion rate. |
| Volumetric water content | v | (0.05) | Not used | | No cover material. |
| Unsaturated Zone Parameters | | | | | |
| Thickness (m) | | (4) | 9.895** | BoundedLogN(2.29, 26, 1.276, 0.18, 320) | |
| Dry bulk density (g/cm ³) | | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Total porosity | | (0.4) | 0.425* | TruncN(0.425, 0.0867, 0.001, 0.999) | |
| Effective porosity | | (0.2) | 0.355* | TruncN(0.355, 0.0906, 0.001, 0.999) | |
| Field capacity | | (0.3) | 0.2 | | Set to 0.2 to be consistent with the RESRAD default value. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|--|---|
| Hydraulic conductivity (m/y) | | (10) | 9.974** | BoundedLogN(2.3, 2.11, 0.004, 9250) | |
| Soil b parameter | | (5.3) | 2.895** | BoundedLogN(1.06, 0.66, 0.5, 30) | |
| Longitudinal dispersivity (m) | v | 1 | | | |
| Saturated Zone Hydrological Data | | | | | |
| Thickness of saturated zone (m) | v | (100) | 3000 | | Value selected to avoid water mounding in the saturated zone. |
| Dry bulk density of saturated zone (g/cm ³) | | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Total porosity | | (0.4) | 0.425* | TruncN(0.425, 0.0867, 0.001, 0.999) | |
| Effective porosity | | (0.2) | 0.355* | TruncN(0.355, 0.0906, 0.001, 0.999) | |
| Hydraulic conductivity (m/y) | | (100) | 9.974** | BoundedLogN(2.3, 2.11, 0.004, 9250) | |
| Hydraulic gradient | | (0.02) | 0.00604** | BoundedLogN(-5.11, 1.77, 7e-5, 0.5) | |
| Longitudinal dispersivity (m) | v | 10 | | | |
| Horizontal lateral dispersivity (m) | v | 3 | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|--|-----------------------------------|
| Disperse vertically? | v | Yes | | | |
| Vertical lateral dispersivity (m) | v | 1 | | | |
| Do not disperse vertically? | v | No | | | |
| Value averaged over length of saturated zone | | | | | |
| Irrigation rate (m/y) | | 0.2 | Not used | | Vertical dispersion was selected. |
| Evapotranspiration coefficient | | 0.5 | Not used | | |
| Runoff coefficient | | 0.2 | Not used | | |
| Depth of aquifer contributing to water source | | | | | |
| Well screen depth (below groundwater table) (m) | | 10 | 15.33* | Triangular(6, 10, 30) | |
| Surface water body (below groundwater table) (m) | v | 10 | | | |
| Agriculture Area Parameters | | | | | |
| Fruite, grain, and non-leafy field | | | | | |
| Area (m ²) | v | 1000 | | | |
| Fraction of area directly over primary contamination | v | 0 | | | Scenario definition. |
| Irrigation applied per year (m/y) | v | 0.2 | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|--|--|
| Evapotranspiration coefficient | v | (0.5) | 0.625* | Uniform(0.5, 0.75) | |
| Runoff coefficient | v | (0.2) | 0.45* | Uniform(0.1,0.8) | |
| Depth of soil mixing layer or plow layer (m) | v | (0.15) | 0.25* | Triangular(0.0, 0.15, 0.6) | |
| Total water filled porosity | v | 0.3 | | | In RESRAD, the parameter value is calculated using the infiltration rate, saturated hydraulic conductivity, b parameter, and total porosity. The saturated hydraulic conductivity, b parameter, and total porosity are no longer input parameters for the agricultural area in RESRAD-Offsite. |
| Erosion rate (m/y) | v | 0.0009856 | | | The parameter value is calculated by RESRAD-Offsite using other parameters. It is an input parameter in RESRAD and the default value is 0.001. |
| Dry bulk density of soil (g/cm ³) | v | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Soil erodibility factor (tons/acre) | v | 0.3 | | | The parameter is used to calculate the erosion rate. |
| Slope-length-steepness factor | v | 1 | | | The parameter is used to calculate the erosion rate. |
| Cropping management factor | v | 0.11 | | | The parameter is used to calculate the erosion rate. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|---------------------------------|-------------------------------|---|--|--|
| Conservation practice factor | v | 1 | | | The parameter is used to calculate the erosion rate. |
| Leafy vegetable field | | | | | |
| Area (m ²) | v | 1000 | | | |
| Fraction of area directly over primary contamination | v | 0 | | | Scenario definition. |
| Irrigation applied per year (m/y) | v | 0.2 | | | |
| Evapotranspiration coefficient | v | (0.5) | 0.625* | Uniform(0.5, 0.75) | |
| Runoff coefficient | v | (0.2) | 0.45* | Uniform(0.1, 0.8) | |
| Depth of soil mixing layer or plow layer (m) | v | (0.15) | 0.25* | Triangular(0.0, 0.15, 0.6) | |
| Total water filled porosity | v | 0.3 | | | In RESRAD, the parameter value is calculated using the infiltration rate, saturated hydraulic conductivity, b parameter, and total porosity. The saturated hydraulic conductivity, b parameter, and total porosity are no longer input parameters for the agricultural area in RESRAD-Offsite. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|--|--|
| Erosion rate (m/y) | v | 0.0009856 | | | The value is calculated by RESRAD-Offsite using other input parameters. It is an input parameter in RESRAD and the default value is 0.001. |
| Dry bulk density of soil (g/cm ³) | v | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Soil erodibility factor (tons/acre) | v | 0.3 | | | The parameter is used to calculate erosion rate. |
| Slope-length-steepness factor | v | 1 | | | The parameter is used to calculate erosion rate. |
| Cropping management factor | v | 0.11 | | | The parameter is used to calculate erosion rate. |
| Conservation practice factor | v | 1 | | | The parameter is used to calculate erosion rate. |
| Livestock Feed Growing Area Parameters | | | | | |
| Pasture and silage field | | | | | |
| Area (m ²) | v | 10000 | | | |
| Fraction of area directly over primary contamination | v | 0 | | | Scenario definition. |
| Irrigation applied per year (m/y) | v | (0.2) | 0 | | No irrigation for livestock feed growing area. |
| Evapotranspiration coefficient | v | (0.5) | 0.625 * | Uniform(0.5, 0.75) | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter In RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|---|--|
| Runoff coefficient | v | (0.2) | 0.45 * | Uniform(0.1, 0.8) | |
| Depth of soil mixing layer or plow layer (m) | v | (0.15) | 0.25 * | Triangular(0.0, 0.15, 0.6) | |
| Total water filled porosity | v | 0.3 | | | In RESRAD, the parameter value is calculated using the infiltration rate, saturated hydraulic conductivity, b parameter, and total porosity. The saturated hydraulic conductivity, b parameter, and total porosity are no longer input parameters for the agricultural area in RESRAD-Offsite. |
| Erosion rate (m/y) | v | 0.0009856 | | | The value is calculated by RESRAD-Offsite using other input parameters. It is an input parameter in RESRAD and the default value is 0.001. |
| Dry bulk density of soil (g/cm ³) | v | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Soil erodibility factor (tons/acre) | v | 0.3 | | | The parameter is used to calculate erosion rate. |
| Slope-length-steepness factor | v | 1 | | | The parameter is used to calculate erosion rate. |
| Cropping management factor | v | 0.11 | | | The parameter is used to calculate erosion rate. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter In RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|--|--|
| Conservation practice factor | v | 1 | | | The parameter is used to calculate erosion rate. |
| Grain field | | | | | |
| Area (m ²) | v | 10000 | | | |
| Fraction of area directly over primary contamination | v | 0 | | | |
| Irrigation applied per year (m/y) | v | (0.2) | 0 | | No irrigation for livestock feed growing area. |
| Evapotranspiration coefficient | v | (0.5) | 0.625* | Uniform(0.5, 0.75) | |
| Runoff coefficient | v | (0.2) | 0.45* | Uniform(0.1, 0.8) | |
| Depth of soil mixing layer or plow layer (m) | v | (0.15) | 0.25* | Triangular(0.0, 0.15, 0.6) | |
| Total water filled porosity | v | 0.3 | | | In RESRAD, the parameter value is calculated using the infiltration rate, saturated hydraulic conductivity, b parameter, and total porosity. The saturated hydraulic conductivity, b parameter, and total porosity are no longer input parameters for the agricultural area in RESRAD-Offsite. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|---------------------------------|-------------------------------|---|--|--|
| Erosion rate (m/y) | v | 0.0009856 | | | The parameter value is calculated by RESRAD-Offsite using other input parameters. It is an input parameter in RESRAD and the default value is 0.001. |
| Dry bulk density of soil (g/cm ³) | v | (1.5) | 1.52* | TruncN(1.52, 0.230, 0.001, 0.999) | |
| Soil erodibility factor (tons/acre) | v | 0.3 | | | The parameter is used to calculate erosion rate. |
| Slope-length-steepness factor | v | 1 | | | The parameter is used to calculate erosion rate. |
| Cropping management factor | v | 0.11 | | | The parameter is used to calculate erosion rate. |
| Conservation practice factor | v | 1 | | | The parameter is used to calculate erosion rate. |
| Surface Water Body Parameters | | | | | |
| Sediment delivery ratio | v | (1) | 0.5 | / Uniform(0, 1) | Used to determine the amount of eroded radionuclides getting to the surface water body. |
| Volume of surface water body (m ³) | v | 150000 | | | The surface water body was assumed to be of a circular shape, with a radius of 100 m and a depth of 4.77 m in dose analyses. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (If other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (If other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|--|--|
| Mean residence time of water in surface water body (y) | v | (1) | 9.609×10^{-4} (8.4175 hr) | | The baseline value was calculated based on the volume of the surface water body and a flow rate of 4.95 m ³ /sec. |
| Air Transport Parameters | | | | | |
| Chi/Q (s/m ³) for fruit, grain, non-leafy vegetable field | v | (0) | 5.97×10^{-6} | | Value from CAP88-PC for a distance of 800 m. |
| Chi/Q (s/m ³) for leafy vegetable field | v | (0) | 5.97×10^{-6} | | Value from CAP88-PC for a distance of 800 m. |
| Chi/Q (s/m ³) for pasture and silage field | v | (0) | 5.97×10^{-6} | | Value from CAP88-PC for a distance of 800 m. |
| Chi/Q (s/m ³) for grain field | v | (0) | 5.97×10^{-6} | | Value from CAP88-PC for a distance of 800 m. |
| Groundwater Transport Parameters | | | | | |
| Distance from downgradient edge of contamination to | | | | | |
| Well in the direction parallel to aquifer flow (m) | v | (100) | 800 | | Assumed the well is located at the center of the established living area. |
| Surface water body in the direction parallel to aquifer flow (m) | v | (100) | 800 | | Assumed the center of the surface water body is 800 m from the edge of the primary contaminated area. |
| Distance from center of contamination to | | | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|--|---|
| Well in the direction perpendicular to aquifer flow (m) | v | 0 | | | Assumed the well is located at the center of the established living area, which is located downgradient from the primary contaminated site. |
| Near edge of surface water body in the direction parallel to aquifer flow (m) | v | (-125) | -100 | | The surface water body was assumed to be of a circular shape with a radius of 100 m. |
| Far edge of surface water body in the direction parallel to aquifer flow (m) | v | (125) | 100 | | Same as above. |
| Convergence criterion (fractional accuracy desired) | | 0.001 | | | |
| Number of sub zones (to model dispersion of progeny produced in transit) | | | | | |
| Main sub zones in saturated zone | v | 1 | | | |
| Minor sub zones in last main sub zone in saturated zone | v | Not used | | | |
| Main sub zones in each partially saturated zone | v | 1 | | | |
| Minor sub zones in last main sub zone in each partially saturated zone | v | Not used | | | |
| Retardation and dispersion treatment | | | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|---|--|
| Nuclide specific retardation in all sub zones, longitudinal dispersion in all but the sub zone of transformation? | v | Yes | | | |
| Longitudinal dispersion in all sub zones, nuclide specific retardation in all but the sub zone of transformation, parent retardation in zone of transformation? | v | No | | | |
| Longitudinal dispersion in all sub zones, nuclide specific retardation in all but the sub zone of transformation, progeny retardation in zone of transformation? | v | No | | | |
| Water Use Parameters | | | | | |
| Human consumption | | | | | |
| Quantify (L/y) | | (510) | 409.5 ** | TruncLogN(6.015, 0.489, 0.001, 0.999) | |
| Fraction of water from surface body | | 0 | | | Assuming 90% of the drinking water is from a local well. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|-------------------------------------|---------------------------------|-------------------------------|---|--|---|
| Fraction of water from well | | (1) | 0.9 | | Assuming 90% of the drinking water is from a local well. |
| Number of household individuals | v | 4 | | | The parameter is used to calculate the total amount of water needed from the affected area. |
| Household purposes | | | | | |
| Quantify (L/y) | v | 225 | | | |
| Fraction of water from surface body | | 0 | | | |
| Fraction of water from well | | 1 | | | |
| Beef cattle | | | | | |
| Quantify (L/y) | | 50 | | | |
| Fraction of water from surface body | v | (0) | 0.5 | | |
| Fraction of water from well | v | (1) | 0.5 | | |
| Number of cattle | v | 2 | | | The parameter is used to calculate the total amount of water needed from the affected area. |
| Dairy cows | | | | | |
| Quantify (L/y) | | 160 | | | |
| Fraction of water from surface body | v | (0) | 0.5 | | |
| Fraction of water from well | v | (1) | 0.5 | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|-------------------------------------|-------------------------------------|-------------------------------|---|--|---|
| Number of cows | v | 2 | | | The parameter is used to calculate the total amount of water needed from the affected area. |
| Irrigation applied per year | | | | | |
| Fruit, grain, non-leafy vegetables | | | | | |
| Quantify (m/y) | v | 0.2 | | | Value should be consistent with the irrigation rate specified for the same farmed field. |
| Fraction of water from surface body | v | (0) | 0.5 | | |
| Fraction of water from well | v | (1) | 0.5 | | |
| Area of plot (m ²) | v | 1000 | | | Value should be consistent with the size specified for the same farmed field. |
| Leafy vegetables | | | | | |
| Quantify (m/y) | v | 0.2 | | | Value should be consistent with the irrigation rate specified for the same farmed field. |
| Fraction of water from surface body | v | (0) | 0.5 | | |
| Fraction of water from well | v | (1) | 0.5 | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|-------------------------------------|-------------------------------------|-------------------------------|---|--|--|
| Area of plot (m ²) | v | 1000 | | | Value should be consistent with the size specified for the same farmed field. |
| Pasture and silage | | | | | |
| Quantify (m/y) | v | (0.2) | 0 | | Value should be consistent with the irrigation rate specified for the same farmed field. |
| Fraction of water from surface body | v | (0) | 0.5 | | |
| Fraction of water from well | v | (1) | 0.5 | | |
| Area of plot (m ²) | v | 10000 | | | Value should be consistent with the size specified for the same farmed field. |
| Livestock feed grain | | | | | |
| Quantify (m/y) | v | (0.2) | 0 | | Value should be consistent with the irrigation rate specified for the same farmed field. |
| Fraction of water from surface body | v | (0) | 0.5 | | |
| Fraction of water from well | v | (1) | 0.5 | | |
| Area of plot (m ²) | v | 10000 | | | Value should be consistent with the size specified for the same farmed field. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|--|--|
| Well pumping rate (m ³ /y) | | 250 | | | Value kept consistent with the baseline value used for RESRAD. |
| Well pumping rate needed to specified water use (m ³ /y) | v | 4884.17 | | | The value was calculated by RESRAD-Offsite based on the various water needs specified. It is listed for reference purposes only. |
| Ingestion Rates | | | | | |
| Consumption rate | | | | | |
| Drinking water (L/y) | | (510) | 409.5** | TruncLogN(6.015, 0.489, 0.001, 0.999) | |
| Fish (kg/y) | | (5.4) | 155.6* | / Triangular(2.0, 56.3, 408.5) | Baseline distribution from 1997 EPA Exposure Factors Handbook. |
| Other aquatic food (kg/y) | | (0.9) | 0 | | Scenario definition. No ocean fish. |
| Fruit, grain, non-leafy vegetables (kg/y) | | (160) | 210.33* | Triangular(135, 178, 318) | |
| Leafy vegetables (kg/y) | | (14) | 22.667* | / Triangular(13, 25, 30) | |
| Meat (kg/y) | | (63) | 222.1* | / Triangular(5.0, 72.6, 588.7) | |
| Milk (L/y) | | (92) | 120.67* | Triangular(60, 102, 200) | |
| Soil (incidental) (g/y) | | (36.5) | 18.27* | Triangular(0, 18.3, 36.5) | |

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Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|------------------------------------|---------------------------------|-------------------------------|---|---|---|
| Fraction from affected area | | | | | |
| Drinking water | | (1) | 0.9 | | To be consistent with the baseline value for RESRAD. |
| Fish | | (0.5) | 0.463* | Triangular(0, 0.39, 1) | |
| Other aquatic food | | (0.5) | 0 | | Scenario definition. No ocean fish. |
| Fruit, grain, non-leafy vegetables | | 0.5 | | | |
| Leafy vegetables | | 0.5 | | | |
| Meat | | 1 | | | |
| Milk | | 1 | | | |
| Livestock Intakes | | | | | |
| Meat Cows | | | | | |
| Water (L/d) | | 50 | | | Value kept consistent with the one specified in "Water Use". |
| Pasture and silage (kg/d) | v | 14 | | | RESRAD-Offsite divides the total fodder ingestion rate of 68 kg/d used in RESRAD to pasture and silage ingestion rate of 14 kg/d and grain ingestion rate of 54 kg/d. |

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Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter In RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|-------------------------------------|-------------------------------------|-------------------------------|---|---|--|
| Grain (kg/d) | v | 54 | | | RESRAD-Offsite divides the total fodder ingestion rate of 68 kg/d used in RESRAD to pasture and silage ingestion rate of 14 kg/d and grain ingestion rate of 54 kg/d. |
| Soil from pasture and silage (kg/d) | v | 0.1 | | | RESRAD-Offsite divides the livestock total soil ingestion rate of 0.5 kg/d used in RESRAD to soil ingestion rate from pasture and silage of 0.1 kg/d and soil ingestion rate from grain of 0.4 kg/d. |
| Soil from grain (kg/d) | v | 0.4 | | | RESRAD-Offsite divides the livestock total soil ingestion rate of 0.5 kg/d used in RESRAD to soil ingestion rate from pasture and silage of 0.1 kg/d and soil ingestion rate from grain of 0.4 kg/d. |
| Milk Cows | | | | | |
| Water (L/d) | | 160 | | | Water kept consistent with the one specified in "Water Use". |
| Pasture and silage (kg/d) | v | 44 | | | RESRAD-Offsite divides the total fodder ingestion rate of 55 kg/d used in RESRAD to pasture and silage ingestion rate of 44 kg/d and grain ingestion rate of 11 kg/d. |

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Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|-------------------------------------|-------------------------------------|-------------------------------|---|--|--|
| Grain (kg/d) | v | 11 | | | RESRAD-Offsite divides the fodder ingestion rate of 55 kg/d used in RESRAD to pasture and silage ingestion rate of 44 kg/d and grain ingestion rate of 11 kg/d. |
| Soil from pasture and silage (kg/d) | v | 0.4 | | | RESRAD-Offsite divides the livestock total soil ingestion rate of 0.5 kg/d used in RESRAD to soil ingestion rate from pasture and silage of 0.4 kg/d and soil ingestion rate from grain of 0.1 kg/d. |
| Soil from grain (kg/d) | v | 0.1 | | | RESRAD-Offsite divides the livestock total soil ingestion rate of 0.5 kg/d used in RESRAD to soil ingestion rate from pasture and silage of 0.4 kg/d and soil ingestion rate from grain of 0.1 kg/d. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|--|---|
| Livestock Feed Factors | | | | | |
| Pasture and silage | | | | | |
| Wet weight crop yield (kg/m ²) | v | 1.1 | | | RESRAD-Offsite divides fodder into two categories: (1) pasture and silage, and (2) grain. Default values for pasture and silage were set to the same as those for fodder in RESRAD. |
| Duration of growing season (y) | v | 0.08 | | | See "wet weight crop yield". |
| Foliage to food transfer coefficient | v | 1 | | | See "wet weight crop yield". |
| Weathering removal constant (1/yr) | v | 20 | | | See "wet weight crop yield". |
| Foliar interception factor for irrigation | v | 0.25 | | | See "wet weight crop yield". |
| Foliar interception factor for dust | v | 0.25 | | | See "wet weight crop yield". |
| Root depth (m) | v | 0.9 | | | RESRAD uses one root depth (0.9 m) for all plant categories. RESRAD-Offsite has different root depths for different plant categories. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|---------------------------------|-------------------------------|---|--|--|
| Grain | | | | | |
| Wet weight crop yield (kg/m ²) | v | 0.7 | | | RESRAD-Offsite divides fodder into two categories: (1) pasture and silage, and (2) grain. Default values for grain were set to the same as those for non-leafy plants in RESRAD. |
| Duration of growing season (y) | v | 0.17 | | | See "wet weight crop yield". |
| Foliage to food transfer coefficient | v | 0.1 | | | See "wet weight crop yield". |
| Weathering removal constant (1/yr) | v | 20 | | | See "wet weight crop yield". |
| Foliar interception factor for irrigation | v | 0.25 | | | See "wet weight crop yield". |
| Foliar interception factor for dust | v | 0.25 | | | See "wet weight crop yield". |
| Root depth (m) | v | 1.2 | | | RESRAD uses one root depth (0.9 m) for all plant categories. RESRAD-Offsite has different root depths for different plant categories. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|--|---|
| Plant Factors | | | | | |
| Fruit, grain, non-leafy | | | | | |
| Wet weight crop yield (kg/m ²) | | (0.7) | 1.751** | TruncLogN(0.56, 0.48, 0.001, 0.999) | |
| Duration of growing season (y) | | 0.17 | | | |
| Foliage to food transfer coefficient | | 0.1 | | | |
| Weathering removal constant (1/yr) | | (20) | 35.70* | Triangular(5.1, 18, 84) | |
| Foliar interception factor for irrigation | | 0.25 | | | |
| Foliar interception factor for dust | | 0.25 | | | |
| Root depth (m) | v | 1.2 | | | RESRAD uses one root depth (0.9 m) for all plant categories. RESRAD-Offsite has different root depths for different plant categories. |
| Leafy vegetables | | | | | |
| Wet weight crop yield (kg/m ²) | | 1.5 | | | |
| Duration of growing season (y) | | 0.25 | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|---------------------------------|-------------------------------|---|--|---|
| Foliage to food transfer coefficient | | 1 | | | |
| Weathering removal constant (1/yr) | | 20 | | | |
| Foliar interception factor for irrigation | | (0.25) | 0.56* | Triangular(0.06, 0.67, 0.95) | |
| Foliar interception factor for dust | | 0.25 | | | |
| Root depth (m) | v | 0.9 | | | RESRAD uses one root depth (0.9 m) for all plant categories. RESRAD-Offsite has different root depths for different plant categories. |
| Inhalation and External Gamma Data | | | | | |
| Inhalation rate (m ³ /y) | | (8400) | 8627* | Triangular(4380, 8400, 13100) | |
| Mass loading for inhalation (g/m ³) | | (0.0001) | 2.45E-05* | Continuous Linear | |
| Mean on-site mass loading (g/m ³) | | (0.0001) | 2.45E-05 | | |
| Indoor dust filtration factor | | (0.4) | 0.55* | Uniform(0.15, 0.95) | |
| External gamma shielding factor | | (0.7) | 0.27** | BoundedLogN(-1.3, 0.59, 0.044, 1) | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|-------------------------------------|-------------------------------|---|---|---|
| External Radiation Shape and Area Factors | | | | | |
| Shape of the plane of the primary contamination | | | | | |
| Circular? | | Yes | | | |
| Polygonal? | | No | | | |
| On-site | | | | | |
| Scale (m) | | | not used | | The receptor is not located on-site. |
| Receptor location X (m): | | | not used | | The receptor is not located on-site. |
| Receptor location Y (m): | | | not used | | The receptor is not located on-site. |
| Off-site | | | | | |
| Scale (m) | v | | 2500 | | |
| Receptor location X (m): | v | | 2410 | | Value determined on the basis of the selected scale, radius of the contaminated zone, and the receptor distance (800 m) from the edge of the contaminated zone. |
| Receptor location Y (m): | v | | 1250 | | Value determined on the basis of the selected scale. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|---|---|
| Occupancy Factors | | | | | |
| Fraction of time spent on primary contamination | | | | | |
| Indoors | | (0.5) | 0 | | The receptor is not located on-site. |
| Outdoors | | 0 | | | The receptor is not located on-site. |
| Fraction of time spent off-site, within the range of radiation emanating from primary contamination (whether cultivated or not) | | | | | |
| Indoors | v | (0) | 0.651* | | Value selected to be consistent with the RESRAD baseline value. |
| Outdoors | v | (0.4) | 0.25 | | Value selected to be consistent with RESRAD baseline value. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|-------------------------------------|-------------------------------|---|--|--|
| Fraction of time spent in farmed areas (including primary and secondary contaminated areas) | | | | | |
| Fruit, grain and non-leafy vegetable fields | v | (0.1) | 0.0625 | | Value was determined by distributing the outdoor time fractions (25%) evenly among the four off-site fields. |
| Leafy vegetable fields | v | (0.1) | 0.0625 | | Value was determined by distributing the outdoor time fractions (25%) evenly among the four off-site fields. |
| Pasture and silage fields | v | (0.1) | 0.7135 | | Time fraction spent on this field was determined by distributing the outdoor time fractions (25%) evenly among the four off-site fields. A house was assumed to be collocated with the field, therefore, the time fraction spent inside the house was added to the time fraction , spent on the field. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|--|---------------------------------|-------------------------------|---|---|--|
| Livestock grain fields | v | (0.1) | 0.0625 | | Value was determined by distributing the outdoor time fractions (25%) evenly among the four off-site fields. |
| Radon Data | | | | | |
| Effective radon diffusion coefficient of cover (m ² /s) | | 2 x 10 ⁻⁶ | not used | | The house is not constructed on the primary contamination area. |
| Effective radon diffusion coefficient of contaminated zone (m ² /s) | | | not used | | Same as above. |
| Effective radon diffusion coefficient of floor (m ² /s) | | 3 x 10 ⁻⁷ | not used | | Same as above. |
| Thickness of floor and foundation (m) | | 0.15 | not used | | Same as above. |
| Density of floor and foundation (m) | | 2.4 | not used | | Same as above. |
| Total porosity of floor and foundation | | 0.1 | not used | | Same as above. |
| Volumetric water content of floor and foundation | | 0.03 | not used | | Same as above. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter In RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---|---------------------------------|-------------------------------|---|--|----------------|
| Depth of foundation below ground level (m) | | -1 | not used | | Same as above. |
| Radon vertical dimension of mixing (m) | | 2 | not used | | Same as above. |
| Building room height (m) | | 2.5 | not used | | Same as above. |
| Building air exchange rate (1/h) | | 0.5 | not used | | Same as above. |
| Building indoor area factor | | 0 | not used | | Same as above. |
| Rn-222 emanation coefficient | | 0.25 | not used | | Same as above. |
| Rn-220 emanation coefficient | | 0.15 | not used | | Same as above. |
| C-14 Data | | | | | |
| Thickness of evasion layer for C-14 in soil (m) | | 0.3 | 0.367* | Triangular(0.2, 0.3, 0.6) | |
| C-14 evasion flux rate from soil | | 7×10^{-7} | | | |
| C-12 evasion flux rate from soil | | 1×10^{-10} | | | |
| Fraction of vegetation carbon absorbed from soil | | 0.02 | | | |
| Fraction of vegetation carbon absorbed from air | | 0.98 | | | |
| User selected inhalation DCF for C-14/DCF for CO2 | | 88.9 | | | |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter in RESRAD-Offsite | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|---------------------------------------|---------------------------------|-------------------------------|---|--|--|
| Mass Fraction of C-12 | | | | | |
| Contaminated soil | | 0.03 | | | |
| Local water | | 0.00002 | | | |
| Fruit, grain, non-leafy vegetables | | 0.4 | | | |
| Leafy vegetables | | 0.09 | | | |
| Pasture and silage | v | 0.09 | | | |
| Grain | v | 0.4 | | | |
| Meat | | 0.24 | | | |
| Milk | | 0.07 | | | |
| Tritium Data | | | | | |
| Humidity in air (g/m ³) | | (8) | 7.243** | TruncLogN(1.98, 0.334, 0.001, 0.999) | |
| Mass fraction of water in | | | | | |
| Fruit, grain and non-leafy vegetables | v | 0.8 | | | In RESRAD, it is hard wired in the code. |
| Leafy vegetable | v | 0.8 | | | In RESRAD, it is hard wired in the code. |
| Pasture and silage | v | 0.8 | | | In RESRAD, it is hard wired in the code. |
| Grain | v | 0.8 | | | In RESRAD, it is hard wired in the code. |

Table A.9 RESRAD-Offsite Baseline Parameter Values and Distributions (continued)

| Input Parameters | New Parameter In RESRAD-Offsite *** | RESRAD-Offsite Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distribution/ Baseline Distributions (if other than NUREG/CR-6697) | Comments |
|------------------|-------------------------------------|-------------------------------|---|--|--|
| Meat | v | 0.6 | | | In RESRAD, it is hard wired in the code. |
| Milk | v | 0.88 | | | In RESRAD, it is hard wired in the code. |

Table A.10 RESRAD-Offsite Baseline Parameter Correlations for Probabilistic Analyses

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|--|---|-------------------------|--|
| Including all the correlations in Table A.8 and the followings | | | |
| K_d of Co-57 in sediment of surface water body | K_d of Co-60 in sediment of surface water body | 0.99 | To ensure the same K_d value was used by different isotopes of the same element. |
| K_d of Co-57 in fruit, grain, non-leafy fields | K_d of Co-60 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Co-57 in leafy vegetable fields | K_d of Co-60 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Co-57 in pasture, silage growing areas | K_d of Co-60 in pasture, silage growing areas | 0.99 | Same as above. |
| K_d of Co-57 in livestock feed grain fields | K_d of Co-60 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Cs-134 in sediment of surface water body | K_d of Cs-137 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Cs-134 in fruit, grain, non-leafy fields | K_d of Cs-137 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Cs-134 in leafy vegetable fields | K_d of Cs-137 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Cs-134 in pasture, silage growing areas | K_d of Cs-137 in pasture, silage growing areas | 0.99 | Same as above. |

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Table A.10 RESRAD-Offsite Baseline Parameter Correlations for Probabilistic Analyses (continued)

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|---|---|-------------------------|----------------|
| K_d of Cs-134 in livestock feed grain fields | K_d of Cs-137 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of I-125 in sediment of surface water body | K_d of I-131 in sediment of surface water body | 0.99 | Same as above. |
| K_d of I-125 in fruit, grain, non-leafy fields | K_d of I-131 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of I-125 in leafy vegetable fields | K_d of I-131 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of I-125 in pasture, silage growing areas | K_d of I-131 in pasture, silage growing areas | 0.99 | Same as above. |
| K_d of I-125 in livestock feed grain fields | K_d of I-131 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Pu-238 in sediment of surface water body | K_d of Pu-239 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Pu-238 in fruit, grain, non-leafy fields | K_d of Pu-239 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Pu-238 in leafy vegetable fields | K_d of Pu-239 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Pu-238 in pasture, silage growing areas | K_d of Pu-239 in pasture, silage growing areas | 0.99 | Same as above. |

Table A.10 RESRAD-Offsite Baseline Parameter Correlations for Probabilistic Analyses (continued)

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|---|---|--------------------------------|-----------------|
| K_d of Pu-238 in livestock feed grain fields | K_d of Pu-239 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Ra-226 in sediment of surface water body | K_d of Ra-228 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Ra-226 in fruit, grain, non-leafy fields | K_d of Ra-228 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Ra-226 in leafy vegetable fields | K_d of Ra-228 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Ra-226 in pasture, silage growing areas | K_d of Ra-228 in pasture, silage growing areas | 0.99 | Same as above. |
| K_d of Ra-226 in livestock feed grain fields | K_d of Ra-228 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Sr-89 in sediment of surface water body | K_d of Sr-90 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Sr-89 in fruit, grain, non-leafy fields | K_d of Sr-90 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Sr-89 in leafy vegetable fields | K_d of Sr-90 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Sr-89 in pasture, silage growing areas | K_d of Sr-90 in pasture, silage growing areas | 0.99 | Same as above. |

Table A.10 RESRAD-Offsite Baseline Parameter Correlations for Probabilistic Analyses (continued)

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|---|---|-------------------------|----------------|
| K_d of Sr-89 in livestock feed grain fields | K_d of Sr-90 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Th-228 in sediment of surface water body | K_d of Th-229 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Th-228 in fruit, grain, non-leafy fields | K_d of Th-229 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Th-228 in leafy vegetable fields | K_d of Th-229 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Th-228 in pasture, silage growing areas | K_d of Th-229 in pasture, silage growing areas | 0.99 | Same as above. |
| K_d of Th-228 in livestock feed grain fields | K_d of Th-229 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Th-228 in sediment of surface water body | K_d of Th-230 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Th-228 in fruit, grain, non-leafy fields | K_d of Th-230 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Th-228 in leafy vegetable fields | K_d of Th-230 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Th-228 in pasture, silage growing areas | K_d of Th-230 in pasture, silage growing areas | 0.99 | Same as above. |

Table A.10 RESRAD-Offsite Baseline Parameter Correlations for Probabilistic Analyses (continued)

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|---|---|--------------------------------|-----------------|
| K_d of Th-228 in livestock feed grain fields | K_d of Th-230 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Th-228 in sediment of surface water body | K_d of Th-232 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Th-228 in fruit, grain, non-leafy fields | K_d of Th-232 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Th-228 in leafy vegetable fields | K_d of Th-232 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Th-228 in pasture, silage growing areas | K_d of Th-232 in pasture, silage growing areas | 0.99 | Same as above. |
| K_d of Th-228 in livestock feed grain fields | K_d of Th-232 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of Tl-201 in sediment of surface water body | K_d of Tl-202 in sediment of surface water body | 0.99 | Same as above. |
| K_d of Tl-201 in fruit, grain, non-leafy fields | K_d of Tl-202 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of Tl-201 in leafy vegetable fields | K_d of Tl-202 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of Tl-201 in pasture, silage growing areas | K_d of Tl-202 in pasture, silage growing areas | 0.99 | Same as above. |

Table A.10 RESRAD-Offsite Baseline Parameter Correlations for Probabilistic Analyses (continued)

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|--|--|--------------------------------|-----------------|
| K_d of Tl-201 in livestock feed grain fields | K_d of Tl-202 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of U-233 in sediment of surface water body | K_d of U-234 in sediment of surface water body | 0.99 | Same as above. |
| K_d of U-233 in fruit, grain, non-leafy fields | K_d of U-234 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of U-233 in leafy vegetable fields | K_d of U-234 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of U-233 in pasture, silage growing areas | K_d of U-234 in pasture, silage growing areas | 0.99 | Same as above. |
| K_d of U-233 in livestock feed grain fields | K_d of U-234 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of U-233 in sediment of surface water body | K_d of U-235 in sediment of surface water body | 0.99 | Same as above. |
| K_d of U-233 in fruit, grain, non-leafy fields | K_d of U-235 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of U-233 in leafy vegetable fields | K_d of U-235 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of U-233 in pasture, silage growing areas | K_d of U-235 in pasture, silage growing areas | 0.99 | Same as above. |

Table A.10 RESRAD-Offsite Baseline Parameter Correlations for Probabilistic Analyses (continued)

| Parameter 1 | Parameter 2 | Correlation Coefficient | Comments |
|--|--|--------------------------------|-----------------|
| K_d of U-233 in livestock feed grain fields | K_d of U-235 in livestock feed grain fields | 0.99 | Same as above. |
| K_d of U-233 in sediment of surface water body | K_d of U-238 in sediment of surface water body | 0.99 | Same as above. |
| K_d of U-233 in fruit, grain, non-leafy fields | K_d of U-238 in fruit, grain, non-leafy fields | 0.99 | Same as above. |
| K_d of U-233 in leafy vegetable fields | K_d of U-238 in leafy vegetable fields | 0.99 | Same as above. |
| K_d of U-233 in pasture, silage growing areas | K_d of U-238 in pasture, silage growing areas | 0.99 | Same as above. |
| K_d of U-233 in livestock feed grain fields | K_d of U-238 in livestock feed grain fields | 0.99 | Same as above. |

Table A.11 RESRAD-BUILD Baseline Parameter Values and Distributions

| Input Parameters | RESRAD-BUILD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|---|------------------------------------|--|---|---|
| Case | | | | |
| Title | Default case for RESRAD-Build | Scenario dependent | | Scenario definition |
| Input File | Site1.bld | Scenario dependent | | |
| Time Parameters | | | | |
| Exposure Duration (d) | 365 | | | |
| Indoor Fraction | 0.5 | 0.651** | Continuous Linear | Not used due to scenario-specific values. |
| Time for Calculation (yr) | 1 | | | |
| Max. No. of Points for Time Integration | 257 | | | |
| Building Parameters | | | | |
| Number of Rooms | 1 | | | |
| Deposition Velocity (m/s) | (0.01) | 3.9E-4** | LogU(2.7E-6, 2.7E-3) | |

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Table A.11 RESRAD-BUILD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD-BUILD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|----------------------------------|------------------------------------|--|---|---|
| Resuspension Rate (1/s) | (5.0E-7) | 1.3E-6** | LogU(2.8E-10, 1.4E-5) | |
| Air Flow | | | | |
| Building Air Exchange Rate (1/h) | (0.8) | 1.52** | TruncLogN(0.4187, 0.88, 0.001, 0.999) | |
| Area of Room (m ²) | (36) | 150 | | Larger than biosolids loading source area. |
| Height (m) | 2.5 | 2.5 | Triangular (2.4, 3.7, 9.1)/No distribution | |
| Radiological Units | | | | |
| Activity | pCi | | | |
| Dose | mrem | | | |
| Receptor Parameters | | | | |
| Receptor No. | 1 | | | |
| Room No. | 1 | | | |
| Time Fraction | 1 | | | |

Table A.11 RESRAD-BUILD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD-BUILD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions/ Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|---|-----------------------------|---|---|---|
| Breathing Rate (m ³ /d) | (18) | 30.5* | Triangular(12, 33.6, 46) | This distribution represents workers in an occupational setting |
| Ingestion Rate (m ² /h) | (0.0001) | 0 | LogU(2.8E-5, 2.9E-4) / No distribution | Good hygiene habit. |
| Location (m) | (1, 1, 1) | (0, 5.6, 1) | | |
| Shielding Parameter | | | | |
| Source 1/ Receptor 1 | | | | |
| Thickness (cm) | 0 | | Triangular (0, 0, 30) | No shielding considered. |
| Density (g/cc) | 2.4 | | Uniform(2.2, 2.6) | |
| Material | Concrete | | | |
| Source Parameters For Source 1 in Room 1 | | | | |
| Type | Volume | | | |
| Direction | (X) | Z | | Only for a line, surface, and volume source. |
| Location (m) | 0, 0, 0 | | | |

Table A.11 RESRAD-BUILD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD-BUILD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|---|------------------------------------|--|---|---|
| Area (m ²) | (36) | 100 | | Parameter used for a volume or an area source. |
| Air Release Fraction | 0.1 | 0.357 | Triangular (1E-6., 0.07, 1) | |
| Direct Ingestion (g/h) | 0 | | | Unit for a point, line, or surface source is (1/h). |
| Number of Wall Regions | 1 | | | Only for a volume source. |
| Material Type | Concrete | | | Only for a volume source. |
| Wall Region Parameters for Region 1 | | | | Only for a volume source. |
| Thickness (cm) | (15) | 50 | | |
| Density (g/cc) | (2.4) | 1.52 | | Density for dry biosolid material. |
| Erosion (cm/d) | 2.4E-8 | 1.87e-7* | Triangular(0,0,5.6E-7) | |
| Radon Diffusion Coefficient (m ² /s) | 2.0E-5 | | | |
| Porosity | (0.1) | 0.4 | | |

Table A.11 RESRAD-BUILD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD-BUILD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|--|-----------------------------|---|--|--|
| Radon Emanation Fraction | 0.2 | | | |
| Radionuclide Concentration (pCi/g) | (1.0 for Co-60) | 1.0 for all the radionuclides of concern | | Total activity (pCi) is needed for a point source. Unit for a line source is pCi/m, for an area source is pCi/m ² . |
| Tritium Parameters | | | | Only for a volume source. |
| Area (m ²) | (36) | 100 | | |
| Wet+Dry Zone Thickness (cm) | (10) | 50 | | |
| Dry Zone Thickness (cm) | 0 | | | |
| Volumetric Water Content | 0.03 | 0.35 | | Value should be less than the total porosity. |
| Water Fraction Available for Evaporation | 1 | 0.75 | Triangular (0.5, 0.75, 1) | |
| Total Porosity of Contaminated Material | (0.1) | 0.4 | | |
| Density of Material (g/cm ³) | (2.4) | 1.52 | | |

Table A.11 RESRAD-BUILD Baseline Parameter Values and Distributions (continued)

| Input Parameters | RESRAD-BUILD Default Values | Baseline Values (if other than the default) | NUREG/CR-6697 Probabilistic Distributions / Baseline Distributions (if other than NUREG/CR-6697) | Comments for Baseline Values/Distributions |
|------------------------------|-----------------------------|---|--|---|
| Humidity (g/m ³) | (8) | 9.8* | Uniform (6.5, 13.1) | This distribution represents humidity inside the building |
| Erosion Rate (cm/d) | 2.4E-8 | 1.87e-7* | Triangular(0,0,5.6E-7) | |
| Direct Ingestion Rate (g/h) | 0 | | | Good hygiene habit. |
| Air Release Fraction | 0.1 | 0.357 | Triangular (1E-6., 0.07, 1) | |
| Deposition velocity (m/s) | (0.01) | 0 | | |

** Geometric mean value of the distribution.

* Mean value of the distribution.

() - RESRAD-BUILD default value not used as baseline value.

Appendix B
RESRAD and RESRAD-BUILD Codes

1 **B.1 Introduction**

2 RESRAD and RESRAD-BUILD are two multimedia computer codes developed by Argonne
3 National Laboratory (Argonne) under sponsorship of the U.S. Department of Energy (DOE) and
4 U.S. Nuclear Regulatory Commission (NRC) for use in evaluating radioactively contaminated
5 sites and buildings, respectively. Both codes have been widely used in the United States and
6 abroad (Yu, 1999). The RESRAD code (Yu et al., 2001) implements the methodology described
7 in DOE's manual for developing residual radioactive material guidelines and calculates radiation
8 dose and excess lifetime cancer risk to a chronically exposed individual at a site with residual
9 contamination. The RESRAD-BUILD code (Yu et al., 1994) is a pathway analysis model
10 designed to evaluate the potential radiological dose to an individual who works or lives in a
11 building contaminated with radioactive material.

12 The RESRAD code focuses on radioactive contaminants in soil and their transport in air, water,
13 and biological media to a single receptor. Nine exposure pathways are considered in RESRAD:
14 direct exposure; inhalation of particulates and radon; and ingestion of plant foods, meat, milk,
15 aquatic foods, water, and soil. Figure 1 illustrates conceptually the exposure pathways
16 considered in RESRAD. RESRAD calculates time-integrated annual dose, soil cleanup
17 guidelines, radionuclide concentrations, and lifetime cancer risks as a function of time. The code
18 estimates at which time the peak dose occurs for each radionuclide and for all radionuclides
19 summed. The RESRAD code permits sensitivity analysis for various parameters. Graphics are
20 used to show the sensitivity analysis and probabilistic results. Text reports are provided for users
21 to view the deterministic and probabilistic analysis results through a text viewer.

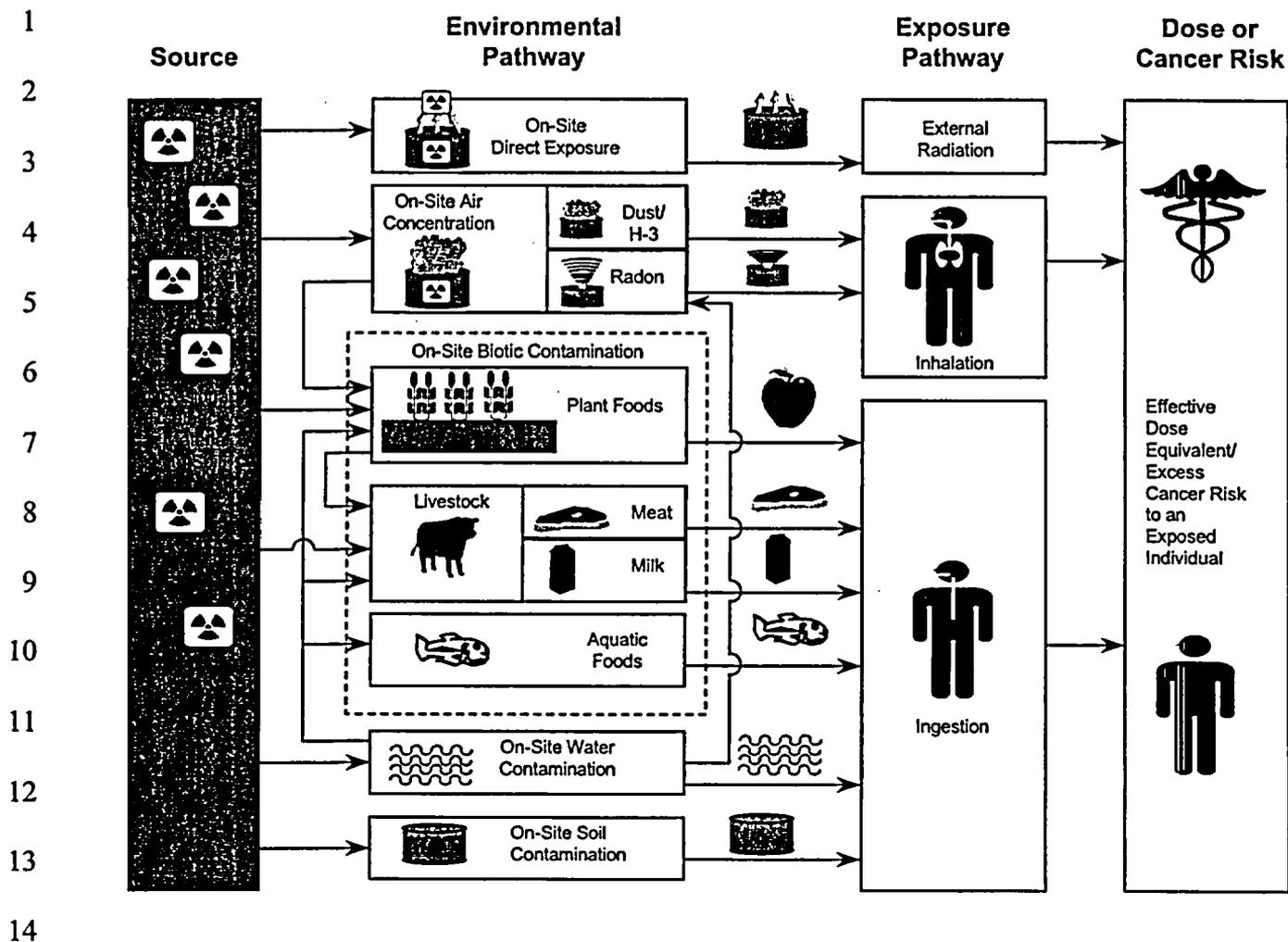
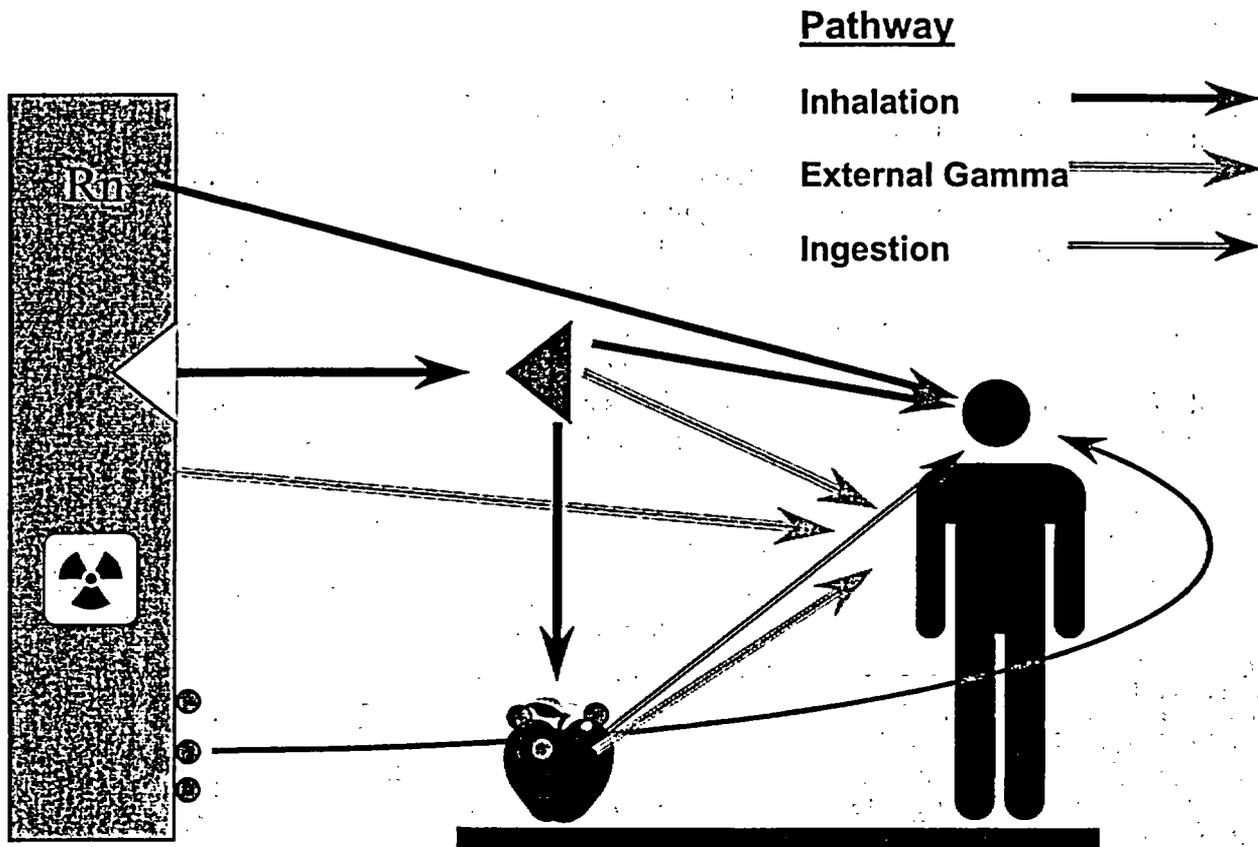


Figure 1. Graphical Representation of Pathways Considered in RESRAD

The RESRAD-BUILD code can model a building with up to 3 rooms or compartments, 10 distinct source locations, 4 source geometries, 10 receptor locations, and 8 shielding materials. A shielding material can be specified between each source-receptor pair for external gamma dose calculations. The RESRAD-BUILD code considers the releases of radionuclides into the indoor air by diffusion, mechanical removal, or erosion. Seven exposure pathways are considered in RESRAD-BUILD: (1) external exposure directly from the source; (2) external exposure to materials deposited on the floor; (3) external exposure due to air submersion; (4) inhalation of airborne radioactive particulates; (5) inhalation of aerosol indoor radon progeny; (6) inadvertent ingestion of radioactive material directly from the sources; and (7) inadvertent ingestion of materials deposited on the surfaces of the building rooms or furniture. Figure 2 conceptually illustrates the exposure pathways considered in RESRAD-BUILD. An air quality model in RESRAD-BUILD evaluates the transport of radioactive dust particulates, tritium, and radon progeny due to (1) air exchange between rooms and with outdoor air, (2) the deposition and resuspension of particulates, and (3) radioactive decay and ingrowth. RESRAD-BUILD has a graphic (3-D display) interface to show the relative positions and shapes of sources and receptors. A text report is provided that contains the deterministic and probabilistic analysis results.

RESRAD-BUILD Pathways



27 **Figure 2. Graphical Representation of Pathways Considered in RESRAD-BUILD**

28
29 The RESRAD and RESRAD-BUILD codes have been widely used, and many supporting
30 documents are available, including benchmarking, verification, and validation documents
31 (Camus et al., 1999; Cheng et al., 1995; Yu, 1999; Yu and Gnanapragasam, 1995; Halliburton
32 NUS Corp., 1994; Faillace et al., 1994; IAEA, 1996; Laniak et al., 1997; Mills et al., 1997; Seitz
33 et al., 1994; Whelan et al., 1999a, 1999b; Gnanapragasam and Yu, 1997a, 1997b; BIOMOVs II,
34 1996; Regens, 1998; Yu et al., 1993a). Both codes have been approved for use by many Federal
35 and State agencies (Yu, 1999).

1 B.2 Probabilistic Modules

2 B.2.1 Overview

3 The probabilistic RESRAD and RESRAD-BUILD codes are extended and enhanced from the
4 deterministic RESRAD and RESRAD-BUILD codes. A pre-processor and a post-processor are
5 incorporated into the RESRAD and RESRAD-BUILD codes to facilitate analysis of the effects of
6 uncertainty in or the probabilistic nature of input parameters in the model. A standard Monte
7 Carlo method or a modified Monte Carlo method, that is, LHS (McKay et al., 1979), can be
8 applied to generate random samples of input parameters. Each set of input parameters is used to
9 generate one set of output results. Figure 3 shows a typical parameter distribution input screen
10 that allows the user to view and edit all currently specified parameter distributions for
11 probabilistic analysis. Once the distribution statistics are specified, the user can click the help
12 button and the distribution will be shown on the screen, as shown in Figure 4.

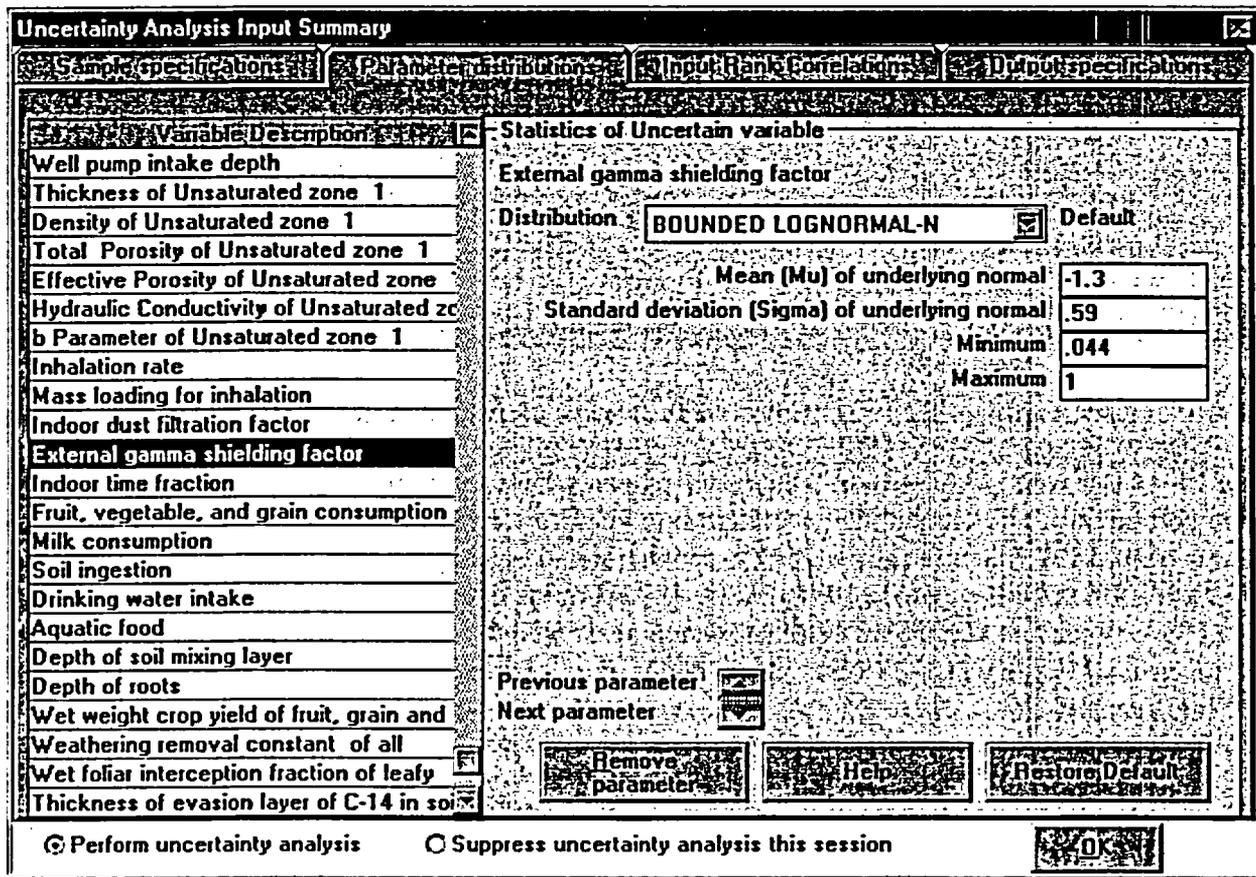


Figure 3. Parameter Distribution Input Screen

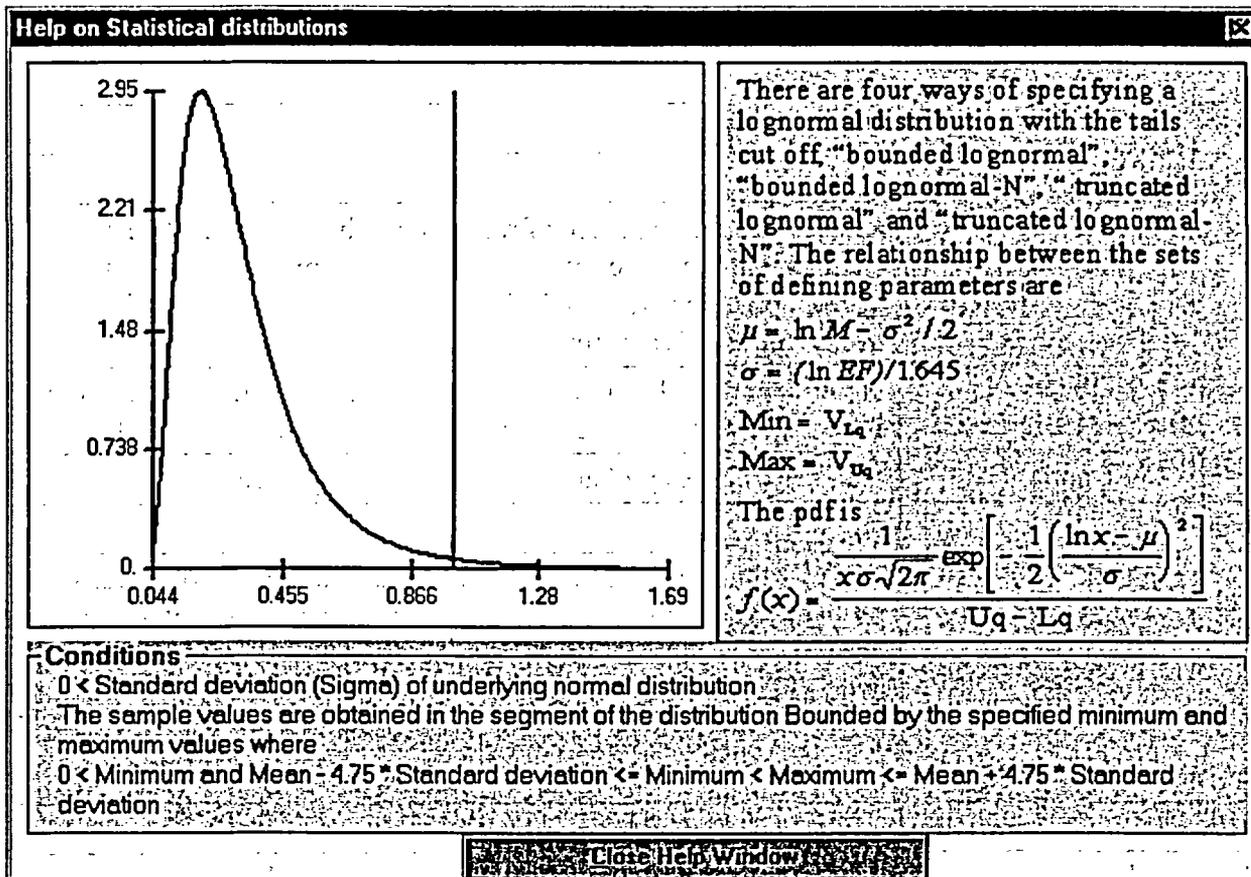


Figure 4. Parameter Distribution Help Screen

1 The results from all input samples are analyzed and presented in a statistical format in terms of
 2 the average value, standard deviation, minimum value, and maximum value. The cumulative
 3 probability distribution of the output is presented in tabular and graphic forms. Scatter plots of
 4 dose against the probabilistic inputs and temporal plots of dose statistics can be viewed.
 5 Regression methods can be applied to find the correlation of the resultant doses with the input
 6 parameters. Partial correlation coefficients (PCCs), partial rank correlation coefficients
 7 (PRCCs), standardized partial regression coefficients (SPRCs), and standardized partial rank
 8 regression coefficients (SPRRCs) are computed and ranked to provide a tool for determining the
 9 relative importance of input parameters in influencing the resultant dose.

10 B.2.2 Sampling Method

11 Samples of the input parameters are generated with an updated version of the LHS computer
 12 code (Iman and Shortencarier, 1984). The uncertainty input form of the user interface collects all
 13 the data necessary for the sample generation and prepares the input file for the LHS code. When
 14 the code is executed (run), the LHS code will be called if the user has requested a
 15 probabilistic/uncertainty analysis. Table B.1 lists the input data and information needed for
 16 sample generation.

Table B.1 Listing of Input Data and Information Needed for Sample Generation

| Input Data | Description |
|---|---|
| <i>Sampling Parameters</i> | |
| Random Seed | Determines the sequence of random numbers generated. This ensures that the same set of observations is produced when the given input file is run on different computers, or when an input file is run at different times on the same computer |
| Number of Observations | Number of sample values to be generated for each input variable for each repetition. The maximum number allowed is 2001 |
| Number of Repetitions | Number of times probabilistic analysis is repeated. |
| <i>Sampling Techniques</i> | |
| Latin Hypercube | The distribution to be sampled is split into a number of equally probable distribution segments, the number being equal to the desired number of observations. A single observation is obtained from each segment |
| Simple Random (Monte Carlo) | The desired number of observations are obtained at random from the whole distribution. |
| <i>Grouping of Observations</i> | |
| Correlated or Uncorrelated | The samples of each variable are grouped together according to the specified correlations. The grouping ensures that the variables for which correlations were not specified are uncorrelated |
| Random | The samples of each variables are grouped together at random. Some pairs of variables may be correlated just by chance. |
| <i>Statistical Distributions</i> | |
| Statistical Distribution and Statistical Parameters | The statistical distribution and its parameters define the set of observations to be generated for a probabilistic variable. The statistical distribution has to be one of the 34 distributions available in the code. The parameters that have to be specified depend on the selected distribution and have to satisfy the conditions of the distribution. These conditions are given in the help screen (Figure 5). The input interface will check that these are satisfied when the user completes inputting the parameters. |
| <i>Input Rank Correlations</i> | |
| Variable 1, Variable 2 | Two variables for which rank correlation is specified |
| Rank Correlation Coefficient | The specified input rank correlation coefficient between two variables. |

1 The input data required for sample generation are divided in three categories: (1) sampling
2 specifications data, (2) statistical distributions data, and (3) input rank correlation data. The
3 input data and information needed for the sample generation include the initial seed value for the
4 random number generator, the number of observations (Nobs), the number of repetitions (Nrep),
5 the sampling technique, the method of grouping the samples generated for the different
6 parameters, the type of statistical distribution for each input parameter, the parameters defining
7 each of the distributions, and any correlations between input parameters.

8 Two sampling techniques are available, LHS and simple random (Monte Carlo) sampling (SRS).
9 The LHS technique is an enhanced, stratified sampling scheme developed by McKay et al.
10 (1979). It divides the distribution of each input parameter into Nobs nonoverlapping regions of
11 equal probability. One sample value is obtained at random (using the current random seed) from
12 each region on the basis of the probability density function for that region. Each time a sample is
13 obtained, a new random seed for use in the next region is also generated by using the current
14 random seed. The sequence of random seeds generated in this manner can be reproduced if there
15 is ever a need to regenerate the same set of samples. After a complete set of Nobs samples of
16 one probabilistic/uncertain parameter has been generated, the same procedure is repeated to
17 generate the samples for the next parameter.

18 The Monte Carlo sampling, or SRS, technique also obtains the Nobs samples at random;
19 however, it picks out each sample from the entire distribution using the probability density
20 function for the whole range of the parameter. Report No. 100 of the International Atomic
21 Energy Agency safety series (IAEA, 1989) discusses the advantages of the two sampling
22 techniques.

23 The Nobs samples generated for each probabilistic/uncertain parameter must be combined to
24 produce Nobs sets of input parameters. Two methods of grouping (or combining) are available
25 — random grouping or correlated/uncorrelated grouping. Under the random grouping, the Nobs
26 samples generated for each parameter are combined randomly to produce (Nobs) sets of inputs.
27 For Nvar probabilistic/uncertain parameters, there are (Nobs!) ways of combining the samples. It
28 is possible that some pairs of parameters may be correlated to some degree in the randomly
29 selected grouping, especially if Nobs is not sufficiently larger than Nvar.

30 In the correlated/uncorrelated grouping, the user specifies the degree of correlation between each
31 correlated parameter by inputting the correlation coefficients between the ranks of the
32 parameters. The pairs of parameters for which the degree of correlation is not specified are
33 treated as being uncorrelated. The code checks whether the user-specified rank correlation
34 matrix is positive definite and suggests an alternative rank correlation matrix if necessary. It then
35 groups the samples so that the rank correlation matrix is as close as possible to the one specified.
36 Both matrices are in the LHS.REP file (which is generated by the RESRAD or RESRAD-BUILD
37 code after the probabilistic analysis is run), and the user should examine the matrices to verify
38 that the grouping is acceptable.

39 Iman and Helton (1985) suggest ways of choosing the number of samples for a given situation.
40 The minimum and maximum doses and risk vary with the number of samples chosen. The
41 accuracies of the mean dose and of the dose values for a particular percentile are dependent on

1 the percentile of interest and on the number of samples. The confidence interval or the (upper or
2 lower) confidence limit of the mean can be determined from the results of a single set of samples.
3 Distribution-free upper (u%, v%) statistical tolerance limits can be computed by using the SRS
4 technique according to the methodology in IAEA Report No. 100 (IAEA, 1989).

5 **B.2.3 Distribution of Parameters**

6 A set of input parameters for uncertainty analysis is chosen through the code's interface. Each
7 parameter chosen must have a probability distribution assigned to it and may be correlated with
8 other input parameters included in the uncertainty analysis. Thirty-four different distribution
9 types are available for selection. The statistical parameters required depend on the distribution,
10 and the appropriate input fields are displayed when a distribution is selected. The conditions to
11 be satisfied by these statistical parameters are given in the help screen (Figure 4). The interface
12 checks whether the statistical parameters satisfy the conditions when the user inputs them, and it
13 red flags any statistical parameters that violate the conditions. Different distribution types and
14 the required distribution data can be found in NUREG/CR-6697 (Yu et al., 2000). The input
15 parameters can be correlated by specifying a pairwise rank correlation matrix. The induced
16 correlation is applied to the ranks of the parameters; hence, the name "rank correlation."

17 **B.2.4 Probabilistic Results**

18 The results of the probabilistic analysis handled by the post-processor are presented in the
19 summary text files.

20 The interactive output provides graphical and tabular results for peak pathway doses, for peak
21 nuclide doses, and for dose at user times for any pathway-nuclide combination in RESRAD. In
22 RESRAD-BUILD, it provides results for dose to each receptor, via each or all pathways, at each
23 user time, from either each or all nuclides in each source or from all sources. The tabular results
24 provided are the minimum, maximum, mean, standard deviation, and the percentile values in
25 steps of 5%, as well as their 95% confidence range where appropriate. Scatter against the
26 probabilistic inputs and cumulative probability plots are available in both RESRAD and
27 RESRAD-BUILD. In addition, RESRAD has temporal plots of the mean, 90%, and 95% of total
28 dose.

29 Printable results are available in the text files. In each case, the file contains statistical data for a
30 collection of resultant doses as a function of user time, pathway, radionuclide, source, and
31 receptor, as appropriate. The statistical data provided for the resultant dose include the average
32 value, standard deviation, minimum value, and maximum value. The cumulative probability
33 distribution of the resultant dose is presented in a tabular form in terms of percentile values in
34 steps of 2.5%. Separate tables are provided for each repetition in RESRAD, giving the
35 minimum, maximum, mean, median, and the 90th%, 95th%, 97.5th%, and the 99th% of total
36 dose (summed over nuclides and pathways) at graphical times. A single table summarizes the
37 peak of the mean total dose for all observations and the time of the same for each repetition.

1 Tabulations are provided of the correlation of the resultant doses with the input parameters as
2 computed by regression methods. The input parameters are ranked according to their relative
3 importance and their contribution to the overall uncertainty. The parameter ranks and
4 correlations are discussed in detail in NUREG/CR-6676 (Kamboj et al., 2000).

5 Although the RESRAD and RESRAD-BUILD codes provide easy to use, user-friendly interfaces
6 for probabilistic analysis, users need to employ this feature with caution. The saying "garbage in,
7 garbage out" is not only true for the deterministic codes, it is especially true for the probabilistic
8 codes. As a matter of fact, because there are more parameters (such as distribution characteristic
9 parameters) in the probabilistic codes, users need to obtain more information on the site and
10 perhaps need to better characterize the site to ensure properly modeling.

11 The probabilistic versions of the RESRAD and RESRAD-BUILD codes provide tools for
12 studying the uncertainty in dose assessment caused by uncertainty in the input parameters.
13 Although the codes are designed to be user-friendly, they must be used with caution, and it is
14 important that users be properly trained and that sufficient site-specific (probabilistic) data be
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Appendix C
Incinerator Control/Release Fractions

1 C.1 Introduction

2 Several types of incineration systems are in use for treating wastewater sludges (Brunner, 1991;
3 Tchobanoglous and Burton, 1991). In decreasing order of prevalence in the industry, there are:
4 multiple hearth furnaces; fluid bed furnaces; conveyer furnaces; and cyclone furnaces. These
5 operate at different temperatures, and give rise to differing amounts of volatilization of
6 radionuclide contaminants. Incinerators operated to manage wastewater sludges are usually
7 operated below the clinker temperature (the temperature at which ash fusion occurs), which is
8 about 1800 °F (980 °C) (Brunner, 1991). Formation of clinkers may interfere with the operation
9 of multiple hearth and fluid bed incinerators (Brunner, 1991). Consequently, an incinerator
10 system for sludges can be expected to produce an ash waste rather than a melt waste.

11 C.2 Regulatory Values for Release Fraction

12 EPA (1988) described potential offsite releases from an incinerator, and based the volatility
13 fractions for radionuclides on the recommendations of Oztunali and Roles (1984). These
14 recommendations are presented in Table C.1. In this table, the decontamination factor is defined
15 as the mass rate of contaminant in the feed divided by the mass rate of contaminant that exits the
16 stack and is available for transport to an offsite receptor. The release fraction is defined as the
17 inverse of the decontamination factor, so that it represents the fraction of the feed that exits the
18 stack.

19 These factors were estimated using various means described by Oztunali and Roles (1984). The
20 decontamination factor of 400 for particulates was used for all radionuclides except the ones
21 specifically identified in Table C.1. This decontamination factor, in turn, was derived from data
22 in a 1977 publication on fly ash releases from various kinds of incinerators. Oztunali and Roles
23 (1984) noted that even in the mid-1980s, these rates would exceed even the most minimal air
24 pollutant standards for particulates. For the decontamination factors for the remaining
25 radionuclides, Oztunali and Roles (1984) cite the earlier data compilation of Wild et al. (1981).
26 In turn, Wild et al. (1981) state that the value for iodine was based on data for specific fluid bed
27 equipment (Aerojet Company, 1975; 1979). Wild et al. (1981) also clearly acknowledge that the
28 values for H-3 and C-14 are purely arbitrary, owing to a lack of data.

29 This review of the genesis of these release fraction numbers suggests that they are either founded
30 on out-of-date air emissions technology or are unsupported by data. Consequently, these values
31 are not recommended for further use.

32 C.3 Assessment of Aaberg et al (1995a)

33 Aaberg et al. (1995a) conducted a dose assessment of workers and the public from operation of a
34 generic commercial rotary kiln incinerator, used for mixed waste – co-mingled DOE waste and
35 commercial waste. Throughput of the facility was assumed to be 30,000 t yr⁻¹ for the base case,
36 with a secondary case of 150,000 t yr⁻¹ to represent a larger incinerator. Releases from the
37 incinerator were calculated using the CAP88-PC computer program. A number of the dispersion
38 and food chain parameters were taken to be CAP88-PC defaults.

1 As part of the assessment, the authors conducted an evaluation of contaminant partitioning. One
2 step in that evaluation was a literature search of partitioning values in incinerators. Values were
3 identified for the elements shown in Table C.2. Aaberg et al. noted that there were
4 inconsistencies in methods and reporting, and that none of the extant data were considered
5 complete or satisfactory. They do not provide specific citations for the values given in
6 Table C.2, nor do they identify the types of equipment and operating conditions represented by
7 the data. As a result, it is not clear how broad the conditions are that lead to these data. They
8 state that because of the inadequacies of the data sets, they investigated the thermodynamics of
9 the system. In this way, they developed a set of self-consistent partitioning values to be used in
10 their risk assessment, Table C.3. They do not describe in detail the basis for these values, but
11 the foundation appears to be primarily thermodynamic modeling based on free energy
12 calculations. The values appear to be for a high-temperature furnace, since the bottoms are
13 described as slag rather than ash.

14 Additional information on the basis for the partitioning assumptions given in Table 3 is provided
15 by Aaberg et al. (1995b). This paper is described as an "extension of the technical analysis"
16 documented by Aaberg et al. (1995a), and it is assumed that the partitioning methodology is
17 similar in the two reports. Aaberg et al. (1995b) assumed thermodynamic equilibrium to exist in
18 the thermal processing apparatus, and considered an oxygen-rich rotary kiln and an oxygen-
19 deficient plasma arc furnace. Partitioning between gas and solid phases was assumed to be a
20 function of vapor pressure and its concentration of the contaminant. Conditions in the
21 incinerator were assumed to be 1000-2000 K, so the incinerator would have produced a slag.
22 The model was run in the computer code HSC Chemistry for Windows, assuming ideal solution
23 behavior. Additional details of the calculational approach apparently are given by Burger (1995),
24 but this report is not readily available.

25 Aaberg et al. (1995a) noted that the stack release values used in this study were based on generic
26 assumptions about air pollution control equipment used at the facility, and that the use of specific
27 equipment might alter these assumptions. The assumed removal efficiency of the equipment was
28 stated to be 5 percent for carbon, 10 percent for hydrogen, and 99.95 percent for uranium,
29 thorium, and other refractory metals.

30 **C.4 Review by Liekhus et al. (1997)**

31 Liekhus et al. (1997) conducted a review of the empirical bases for partitioning between waste
32 streams in high-temperature treatment equipment. The review considered both equipment for
33 combustion, in which excess air leads to oxidizing conditions during reaction, and for pyrolysis,
34 in which reactions occur in an oxygen deficient condition. Many of the applications were for
35 very high temperature technology, above the ash clinker temperature. That is, the bottoms waste
36 stream in most of these applications is a melt rather than an ash. As noted above, municipal
37 wastewater combustion typically is kept below the clinker temperature to prevent clogging the
38 equipment. Consequently, many of the data cited may not be directly applicable to wastewater
39 combustors, and it is not clear how large the differences may be. As a result, for the purposes of
40 the current report, only the portions of Liekhus et al. (1997) related to ash-generating systems
41 that use excess air are presented in detail here.

1 Liekhus et al. (1997) (page C-178) noted that there has never been an explicit partitioning study
2 where the known amounts of metals and radionuclides are simultaneously reported in feed,
3 bottoms ash, fly ash, and off gas. However, they cite a number of more limited sets of data that
4 partly describe the partitioning between feed material and ash. A summary of data is presented in
5 Table D-4 for the mass percent of contaminants in feed that partitioned to bottom ash. A similar
6 summary is presented in Table C.5 for data on fractions captured by the air pollution control
7 systems of the incinerators. Empty spaces in the tables indicate materials that were not included
8 in the original studies. These tables represent a variety of experimental conditions that are
9 described in detail by Liekhus et al. (1997). This variety of conditions accounts for some of the
10 spread in values in the table, but it also makes it difficult to derive general information from the
11 data.

12 **C.5 503 Metals Partitioning Information**

13 Table C.6 lists the control efficiencies for Cleveland's sludge incinerators for the 503 metals, as
14 reported by T. Lenhart of Northeast Ohio Regional Sewer District (NEORD) (Lenhart, 2001).
15 These efficiencies were established in formal testing as required by the 503 regulations for the
16 year 2000. NEORD believes they are representative of sludge incinerators nationwide. The
17 Westerly and Southerly incinerators are multiple hearth incinerators burning dewatered sludge
18 cake. Easterly is a fluidized bed burning skimmings. Control efficiency is the percentage of
19 metal in the sludge feed that does not leave the stack. NEORD states that the control value may
20 be indicative of either the failure to volatilize or the removal by air pollution control devices.
21 These values support the information from Aaberg that describes control efficiencies of greater
22 than 95% for most metals.

23 **C.6 Summary**

24 The literature on partitioning of contaminants between waste streams from an incinerator is
25 remarkably sparse. Few complete data sets are available for comparisons with models. The
26 most complete set of values for use in model inputs appears to be those reported by Aaberg et al.
27 (1995a) in their dose assessment of incinerator operation. These values have two drawbacks for
28 use in the current analysis. The basis for the calculation was a rotary kiln system operating at
29 higher temperatures than are typical of wastewater sludge. Also, the details of the analysis are
30 not well described, and must be deduced from related publications from the same research group
31 at about the same time. Despite these problems, these values are the only self consistent and
32 reasonably complete set in the literature. As a result, the values of Aaberg et al. (1995a) have
33 been adopted for use in assessing wastewater sludge incineration.

1 **Table C.1 Volatilization Fractions Recommended by Oztunali and Roles (1984)**
 2 **for the Reference Pathological and Hazardous Waste Incinerators**

| 3 Nuclide | 4 Decontamination Factor | 5 Release Fraction |
|------------------|---------------------------------|---------------------------|
| 6 H-3 | 1.1 | 0.9 |
| 7 C-14 | 1.3 | 0.75 |
| 8 Cl-36 | 100 | 0.01 |
| 9 Tc-99 | 100 | 0.01 |
| 10 Ru-103 | 100 | 0.01 |
| 11 Ru-106 | 100 | 0.01 |
| 12 I-125 | 100 | 0.01 |
| 13 I-129 | 100 | 0.01 |
| 14 All others | 400 | 0.0025 |

15 **Table C.2 Summary Range of Partitioning Values Found in the Literature by**
 16 **Aaberg et al. (1995a)**

| 17 Element | 18 Bottom Ash or Slag | 19 Fly Ash | 20 Stack Emissions |
|-------------------|------------------------------|-------------------|---------------------------|
| 21 Cs | 60-90 | 30-50 | 0.2 |
| 22 Sr | 45-95 | 2-20 | 0.05 |
| 23 Zr | 60-95 | 40-60 | <1 |
| 24 Co | 70-98 | 12-20 | 0.5 |
| Zn | 30-70 | 20-60 | 1 |
| Sb | 10-80 | 20-80 | 1 |
| U | 65-100 | 1-35 | <1 |

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Table C.3 Element Partitioning Assumptions Used by Aaberg et al. (1995a)

| Element | Fl/ASH | Slope | Stock |
|---------|--------|-------|--------|
| H | 0.1 | 0 | 0.9 |
| Be | 0.1 | 0.90 | 0.001 |
| C | 0.02 | 0.03 | 0.95 |
| Na | 0.1 | 0.90 | 0.001 |
| P | 0.13 | 0.85 | 0.02 |
| S | 0.65 | 0.30 | 0.05 |
| Sc | 0.05 | 0.95 | 0.0005 |
| V | 0.1 | 0.90 | 0.001 |
| Cr | 0.35 | 0.65 | 0.002 |
| Mn | 0.35 | 0.65 | 0.002 |
| Fe | 0.45 | 0.55 | 0.005 |
| Co | 0.34 | 0.65 | 0.01 |
| Ni | 0.4 | 0.60 | 0.005 |
| Zn | 0.49 | 0.50 | 0.01 |
| Ge | 0.5 | 0.50 | 0.001 |
| As | 0.5 | 0.50 | 0.005 |
| Se | 0.8 | 0.10 | 0.10 |
| Sr | 0.05 | 0.95 | 0.0001 |
| Y | 0.05 | 0.95 | 0.0005 |
| Zr | 0.05 | 0.95 | 0.0005 |
| Nb | 0.05 | 0.95 | 0.001 |
| Tc | 0.50 | 0.40 | 0.10 |
| Ru | 0.59 | 0.40 | 0.01 |
| Ag | 0.20 | 0.80 | 0.001 |
| Sn | 0.02 | 0.98 | 0.001 |
| Sb | 0.43 | 0.55 | 0.02 |
| Te | 0.49 | 0.50 | 0.01 |
| I | 0.68 | 0.02 | 0.30 |
| Cs | 0.20 | 0.80 | 0.002 |
| Ce | 0.05 | 0.95 | 0.001 |
| Pm | 0.05 | 0.95 | 0.001 |
| Sm | 0.05 | 0.95 | 0.001 |
| Eu | 0.05 | 0.95 | 0.001 |
| Hg | 0.90 | 0.05 | 0.05 |
| Bi | 0.70 | 0.30 | 0.005 |
| Ra | 0.10 | 0.90 | 0.0005 |
| Th | 0.02 | 0.98 | 0.0005 |
| U | 0.02 | 0.98 | 0.0005 |
| Np | 0.02 | 0.98 | 0.0005 |
| Pu | 0.02 | 0.98 | 0.0005 |
| Am | 0.02 | 0.98 | 0.0005 |

1 **Table C.4 Summary of Data Presented by Liekhus et al. (1997) for Normalized**
 2 **Mass Percent of Feed Element in Bottom Ash (information adapted**
 3 **from Table 4-11 of Liekhus et al.). Values are rounded to the nearest**
 4 **percent.**

| Element | ACERC | SWIFT | BRATR | APTUS |
|---------|-------|----------------|-----------------|------------------|
| Ag | | 24-93 | | 90-96 |
| As | | 80-99 | 70-97 | 24-75 |
| Ba | | 98-99 | 70-98 | 97-98 |
| Be | | | | 99-100 |
| Bi | | | 70-72 | 98-99 |
| Ca | | | | 0-100 |
| Cd | 18-45 | 8-34 | 22-91 | 81-94 |
| Cr | 25-58 | 96-99 | 68-91 | 99-100 |
| Cu | | | 75-99 | 88-93 |
| Hg | | 0 for all runs | 31-92 | 16-27 |
| Mg | | | 99-100 | 99-100 |
| Mn | | | | 98-99 |
| Ni | | 98-99 | 88-129 | 99-100 |
| Pb | 22-62 | 13-62 | 35-99 | 17-18 |
| Sb | | 98-100 | | 46-53 |
| Se | | | | 93-99 |
| Sr | | | 99 for two runs | 80-87 |
| Te | | | | 100 for two runs |
| Tl | | 13-29 | | 30-98 |
| Zn | | | 48-98 | 15-37 |

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1. Advanced Combustion Engineering Research Center, Bench Scale Rotary Reactor, summary of data from 7 runs.
 2. Solid Waste Incineration Test Facility, Rotary Kiln System, summary of data from 9 runs.
 3. US EPA Incineration Research Facility. Rotary Kiln Incinerator, summary of data for 10 runs.
 4. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, Kansas, summary of data from 2 runs.

1 **Table C.5 Summary of Data Presented by Liekhus et al. (1997) for Normalized**
 2 **Mass Percent of Feed Element Captured by the Air Pollution Control**
 3 **System (information adapted from Table 4-12 of Liekhus et al.).**
 4 **Values have been rounded to the nearest percent**

| Element | SWUST | EPA IRF | APTUS |
|---------|------------------|-------------------|---------------|
| Ag | 7-100 | | 4-9 |
| As | 1-100 | 5-30 | 25-77 |
| Ba | 1-100 | 3-11 | 2-3 |
| Be | | | 0-1 |
| Bi | | 28-30 (2 runs) | 1-2 |
| Ca | | | 0-100 |
| Cd | 74-100 | 9-78 | 6-18 |
| Cr | 1-100 | 9-32 | 0-1 |
| Cu | | 1-15 | 8-11 |
| Hg | 100 for all runs | 7-97 | 73-84 |
| Mg | | 0.07-0.2 (2 runs) | 0-1 |
| Mn | | | 1-2 |
| Ni | 1-100 | 11-30 (2 runs) | 0-1 |
| Pb | 38-100 | 1-65 | 81-82 |
| Sb | 0-100 | | 47-54 |
| Se | | | 0-7 |
| Sr | | 0.3-0.6 (2 runs) | 13-19 |
| Te | | | 0 (both runs) |
| Tl | 71-100 | | 1-69 |
| Zn | | 1-5 (2 runs) | 63-85 |

5. Solid Waste Incineration Test Facility, Rotary Kiln System, summary of data from 9 runs.
 6. EPA Incineration Research Facility. Rotary Kiln Incinerator, summary of data for 8 runs.
 7. APTUS Hazardous Waste Rotary Kiln Incinerator, Coffeyville, Kansas, summary of data from 2 runs.

30 **Table C.6 Average Control Efficiencies for the Easterly, Southerly and Westerly**
 31 **Incinerators**

| Plant | Arsenic | Cadmium | Chromium | Lead | Nickel |
|-----------|---------|---------|----------|--------|--------|
| Easterly | 0.9174 | 0.8920 | 0.9476 | 0.9446 | 0.9647 |
| Southerly | 0.9951 | 0.9570 | 0.9992 | 0.9981 | 0.9984 |
| Westerly | 0.9787 | 0.9401 | 0.9994 | 0.9734 | 0.9944 |

1 C.7 References

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Appendix D
Conversion Between Radon Doses and
Working Level Concentrations

1 **D.1 Dose- and Concentration-To-Source Ratios in Working Level**
 2 **Units**

3 This subsection describes the conversion between radon-pathway doses and Working Level
 4 concentration levels in the onsite resident and POTW loading worker scenarios. For Rn-220 and
 5 Rn-222 progeny, the conversion between the two dosimetric quantities committed effective dose
 6 equivalent (CEDE) and Working Level Months (WLM) used by RESRAD and
 7 RESRAD-BUILD is given by the equation

8
$$D_{\text{mrem CEDE}} = D_{\text{WLM}} \times [\text{Conversion Factor}] \quad (\text{D.1})$$

9 with the conversion factors listed in Table D.1.

11 **Table D.1 Radon Dosimetry Conversions Used in RESRAD and RESRAD-BUILD**

12

| Radon Isotope | Indoor or Outdoor | Conversion Factor (mrem CEDE per WLM) |
|---------------|-------------------|--|
| Rn-220 | Indoor | 150 |
| | Outdoor | 250 |
| Rn-222 | Indoor | 760 |
| | Outdoor | 570 |

15 The conversion between dose in WLM and the concentrations of radon progeny in Working
 16 Levels (WL) is given by the equation:
 17

18
$$D_{\text{WLM}} = 51.5 \times \text{time fraction} \times C_{\text{WL}} \quad (\text{D.2})$$

19 where time fraction is the fraction of time spent indoors or outdoors at the site. The values used
 20 in this assessment, listed in Appendix A, have been reproduced in Table D.2, along with the
 21 conversion factors derived from using Equation (D.1).
 22

23 **Table D.2 Time Fractions and WL to WLM Conversion Factors**

24

| Scenario | Indoor or Outdoor | Time Fraction | Conversion Factor (WLM per WL) |
|---------------------|-------------------|---------------|-----------------------------------|
| Onsite Resident | Indoor | 0.651 | 33.5 |
| | Outdoor | 0.25 | 12.9 |
| POTW Loading Worker | Indoor | 0.228 | 11.7 |

26
27

1 The conversion from dose to pCi/l of Rn-220 or Rn-222 is not straightforward, since RESRAD
 2 and RESRAD-BUILD calculate directly the individual concentrations of radon daughter products
 3 (rather than using the equilibrium fraction approach). For the Onsite Resident, the parameters
 4 that determine this conversion were not varied, so the conversion factor is a constant 6.9×10^{-3}
 5 WL per pCi Rn-222/l. For the POTW Loading Worker, the conversion factor may range from
 6 $0.5 \times 10^{-3} \sim 3 \times 10^{-3}$ WL per pCi/l for both Rn-220 and Rn-222. More detailed formulae for this
 7 conversion are given in the following subsection.

8 **D.2 Development of Publicly Owned Treatment Works Loading** 9 **Worker Radon Dose Fitting Functions**

10 For the POTW Loading Worker subscenario, the approximate expressions for the DSR as a
 11 function of building parameters developed in Chapter 7 were derived from parameter sensitivity
 12 analyses of the RESRAD-BUILD code. It should be emphasized that these fitting formulae are
 13 only valid under changes in the source dimensions, the room dimensions, the source bulk density,
 14 and the air exchange rate. *They will NOT necessarily be valid if other baseline parameters*
 15 *(listed in Appendix A) are changed.*

16 The first quantity calculated by RESRAD-BUILD is the air concentration of radon isotopes. For
 17 a unit concentration source, following fitting formulae were derived for the CSR ratio, where the
 18 concentration is the activity in pCi/l of Rn-220 or Rn-222:

$$19 \quad CSR_{\text{pCi Rn-220/l per pCi/g Th-228}} \approx 720 \times (45 + \lambda_x)^{-1} r_{\text{sludge}} A_{\text{sludge}} / V_{\text{room}} \quad (\text{D.3})$$

$$20 \quad CSR_{\text{pCi Rn-222/l per pCi/g Ra-226}} \approx 1.49 \times (0.008 + \lambda_x)^{-1} r_{\text{sludge}} V_{\text{sludge}} / V_{\text{room}} \quad (\text{D.4})$$

21 Here λ_x is the room air exchange rate in exchanges per hour, r_{sludge} is the bulk density of the
 22 sludge in grams per cubic cm, V_{sludge} is the total volume of sludge in the room in cubic meters,
 23 and V_{room} is the total volume of the room in cubic meters, and A_{sludge} is the *surface area* of the pile
 24 of sludge in the room in square meters. The formula are accurate to a few percent.¹

25 The following fitting formulae were derived converting between concentrations in WL and
 26 concentrations in pCi/l were derived from sensitivity analyses of the baseline RESRAD-BUILD
 27 calculation:

$$28 \quad C_{\text{WL Rn-220}} \approx C_{\text{pCi Rn-220/l}} \times 0.00417 \times (1.25 h_{\text{room}}^{-0.77} + \lambda_x)^{-1} \quad (\text{D.5})$$

$$29 \quad C_{\text{WL Rn-222}} \approx C_{\text{pCi Rn-222/l}} \times 0.00625 \times (2.69 h_{\text{room}}^{-0.13} + \lambda_x)^{-1} \quad (\text{D.6})$$

30 where h_{room} is the height of the room in meters.

1 The motivation for the $(\text{constant} + \lambda_x)^{-1}$ formulae is that for multiple 1st order kinetic processes (such as are assumed for decay, air exchange, plate-out, etc.), the kinetic *rates* are additive. Furthermore, the equilibrium concentration of a kinetic process will be proportional to the source injection rate and inversely proportional to the sum of the kinetic rates.

1 Combining equations (D.3)-(D.6) leads to the following Concentration-to-Source-Ratios:

2
$$CSR_{WL \text{ Rn-220 per pCi/g Th-228}} \approx 3.00 \times (45 + \lambda_x)^{-1} \times (1.25 h_{\text{room}}^{-0.77} + \lambda_x)^{-1} r_{\text{sludge}} A_{\text{sludge}} / V_{\text{room}} \quad (\text{D.7})$$

3
$$CSR_{WL \text{ Rn-222 per pCi/g Ra-226}} \approx 0.00931 \times (0.008 + \lambda_x)^{-1} \times (2.69 h_{\text{room}}^{-0.13} + \lambda_x)^{-1} r_{\text{sludge}} V_{\text{sludge}} / V_{\text{room}} \quad (\text{D.8})$$

4 Furthermore, using equation (D.2) leads to the Dose-to-Source-Ratios in terms of WLM:

5
$$DSR_{WLM \text{ Rn-220 per pCi/g Th-228}} \approx 35.2 \times (45 + \lambda_x)^{-1} \times (1.25 h_{\text{room}}^{-0.77} + \lambda_x)^{-1} r_{\text{sludge}} A_{\text{sludge}} / V_{\text{room}} \quad (\text{D.9})$$

6
$$DSR_{WLM \text{ Rn-222 per pCi/g Ra-226}} \approx 0.109 \times (0.008 + \lambda_x)^{-1} \times (2.69 h_{\text{room}}^{-0.13} + \lambda_x)^{-1} r_{\text{sludge}} V_{\text{sludge}} / V_{\text{room}} \quad (\text{D.10})$$

7 Finally, using equation (D.1) leads to the radon term of the formulae in Chapter 7:

8
$$DSR_{\text{mrem(radon) per pCi/g Th-228}} \approx 5290 \times (45 + \lambda_x)^{-1} \times (1.25 h_{\text{room}}^{-0.77} + \lambda_x)^{-1} r_{\text{sludge}} A_{\text{sludge}} / V_{\text{room}} \quad (\text{D.11})$$

9
$$DSR_{\text{mrem(radon) per pCi/g Ra-226}} \approx 83.1 \times (0.008 + \lambda_x)^{-1} \times (2.69 h_{\text{room}}^{-0.13} + \lambda_x)^{-1} r_{\text{sludge}} V_{\text{sludge}} / V_{\text{room}} \quad (\text{D.12})$$

10 These formulae can be used to estimate site-specific radon concentrations and doses for the
11 POTW Loading Worker scenario.

Appendix E
Probabilistic Percentiles for
Dose-to-Source Ratios

- 1 This Appendix contains the probabilistic results for the Dose-to-Source Ratios for each scenario.
- 2 Note that the scaling factors to account for multiple years of application and waiting periods were
- 3 provided in Chapter 6.

Table E.1 Onsite Resident DSR Percentiles

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 3.64e-03 | 3.97e-03 | 4.26e-03 | 4.47e-03 | 4.67e-03 | 4.83e-03 | 5.04e-03 | 5.22e-03 | 5.39e-03 | 5.56e-03 | 5.77e-03 | 5.98e-03 | 6.21e-03 | 6.51e-03 | 6.87e-03 | 7.22e-03 | 7.70e-03 | 8.65e-03 | 1.06e-02 | 6.25e-03 |
| Am-241 | 2.54e-04 | 2.93e-04 | 3.27e-04 | 3.57e-04 | 3.84e-04 | 4.15e-04 | 4.39e-04 | 4.68e-04 | 4.99e-04 | 5.26e-04 | 5.54e-04 | 5.86e-04 | 6.28e-04 | 6.68e-04 | 7.22e-04 | 7.98e-04 | 8.88e-04 | 1.07e-03 | 1.43e-03 | 7.60e-04 |
| Be-7 | 7.44e-05 | 7.83e-05 | 8.14e-05 | 8.43e-05 | 8.70e-05 | 8.96e-05 | 9.24e-05 | 9.50e-05 | 9.79e-05 | 1.01e-04 | 1.04e-04 | 1.08e-04 | 1.11e-04 | 1.16e-04 | 1.21e-04 | 1.27e-04 | 1.35e-04 | 1.46e-04 | 1.63e-04 | 1.07e-04 |
| C-14 | 3.18e-04 | 4.17e-04 | 5.10e-04 | 5.98e-04 | 7.07e-04 | 8.18e-04 | 9.30e-04 | 1.05e-03 | 1.20e-03 | 1.35e-03 | 1.56e-03 | 1.87e-03 | 2.16e-03 | 2.69e-03 | 3.45e-03 | 4.45e-03 | 6.15e-03 | 9.83e-03 | 2.42e-02 | 7.76e-03 |
| Ce-141 | 5.51e-05 | 5.78e-05 | 6.00e-05 | 6.20e-05 | 6.40e-05 | 6.59e-05 | 6.77e-05 | 6.97e-05 | 7.17e-05 | 7.38e-05 | 7.61e-05 | 7.87e-05 | 8.14e-05 | 8.46e-05 | 8.83e-05 | 9.28e-05 | 9.84e-05 | 1.06e-04 | 1.19e-04 | 7.85e-05 |
| Co-57 | 4.47e-04 | 4.76e-04 | 4.99e-04 | 5.16e-04 | 5.34e-04 | 5.52e-04 | 5.70e-04 | 5.88e-04 | 6.07e-04 | 6.24e-04 | 6.44e-04 | 6.65e-04 | 6.89e-04 | 7.18e-04 | 7.50e-04 | 7.87e-04 | 8.43e-04 | 9.13e-04 | 1.03e-03 | 6.66e-04 |
| Co-60 | 1.78e-02 | 1.89e-02 | 1.98e-02 | 2.06e-02 | 2.13e-02 | 2.21e-02 | 2.27e-02 | 2.33e-02 | 2.40e-02 | 2.48e-02 | 2.55e-02 | 2.64e-02 | 2.73e-02 | 2.83e-02 | 2.98e-02 | 3.13e-02 | 3.32e-02 | 3.60e-02 | 4.06e-02 | 2.64e-02 |
| Cr-51 | 2.41e-05 | 2.55e-05 | 2.65e-05 | 2.74e-05 | 2.83e-05 | 2.91e-05 | 2.99e-05 | 3.08e-05 | 3.17e-05 | 3.26e-05 | 3.37e-05 | 3.48e-05 | 3.61e-05 | 3.75e-05 | 3.91e-05 | 4.10e-05 | 4.36e-05 | 4.69e-05 | 5.26e-05 | 3.47e-05 |
| Cs-134 | 1.13e-02 | 1.20e-02 | 1.26e-02 | 1.31e-02 | 1.35e-02 | 1.40e-02 | 1.44e-02 | 1.48e-02 | 1.53e-02 | 1.58e-02 | 1.64e-02 | 1.70e-02 | 1.77e-02 | 1.84e-02 | 1.93e-02 | 2.03e-02 | 2.16e-02 | 2.33e-02 | 2.63e-02 | 1.71e-02 |
| Cs-137 | 5.07e-03 | 5.50e-03 | 5.81e-03 | 6.04e-03 | 6.27e-03 | 6.48e-03 | 6.71e-03 | 6.98e-03 | 7.26e-03 | 7.52e-03 | 7.85e-03 | 8.15e-03 | 8.49e-03 | 8.90e-03 | 9.36e-03 | 9.96e-03 | 1.06e-02 | 1.17e-02 | 1.35e-02 | 8.35e-03 |
| Eu-154 | 8.49e-03 | 9.02e-03 | 9.41e-03 | 9.73e-03 | 1.00e-02 | 1.03e-02 | 1.07e-02 | 1.10e-02 | 1.13e-02 | 1.17e-02 | 1.20e-02 | 1.25e-02 | 1.29e-02 | 1.34e-02 | 1.40e-02 | 1.47e-02 | 1.56e-02 | 1.69e-02 | 1.88e-02 | 1.23e-02 |
| Fe-59 | 1.57e-03 | 1.65e-03 | 1.72e-03 | 1.78e-03 | 1.84e-03 | 1.90e-03 | 1.95e-03 | 2.00e-03 | 2.06e-03 | 2.13e-03 | 2.19e-03 | 2.27e-03 | 2.35e-03 | 2.44e-03 | 2.55e-03 | 2.67e-03 | 2.84e-03 | 3.07e-03 | 3.43e-03 | 2.26e-03 |
| H-3 | 1.35e-06 | 1.56e-06 | 1.75e-06 | 1.93e-06 | 2.10e-06 | 2.26e-06 | 2.44e-06 | 2.61e-06 | 2.80e-06 | 3.04e-06 | 3.32e-06 | 3.62e-06 | 3.98e-06 | 4.45e-06 | 5.08e-06 | 5.87e-06 | 7.00e-06 | 8.67e-06 | 1.20e-05 | 4.31e-06 |
| I-125 | 4.75e-05 | 6.31e-05 | 7.34e-05 | 8.59e-05 | 9.88e-05 | 1.11e-04 | 1.25e-04 | 1.39e-04 | 1.53e-04 | 1.68e-04 | 1.85e-04 | 2.05e-04 | 2.28e-04 | 2.57e-04 | 2.86e-04 | 3.29e-04 | 3.83e-04 | 4.61e-04 | 6.09e-04 | 2.35e-04 |
| I-131 | 1.13e-04 | 1.22e-04 | 1.29e-04 | 1.34e-04 | 1.40e-04 | 1.46e-04 | 1.51e-04 | 1.56e-04 | 1.61e-04 | 1.67e-04 | 1.73e-04 | 1.80e-04 | 1.87e-04 | 1.95e-04 | 2.04e-04 | 2.17e-04 | 2.29e-04 | 2.51e-04 | 2.79e-04 | 1.80e-04 |
| In-111 | 5.46e-05 | 5.73e-05 | 5.95e-05 | 6.15e-05 | 6.34e-05 | 6.52e-05 | 6.72e-05 | 6.91e-05 | 7.11e-05 | 7.32e-05 | 7.55e-05 | 7.81e-05 | 8.08e-05 | 8.40e-05 | 8.76e-05 | 9.20e-05 | 9.77e-05 | 1.05e-04 | 1.18e-04 | 7.79e-05 |
| K-40 | 1.05e-03 | 1.12e-03 | 1.17e-03 | 1.21e-03 | 1.25e-03 | 1.29e-03 | 1.33e-03 | 1.37e-03 | 1.41e-03 | 1.45e-03 | 1.50e-03 | 1.55e-03 | 1.61e-03 | 1.68e-03 | 1.75e-03 | 1.83e-03 | 1.95e-03 | 2.10e-03 | 2.34e-03 | 1.54e-03 |
| La-138 | 2.22e-03 | 3.04e-03 | 4.05e-03 | 5.19e-03 | 6.55e-03 | 7.63e-03 | 8.51e-03 | 9.12e-03 | 9.59e-03 | 1.00e-02 | 1.05e-02 | 1.10e-02 | 1.15e-02 | 1.21e-02 | 1.27e-02 | 1.34e-02 | 1.43e-02 | 1.55e-02 | 1.78e-02 | 9.82e-03 |
| Np-237 | 3.23e-03 | 4.12e-03 | 4.82e-03 | 5.48e-03 | 6.17e-03 | 6.88e-03 | 7.79e-03 | 8.73e-03 | 9.88e-03 | 1.11e-02 | 1.24e-02 | 1.45e-02 | 1.72e-02 | 2.07e-02 | 2.73e-02 | 4.00e-02 | 6.15e-02 | 1.03e-01 | 2.42e-01 | 6.26e-02 |
| Pa-231 | 2.15e-03 | 3.11e-03 | 4.03e-03 | 4.78e-03 | 5.37e-03 | 6.03e-03 | 6.62e-03 | 7.32e-03 | 8.10e-03 | 8.79e-03 | 9.69e-03 | 1.06e-02 | 1.19e-02 | 1.34e-02 | 1.54e-02 | 1.80e-02 | 2.30e-02 | 3.06e-02 | 4.75e-02 | 1.62e-02 |
| Pb-210 | 1.93e-03 | 2.50e-03 | 2.93e-03 | 3.34e-03 | 3.82e-03 | 4.25e-03 | 4.68e-03 | 5.04e-03 | 5.50e-03 | 5.93e-03 | 6.52e-03 | 7.20e-03 | 7.82e-03 | 8.64e-03 | 9.72e-03 | 1.09e-02 | 1.26e-02 | 1.50e-02 | 1.88e-02 | 7.73e-03 |
| Po-210 | 3.03e-04 | 4.16e-04 | 5.17e-04 | 6.26e-04 | 7.18e-04 | 8.30e-04 | 9.37e-04 | 1.04e-03 | 1.19e-03 | 1.34e-03 | 1.54e-03 | 1.75e-03 | 1.96e-03 | 2.23e-03 | 2.59e-03 | 3.01e-03 | 3.51e-03 | 4.44e-03 | 6.13e-03 | 2.06e-03 |
| Pu-238 | 1.76e-04 | 2.15e-04 | 2.42e-04 | 2.70e-04 | 3.02e-04 | 3.30e-04 | 3.55e-04 | 3.82e-04 | 4.12e-04 | 4.41e-04 | 4.75e-04 | 5.08e-04 | 5.41e-04 | 5.86e-04 | 6.34e-04 | 6.91e-04 | 7.77e-04 | 9.11e-04 | 1.23e-03 | 5.45e-04 |
| Pu-239 | 1.99e-04 | 2.40e-04 | 2.75e-04 | 3.08e-04 | 3.39e-04 | 3.68e-04 | 3.98e-04 | 4.30e-04 | 4.60e-04 | 4.92e-04 | 5.30e-04 | 5.72e-04 | 6.12e-04 | 6.58e-04 | 7.16e-04 | 7.80e-04 | 8.74e-04 | 1.02e-03 | 1.35e-03 | 6.37e-04 |
| Ra-226 | 1.65e-01 | 1.67e-01 | 1.68e-01 | 1.69e-01 | 1.69e-01 | 1.70e-01 | 1.71e-01 | 1.72e-01 | 1.73e-01 | 1.74e-01 | 1.75e-01 | 1.76e-01 | 1.77e-01 | 1.78e-01 | 1.80e-01 | 1.82e-01 | 1.84e-01 | 1.87e-01 | 1.94e-01 | 1.76e-01 |
| Ra-228 | 1.45e-02 | 1.55e-02 | 1.62e-02 | 1.68e-02 | 1.75e-02 | 1.80e-02 | 1.87e-02 | 1.92e-02 | 1.99e-02 | 2.05e-02 | 2.12e-02 | 2.19e-02 | 2.28e-02 | 2.37e-02 | 2.46e-02 | 2.61e-02 | 2.79e-02 | 3.09e-02 | 3.55e-02 | 2.24e-02 |
| Sm-153 | 4.62e-06 | 4.85e-06 | 5.05e-06 | 5.21e-06 | 5.36e-06 | 5.52e-06 | 5.69e-06 | 5.85e-06 | 6.01e-06 | 6.19e-06 | 6.38e-06 | 6.59e-06 | 6.83e-06 | 7.06e-06 | 7.38e-06 | 7.75e-06 | 8.22e-06 | 8.88e-06 | 9.93e-06 | 6.57e-06 |
| Sr-89 | 1.46e-05 | 1.86e-05 | 2.36e-05 | 2.75e-05 | 3.21e-05 | 3.75e-05 | 4.28e-05 | 4.86e-05 | 5.56e-05 | 6.41e-05 | 7.30e-05 | 8.32e-05 | 9.66e-05 | 1.13e-04 | 1.34e-04 | 1.59e-04 | 1.99e-04 | 2.66e-04 | 4.11e-04 | 1.29e-04 |
| Sr-90 | 9.00e-04 | 1.25e-03 | 1.61e-03 | 1.99e-03 | 2.34e-03 | 2.74e-03 | 3.20e-03 | 3.66e-03 | 4.21e-03 | 4.90e-03 | 5.53e-03 | 6.38e-03 | 7.36e-03 | 8.81e-03 | 1.04e-02 | 1.23e-02 | 1.57e-02 | 2.13e-02 | 3.23e-02 | 1.01e-02 |
| Th-228 | 1.19e-02 | 1.25e-02 | 1.29e-02 | 1.33e-02 | 1.36e-02 | 1.40e-02 | 1.43e-02 | 1.47e-02 | 1.50e-02 | 1.55e-02 | 1.59e-02 | 1.63e-02 | 1.68e-02 | 1.73e-02 | 1.80e-02 | 1.88e-02 | 1.99e-02 | 2.13e-02 | 2.36e-02 | 1.62e-02 |
| Th-229 | 2.54e-03 | 2.73e-03 | 2.86e-03 | 2.99e-03 | 3.10e-03 | 3.20e-03 | 3.29e-03 | 3.39e-03 | 3.47e-03 | 3.58e-03 | 3.69e-03 | 3.82e-03 | 3.95e-03 | 4.09e-03 | 4.27e-03 | 4.47e-03 | 4.74e-03 | 5.10e-03 | 5.71e-03 | 3.87e-03 |
| Th-230 | 9.18e-04 | 2.88e-03 | 5.78e-03 | 8.50e-03 | 1.28e-02 | 1.70e-02 | 2.10e-02 | 2.62e-02 | 3.16e-02 | 3.63e-02 | 4.10e-02 | 4.51e-02 | 4.84e-02 | 5.14e-02 | 5.37e-02 | 5.61e-02 | 5.80e-02 | 6.01e-02 | 6.24e-02 | 3.37e-02 |

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Table E.1 Onsite Resident DSR Percentiles (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 1.35e-02 | 2.06e-02 | 2.36e-02 | 2.50e-02 | 2.64e-02 | 2.75e-02 | 2.86e-02 | 2.96e-02 | 3.06e-02 | 3.17e-02 | 3.26e-02 | 3.39e-02 | 3.51e-02 | 3.67e-02 | 3.82e-02 | 4.02e-02 | 4.29e-02 | 4.68e-02 | 5.28e-02 | 3.30e-02 |
| Tl-201 | 8.44e-06 | 8.88e-06 | 9.27e-06 | 9.59e-06 | 9.91e-06 | 1.02e-05 | 1.05e-05 | 1.08e-05 | 1.12e-05 | 1.15e-05 | 1.18e-05 | 1.22e-05 | 1.28e-05 | 1.33e-05 | 1.38e-05 | 1.46e-05 | 1.54e-05 | 1.67e-05 | 1.88e-05 | 1.23e-05 |
| Tl-202 | 1.57e-04 | 1.66e-04 | 1.73e-04 | 1.79e-04 | 1.85e-04 | 1.91e-04 | 1.96e-04 | 2.01e-04 | 2.07e-04 | 2.13e-04 | 2.20e-04 | 2.28e-04 | 2.37e-04 | 2.46e-04 | 2.56e-04 | 2.71e-04 | 2.88e-04 | 3.10e-04 | 3.45e-04 | 2.28e-04 |
| U-233 | 5.77e-05 | 7.58e-05 | 8.96e-05 | 1.05e-04 | 1.17e-04 | 1.33e-04 | 1.47e-04 | 1.66e-04 | 1.85e-04 | 2.06e-04 | 2.31e-04 | 2.64e-04 | 2.95e-04 | 3.32e-04 | 3.76e-04 | 4.33e-04 | 4.93e-04 | 6.24e-04 | 1.09e-03 | 5.76e-04 |
| U-234 | 5.30e-05 | 7.09e-05 | 8.40e-05 | 9.92e-05 | 1.13e-04 | 1.29e-04 | 1.43e-04 | 1.57e-04 | 1.75e-04 | 1.95e-04 | 2.20e-04 | 2.43e-04 | 2.69e-04 | 3.00e-04 | 3.34e-04 | 3.77e-04 | 4.42e-04 | 5.85e-04 | 1.02e-03 | 5.23e-04 |
| U-235 | 8.61e-04 | 1.09e-03 | 1.17e-03 | 1.23e-03 | 1.28e-03 | 1.32e-03 | 1.37e-03 | 1.42e-03 | 1.46e-03 | 1.51e-03 | 1.56e-03 | 1.61e-03 | 1.68e-03 | 1.74e-03 | 1.82e-03 | 1.91e-03 | 2.03e-03 | 2.21e-03 | 2.53e-03 | 1.73e-03 |
| U-238 | 2.13e-04 | 2.54e-04 | 2.75e-04 | 2.91e-04 | 3.07e-04 | 3.21e-04 | 3.35e-04 | 3.50e-04 | 3.66e-04 | 3.83e-04 | 4.02e-04 | 4.21e-04 | 4.42e-04 | 4.65e-04 | 4.94e-04 | 5.38e-04 | 5.96e-04 | 6.76e-04 | 1.00e-03 | 7.07e-04 |
| Xe-131m | 1.11e-06 | 1.19e-06 | 1.24e-06 | 1.29e-06 | 1.34e-06 | 1.38e-06 | 1.42e-06 | 1.46e-06 | 1.50e-06 | 1.55e-06 | 1.60e-06 | 1.65e-06 | 1.71e-06 | 1.79e-06 | 1.86e-06 | 1.95e-06 | 2.08e-06 | 2.25e-06 | 2.53e-06 | 1.65e-06 |
| Zn-65 | 3.36e-03 | 3.82e-03 | 4.13e-03 | 4.41e-03 | 4.68e-03 | 4.95e-03 | 5.21e-03 | 5.48e-03 | 5.78e-03 | 6.08e-03 | 6.48e-03 | 6.86e-03 | 7.33e-03 | 7.89e-03 | 8.63e-03 | 9.72e-03 | 1.13e-02 | 1.40e-02 | 2.07e-02 | 8.34e-03 |

Table E.2 Recreational User DSR Percentiles

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 1.55e-03 | 1.62e-03 | 1.64e-03 | 1.65e-03 | 1.66e-03 | 1.67e-03 | 1.68e-03 | 1.69e-03 | 1.70e-03 | 1.71e-03 | 1.72e-03 | 1.73e-03 | 1.74e-03 | 1.76e-03 | 1.77e-03 | 1.79e-03 | 1.82e-03 | 1.85e-03 | 1.91e-03 | 1.74e-03 |
| Am-241 | 4.57e-05 | 4.73e-05 | 4.82e-05 | 4.91e-05 | 5.00e-05 | 5.08e-05 | 5.15e-05 | 5.22e-05 | 5.30e-05 | 5.38e-05 | 5.46e-05 | 5.54e-05 | 5.63e-05 | 5.75e-05 | 5.89e-05 | 6.07e-05 | 6.30e-05 | 6.73e-05 | 8.73e-05 | 6.96e-04 |
| Be-7 | 4.42e-05 | 4.53e-05 | 4.56e-05 | 4.57e-05 | 4.58e-05 | 4.55e-05 |
| C-14 | 1.75e-04 | 2.28e-04 | 2.85e-04 | 3.41e-04 | 4.06e-04 | 4.77e-04 | 5.66e-04 | 6.65e-04 | 7.80e-04 | 9.30e-04 | 1.14e-03 | 1.48e-03 | 2.03e-03 | 3.02e-03 | 5.03e-03 | 1.00e-02 | 1.85e-02 | 3.81e-02 | 9.76e-02 | 2.56e-02 |
| Ce-141 | 3.32e-05 | 3.33e-05 |
| Co-57 | 2.45e-04 | 2.60e-04 | 2.64e-04 | 2.66e-04 | 2.67e-04 | 2.68e-04 | 2.68e-04 | 2.68e-04 | 2.68e-04 | 2.68e-04 | 2.68e-04 | 2.69e-04 | 2.69e-04 | 2.69e-04 | 2.70e-04 | 2.70e-04 | 2.71e-04 | 2.72e-04 | 2.76e-04 | 2.66e-04 |
| Co-60 | 9.61e-03 | 1.04e-02 | 1.06e-02 | 1.07e-02 | 1.07e-02 | 1.08e-02 | 1.09e-02 | 1.09e-02 | 1.10e-02 | 1.06e-02 |
| Cr-51 | 1.39e-05 | 1.44e-05 | 1.46e-05 | 1.47e-05 | 1.48e-05 | 1.49e-05 | 1.49e-05 | 1.49e-05 | 1.49e-05 | 1.47e-05 |
| Cs-134 | 5.88e-03 | 6.01e-03 | 6.04e-03 | 6.05e-03 | 6.06e-03 | 6.07e-03 | 6.08e-03 | 6.09e-03 | 6.10e-03 | 6.11e-03 | 6.12e-03 | 6.13e-03 | 6.15e-03 | 6.17e-03 | 6.18e-03 | 6.21e-03 | 6.24e-03 | 6.30e-03 | 6.40e-03 | 6.12e-03 |
| Cs-137 | 2.52e-03 | 2.55e-03 | 2.56e-03 | 2.57e-03 | 2.58e-03 | 2.59e-03 | 2.59e-03 | 2.60e-03 | 2.61e-03 | 2.61e-03 | 2.62e-03 | 2.63e-03 | 2.64e-03 | 2.66e-03 | 2.67e-03 | 2.70e-03 | 2.72e-03 | 2.77e-03 | 2.86e-03 | 2.64e-03 |
| Eu-154 | 4.89e-03 | 5.19e-03 | 5.28e-03 | 5.32e-03 | 5.33e-03 | 5.34e-03 | 5.35e-03 | 5.35e-03 | 5.35e-03 | 5.36e-03 | 5.26e-03 |
| Fe-59 | 9.16e-04 | 9.47e-04 | 9.56e-04 | 9.61e-04 | 9.63e-04 | 9.64e-04 | 9.65e-04 | 9.65e-04 | 9.65e-04 | 9.66e-04 | 9.67e-04 | 9.67e-04 | 9.67e-04 | 9.56e-04 |
| H-3 | 3.82e-07 | 4.72e-07 | 5.38e-07 | 6.09e-07 | 6.84e-07 | 7.52e-07 | 8.46e-07 | 9.30e-07 | 1.03e-06 | 1.13e-06 | 1.27e-06 | 1.39e-06 | 1.56e-06 | 1.76e-06 | 2.03e-06 | 2.30e-06 | 2.71e-06 | 3.40e-06 | 4.51e-06 | 1.64e-06 |
| I-125 | 6.07e-06 | 7.23e-06 | 8.01e-06 | 8.79e-06 | 9.49e-06 | 1.02e-05 | 1.09e-05 | 1.16e-05 | 1.24e-05 | 1.33e-05 | 1.44e-05 | 1.54e-05 | 1.65e-05 | 1.77e-05 | 1.90e-05 | 2.09e-05 | 2.30e-05 | 2.70e-05 | 3.31e-05 | 1.59e-05 |
| I-131 | 5.46e-05 | 5.59e-05 | 5.66e-05 | 5.69e-05 | 5.72e-05 | 5.73e-05 | 5.75e-05 | 5.77e-05 | 5.79e-05 | 5.81e-05 | 5.83e-05 | 5.85e-05 | 5.87e-05 | 5.90e-05 | 5.94e-05 | 5.97e-05 | 6.02e-05 | 6.10e-05 | 6.23e-05 | 5.83e-05 |
| In-111 | 3.30e-05 |
| K-40 | 6.02e-04 | 6.24e-04 | 6.39e-04 | 6.49e-04 | 6.58e-04 | 6.64e-04 | 6.70e-04 | 6.74e-04 | 6.79e-04 | 6.83e-04 | 6.87e-04 | 6.91e-04 | 6.95e-04 | 6.98e-04 | 7.01e-04 | 7.05e-04 | 7.08e-04 | 7.12e-04 | 7.17e-04 | 6.75e-04 |
| La-138 | 1.38e-03 | 1.84e-03 | 2.39e-03 | 2.90e-03 | 3.56e-03 | 4.12e-03 | 4.56e-03 | 4.84e-03 | 5.08e-03 | 5.23e-03 | 5.35e-03 | 5.43e-03 | 5.49e-03 | 5.53e-03 | 5.56e-03 | 5.57e-03 | 5.59e-03 | 5.59e-03 | 5.60e-03 | 4.66e-03 |
| Np-237 | 7.21e-04 | 8.71e-04 | 9.19e-04 | 9.45e-04 | 9.66e-04 | 9.95e-04 | 1.02e-03 | 1.06e-03 | 1.12e-03 | 1.25e-03 | 1.58e-03 | 3.73e-03 | 8.40e-03 | 1.72e-02 | 3.48e-02 | 6.50e-02 | 1.27e-01 | 2.51e-01 | 6.07e-01 | 1.58e-01 |
| Pa-231 | 1.86e-04 | 2.88e-04 | 4.19e-04 | 5.70e-04 | 7.10e-04 | 8.55e-04 | 1.02e-03 | 1.20e-03 | 1.32e-03 | 1.43e-03 | 1.53e-03 | 1.63e-03 | 1.70e-03 | 1.76e-03 | 1.82e-03 | 1.87e-03 | 1.94e-03 | 2.12e-03 | 1.03e-02 | 1.01e-02 |
| Pb-210 | 7.67e-05 | 9.54e-05 | 1.11e-04 | 1.25e-04 | 1.39e-04 | 1.56e-04 | 1.70e-04 | 1.84e-04 | 2.01e-04 | 2.19e-04 | 2.36e-04 | 2.57e-04 | 2.82e-04 | 3.08e-04 | 3.37e-04 | 3.75e-04 | 4.24e-04 | 4.80e-04 | 6.29e-04 | 2.69e-04 |
| Po-210 | 2.72e-05 | 3.62e-05 | 4.46e-05 | 5.28e-05 | 6.08e-05 | 6.78e-05 | 7.56e-05 | 8.47e-05 | 9.41e-05 | 1.05e-04 | 1.15e-04 | 1.29e-04 | 1.43e-04 | 1.62e-04 | 1.84e-04 | 2.12e-04 | 2.41e-04 | 2.96e-04 | 3.89e-04 | 1.44e-04 |
| Pu-238 | 1.10e-05 | 1.26e-05 | 1.35e-05 | 1.45e-05 | 1.53e-05 | 1.60e-05 | 1.68e-05 | 1.74e-05 | 1.82e-05 | 1.89e-05 | 1.97e-05 | 2.05e-05 | 2.13e-05 | 2.24e-05 | 2.35e-05 | 2.48e-05 | 2.64e-05 | 2.86e-05 | 3.28e-05 | 2.06e-05 |
| Pu-239 | 1.24e-05 | 1.40e-05 | 1.52e-05 | 1.63e-05 | 1.72e-05 | 1.80e-05 | 1.89e-05 | 1.96e-05 | 2.04e-05 | 2.13e-05 | 2.22e-05 | 2.31e-05 | 2.42e-05 | 2.54e-05 | 2.67e-05 | 2.84e-05 | 3.01e-05 | 3.35e-05 | 3.98e-05 | 7.43e-05 |
| Ra-226 | 8.13e-03 | 8.13e-03 | 8.14e-03 | 8.15e-03 | 8.15e-03 | 8.16e-03 | 8.17e-03 | 8.17e-03 | 8.18e-03 | 8.19e-03 | 8.20e-03 | 8.22e-03 | 8.23e-03 | 8.25e-03 | 8.28e-03 | 8.30e-03 | 8.34e-03 | 8.41e-03 | 8.54e-03 | 8.41e-03 |
| Ra-228 | 6.84e-03 | 7.00e-03 | 7.05e-03 | 7.07e-03 | 7.08e-03 | 7.09e-03 | 7.10e-03 | 7.12e-03 | 7.13e-03 | 7.14e-03 | 7.15e-03 | 7.16e-03 | 7.17e-03 | 7.19e-03 | 7.20e-03 | 7.22e-03 | 7.24e-03 | 7.27e-03 | 7.33e-03 | 7.11e-03 |
| Sm-153 | 2.75e-06 | 2.76e-06 | 2.76e-06 | 2.76e-06 | 2.76e-06 | 2.76e-06 | 2.77e-06 | 2.76e-06 |
| Sr-89 | 1.80e-06 | 1.97e-06 | 2.10e-06 | 2.24e-06 | 2.38e-06 | 2.53e-06 | 2.69e-06 | 2.85e-06 | 3.04e-06 | 3.28e-06 | 3.56e-06 | 3.87e-06 | 4.27e-06 | 4.74e-06 | 5.41e-06 | 6.26e-06 | 7.41e-06 | 9.83e-06 | 1.50e-05 | 5.33e-06 |
| Sr-90 | 5.20e-05 | 6.66e-05 | 7.72e-05 | 8.94e-05 | 1.01e-04 | 1.13e-04 | 1.29e-04 | 1.42e-04 | 1.60e-04 | 1.80e-04 | 2.07e-04 | 2.39e-04 | 2.73e-04 | 3.20e-04 | 3.81e-04 | 4.63e-04 | 5.99e-04 | 8.37e-04 | 1.45e-03 | 7.64e-04 |
| Th-228 | 6.12e-03 | 6.19e-03 | 6.21e-03 | 6.22e-03 | 6.24e-03 | 6.25e-03 | 6.26e-03 | 6.28e-03 | 6.29e-03 | 6.30e-03 | 6.31e-03 | 6.32e-03 | 6.33e-03 | 6.35e-03 | 6.36e-03 | 6.38e-03 | 6.41e-03 | 6.44e-03 | 6.48e-03 | 6.27e-03 |
| Th-229 | 1.27e-03 | 1.28e-03 | 1.29e-03 | 1.29e-03 | 1.30e-03 | 1.30e-03 | 1.30e-03 | 1.31e-03 | 1.31e-03 | 1.31e-03 | 1.32e-03 | 1.32e-03 | 1.33e-03 | 1.33e-03 | 1.34e-03 | 1.35e-03 | 1.36e-03 | 1.37e-03 | 1.40e-03 | 1.81e-03 |
| Th-230 | 6.37e-05 | 1.98e-04 | 3.65e-04 | 5.61e-04 | 7.87e-04 | 1.09e-03 | 1.34e-03 | 1.60e-03 | 1.80e-03 | 2.02e-03 | 2.20e-03 | 2.35e-03 | 2.48e-03 | 2.58e-03 | 2.66e-03 | 2.75e-03 | 2.81e-03 | 2.87e-03 | 2.95e-03 | 1.90e-03 |

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Table E.2 Recreational User DSR Percentiles (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 5.72e-03 | 8.23e-03 | 9.63e-03 | 1.04e-02 | 1.09e-02 | 1.12e-02 | 1.14e-02 | 1.16e-02 | 1.17e-02 | 1.18e-02 | 1.18e-02 | 1.19e-02 | 1.19e-02 | 1.19e-02 | 1.20e-02 | 1.20e-02 | 1.21e-02 | 1.21e-02 | 1.22e-02 | 1.12e-02 |
| Tl-201 | 4.90e-06 | 4.90e-06 | 4.90e-06 | 4.90e-06 | 4.90e-06 | 4.90e-06 | 4.91e-06 | 4.91e-06 | 4.91e-06 | 4.91e-06 | 4.91e-06 | 4.91e-06 | 4.92e-06 | 4.92e-06 | 4.93e-06 | 4.94e-06 | 4.95e-06 | 4.97e-06 | 5.01e-06 | 4.93e-06 |
| Tl-202 | 8.89e-05 | 9.20e-05 | 9.33e-05 | 9.39e-05 | 9.42e-05 | 9.43e-05 | 9.44e-05 | 9.44e-05 | 9.44e-05 | 9.45e-05 | 9.45e-05 | 9.45e-05 | 9.45e-05 | 9.46e-05 | 9.46e-05 | 9.47e-05 | 9.48e-05 | 9.50e-05 | 9.54e-05 | 9.38e-05 |
| U-233 | 5.75e-06 | 7.23e-06 | 8.58e-06 | 1.01e-05 | 1.17e-05 | 1.38e-05 | 1.66e-05 | 1.95e-05 | 2.37e-05 | 3.08e-05 | 3.88e-05 | 5.39e-05 | 7.14e-05 | 9.13e-05 | 1.10e-04 | 1.23e-04 | 1.41e-04 | 3.66e-04 | 1.96e-03 | 7.58e-04 |
| U-234 | 4.48e-06 | 5.57e-06 | 6.34e-06 | 7.20e-06 | 8.01e-06 | 8.94e-06 | 9.97e-06 | 1.11e-05 | 1.23e-05 | 1.36e-05 | 1.50e-05 | 1.66e-05 | 1.84e-05 | 2.04e-05 | 2.37e-05 | 3.03e-05 | 5.80e-05 | 2.39e-04 | 1.34e-03 | 9.44e-04 |
| U-235 | 4.36e-04 | 5.51e-04 | 5.84e-04 | 6.01e-04 | 6.09e-04 | 6.14e-04 | 6.16e-04 | 6.17e-04 | 6.18e-04 | 6.19e-04 | 6.20e-04 | 6.21e-04 | 6.22e-04 | 6.24e-04 | 6.26e-04 | 6.29e-04 | 6.41e-04 | 7.92e-04 | 2.15e-03 | 1.38e-03 |
| U-238 | 7.94e-05 | 9.93e-05 | 1.05e-04 | 1.06e-04 | 1.07e-04 | 1.08e-04 | 1.09e-04 | 1.09e-04 | 1.10e-04 | 1.11e-04 | 1.12e-04 | 1.13e-04 | 1.14e-04 | 1.16e-04 | 1.18e-04 | 1.22e-04 | 1.30e-04 | 2.62e-04 | 1.23e-03 | 1.32e-03 |
| Xe-131m | 6.38e-07 | 6.61e-07 | 6.77e-07 | 6.88e-07 | 6.97e-07 | 7.08e-07 | 7.17e-07 | 7.26e-07 | 7.34e-07 | 7.42e-07 | 7.49e-07 | 7.55e-07 | 7.64e-07 | 7.70e-07 | 7.78e-07 | 7.87e-07 | 7.95e-07 | 8.05e-07 | 8.19e-07 | 7.36e-07 |
| Zn-65 | 1.31e-03 | 1.65e-03 | 1.69e-03 | 1.70e-03 | 1.71e-03 | 1.72e-03 | 1.73e-03 | 1.74e-03 | 1.76e-03 | 1.77e-03 | 1.78e-03 | 1.80e-03 | 1.82e-03 | 1.85e-03 | 1.89e-03 | 1.93e-03 | 2.01e-03 | 2.13e-03 | 2.35e-03 | 1.82e-03 |

Table E.3 Nearby Town DSR Percentiles (One Year of Application)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 9.55e-06 | 1.17e-05 | 1.37e-05 | 1.52e-05 | 1.69e-05 | 1.84e-05 | 2.02e-05 | 2.16e-05 | 2.30e-05 | 2.45e-05 | 2.57e-05 | 2.72e-05 | 2.89e-05 | 3.08e-05 | 3.31e-05 | 3.63e-05 | 4.06e-05 | 4.96e-05 | 5.94e-05 | 2.74e-05 |
| Am-241 | 6.62e-07 | 8.12e-07 | 9.64e-07 | 1.06e-06 | 1.18e-06 | 1.28e-06 | 1.39e-06 | 1.48e-06 | 1.59e-06 | 1.68e-06 | 1.76e-06 | 1.86e-06 | 1.98e-06 | 2.11e-06 | 2.27e-06 | 2.51e-06 | 2.85e-06 | 3.49e-06 | 4.22e-06 | 1.90e-06 |
| Be-7 | 8.82e-13 | 1.06e-12 | 1.22e-12 | 1.35e-12 | 1.50e-12 | 1.68e-12 | 1.80e-12 | 1.93e-12 | 2.09e-12 | 2.27e-12 | 2.46e-12 | 2.64e-12 | 2.80e-12 | 3.00e-12 | 3.29e-12 | 3.58e-12 | 4.02e-12 | 4.66e-12 | 6.43e-12 | 2.76e-12 |
| C-14 | 2.55e-07 | 2.79e-07 | 2.98e-07 | 3.14e-07 | 3.28e-07 | 3.40e-07 | 3.52e-07 | 3.63e-07 | 3.73e-07 | 3.83e-07 | 3.93e-07 | 4.04e-07 | 4.16e-07 | 4.29e-07 | 4.42e-07 | 4.58e-07 | 4.75e-07 | 4.96e-07 | 5.22e-07 | 3.86e-07 |
| Ce-141 | 1.70e-11 | 2.01e-11 | 2.25e-11 | 2.49e-11 | 2.67e-11 | 2.87e-11 | 3.14e-11 | 3.38e-11 | 3.67e-11 | 3.96e-11 | 4.22e-11 | 4.52e-11 | 4.86e-11 | 5.22e-11 | 5.56e-11 | 5.90e-11 | 6.23e-11 | 6.59e-11 | 7.12e-11 | 4.15e-11 |
| Co-57 | 2.34e-11 | 2.94e-11 | 3.52e-11 | 4.08e-11 | 4.56e-11 | 5.10e-11 | 5.53e-11 | 6.14e-11 | 6.75e-11 | 7.33e-11 | 7.95e-11 | 8.56e-11 | 9.43e-11 | 1.04e-10 | 1.17e-10 | 1.33e-10 | 1.59e-10 | 2.01e-10 | 2.98e-10 | 1.00e-10 |
| Co-60 | 1.42e-09 | 1.83e-09 | 2.13e-09 | 2.45e-09 | 2.73e-09 | 3.02e-09 | 3.33e-09 | 3.59e-09 | 5.53e-09 | 4.21e-09 | 4.60e-09 | 5.00e-09 | 5.45e-09 | 6.00e-09 | 6.63e-09 | 7.53e-09 | 8.64e-09 | 1.02e-08 | 1.36e-08 | 5.53e-09 |
| Cr-51 | 1.99e-12 | 2.48e-12 | 3.04e-12 | 3.44e-12 | 3.82e-12 | 4.22e-12 | 4.71e-12 | 5.10e-12 | 5.51e-12 | 6.08e-12 | 6.52e-12 | 7.02e-12 | 7.72e-12 | 8.45e-12 | 9.49e-12 | 1.06e-11 | 1.23e-11 | 1.45e-11 | 1.80e-11 | 7.41e-12 |
| Cs-134 | 1.52e-09 | 1.97e-09 | 2.28e-09 | 2.65e-09 | 3.05e-09 | 3.45e-09 | 3.80e-09 | 4.19e-09 | 4.74e-09 | 5.27e-09 | 6.08e-09 | 6.74e-09 | 7.62e-09 | 8.68e-09 | 9.93e-09 | 1.17e-08 | 1.44e-08 | 1.91e-08 | 2.84e-08 | 8.80e-09 |
| Cs-137 | 2.87e-09 | 3.63e-09 | 4.39e-09 | 4.92e-09 | 5.50e-09 | 6.05e-09 | 6.64e-09 | 7.35e-09 | 8.09e-09 | 8.80e-09 | 9.82e-09 | 1.06e-08 | 1.17e-08 | 1.31e-08 | 1.49e-08 | 1.78e-08 | 2.11e-08 | 2.71e-08 | 4.28e-08 | 1.42e-08 |
| Eu-154 | 9.18e-10 | 1.19e-09 | 1.41e-09 | 1.60e-09 | 1.78e-09 | 1.97e-09 | 2.16e-09 | 2.33e-09 | 2.52e-09 | 2.72e-09 | 2.92e-09 | 3.18e-09 | 3.45e-09 | 3.72e-09 | 4.13e-09 | 4.54e-09 | 5.10e-09 | 5.94e-09 | 7.50e-09 | 3.24e-09 |
| Fe-59 | 8.27e-11 | 1.03e-10 | 1.27e-10 | 1.46e-10 | 1.63e-10 | 1.80e-10 | 1.95e-10 | 2.13e-10 | 2.34e-10 | 2.59e-10 | 2.79e-10 | 3.12e-10 | 3.41e-10 | 3.78e-10 | 4.16e-10 | 4.64e-10 | 5.34e-10 | 6.10e-10 | 7.44e-10 | 3.19e-10 |
| H-3 | 1.37e-07 | 1.63e-07 | 1.78e-07 | 1.92e-07 | 2.05e-07 | 2.20e-07 | 2.36e-07 | 2.49e-07 | 2.63e-07 | 2.79e-07 | 2.92e-07 | 3.06e-07 | 3.20e-07 | 3.41e-07 | 3.65e-07 | 3.94e-07 | 4.23e-07 | 4.64e-07 | 5.32e-07 | 2.97e-07 |
| I-125 | 1.80e-09 | 2.21e-09 | 2.61e-09 | 2.93e-09 | 3.27e-09 | 3.69e-09 | 4.08e-09 | 4.44e-09 | 4.79e-09 | 5.31e-09 | 5.77e-09 | 6.39e-09 | 6.93e-09 | 7.64e-09 | 8.46e-09 | 9.52e-09 | 1.08e-08 | 1.25e-08 | 1.55e-08 | 6.54e-09 |
| I-131 | 2.46e-09 | 3.03e-09 | 3.57e-09 | 4.01e-09 | 4.48e-09 | 5.05e-09 | 5.58e-09 | 6.08e-09 | 6.56e-09 | 7.27e-09 | 7.90e-09 | 8.75e-09 | 9.49e-09 | 1.05e-08 | 1.16e-08 | 1.30e-08 | 1.48e-08 | 1.72e-08 | 2.12e-08 | 8.96e-09 |
| In-111 | 5.86e-12 | 7.00e-12 | 8.20e-12 | 9.17e-12 | 1.03e-11 | 1.16e-11 | 1.26e-11 | 1.37e-11 | 1.49e-11 | 1.63e-11 | 1.76e-11 | 1.91e-11 | 2.06e-11 | 2.22e-11 | 2.41e-11 | 2.61e-11 | 2.97e-11 | 3.56e-11 | 4.54e-11 | 2.00e-11 |
| K-40 | 5.78e-11 | 7.01e-11 | 8.29e-11 | 9.62e-11 | 1.07e-10 | 1.17e-10 | 1.28e-10 | 1.39e-10 | 1.51e-10 | 1.62e-10 | 1.77e-10 | 1.91e-10 | 2.06e-10 | 2.19e-10 | 2.42e-10 | 2.69e-10 | 3.10e-10 | 3.64e-10 | 4.94e-10 | 1.99e-10 |
| La-138 | 1.83e-09 | 2.24e-09 | 2.60e-09 | 2.89e-09 | 3.27e-09 | 3.66e-09 | 3.98e-09 | 4.38e-09 | 4.77e-09 | 5.20e-09 | 5.62e-09 | 6.07e-09 | 6.57e-09 | 7.25e-09 | 8.20e-09 | 9.84e-09 | 1.29e-08 | 1.68e-08 | 2.69e-08 | 9.74e-09 |
| Np-237 | 7.36e-07 | 8.89e-07 | 1.01e-06 | 1.13e-06 | 1.28e-06 | 1.43e-06 | 1.55e-06 | 1.67e-06 | 1.84e-06 | 1.96e-06 | 2.08e-06 | 2.22e-06 | 2.34e-06 | 2.50e-06 | 2.69e-06 | 2.91e-06 | 3.23e-06 | 3.88e-06 | 5.00e-06 | 3.10e-06 |
| Pa-231 | 2.99e-06 | 4.50e-06 | 5.50e-06 | 6.68e-06 | 8.19e-06 | 9.45e-06 | 1.09e-05 | 1.25e-05 | 1.41e-05 | 1.59e-05 | 1.75e-05 | 1.96e-05 | 2.20e-05 | 2.48e-05 | 2.74e-05 | 3.10e-05 | 3.49e-05 | 4.16e-05 | 5.30e-05 | 2.02e-05 |
| Pb-210 | 6.67e-08 | 8.06e-08 | 9.38e-08 | 1.05e-07 | 1.16e-07 | 1.25e-07 | 1.37e-07 | 1.46e-07 | 1.55e-07 | 1.65e-07 | 1.75e-07 | 1.82e-07 | 1.92e-07 | 2.05e-07 | 2.22e-07 | 2.44e-07 | 2.84e-07 | 3.28e-07 | 4.04e-07 | 1.86e-07 |
| Po-210 | 2.00e-08 | 2.36e-08 | 2.70e-08 | 2.90e-08 | 3.12e-08 | 3.45e-08 | 3.74e-08 | 4.06e-08 | 4.40e-08 | 4.67e-08 | 5.03e-08 | 5.44e-08 | 5.73e-08 | 6.14e-08 | 6.50e-08 | 6.93e-08 | 7.46e-08 | 8.22e-08 | 9.68e-08 | 5.13e-08 |
| Pu-238 | 5.97e-07 | 7.42e-07 | 8.48e-07 | 9.54e-07 | 1.05e-06 | 1.15e-06 | 1.25e-06 | 1.34e-06 | 1.44e-06 | 1.53e-06 | 1.62e-06 | 1.72e-06 | 1.83e-06 | 1.93e-06 | 2.08e-06 | 2.26e-06 | 2.56e-06 | 3.00e-06 | 3.62e-06 | 1.71e-06 |
| Pu-239 | 6.79e-07 | 8.29e-07 | 9.40e-07 | 1.06e-06 | 1.17e-06 | 1.25e-06 | 1.37e-06 | 1.48e-06 | 1.57e-06 | 1.67e-06 | 1.76e-06 | 1.86e-06 | 1.98e-06 | 2.09e-06 | 2.28e-06 | 2.49e-06 | 2.84e-06 | 3.40e-06 | 3.95e-06 | 1.88e-06 |
| Ra-226 | 1.19e-04 |
| Ra-228 | 1.72e-04 | 1.87e-04 | 1.91e-04 | 1.92e-04 | 1.93e-04 | 1.94e-04 | 1.94e-04 | 1.95e-04 | 1.96e-04 | 1.96e-04 | 1.96e-04 | 1.96e-04 | 1.96e-04 | 1.90e-04 |
| Sm-153 | 1.15e-11 | 1.36e-11 | 1.60e-11 | 1.79e-11 | 1.97e-11 | 2.11e-11 | 2.28e-11 | 2.50e-11 | 2.67e-11 | 2.94e-11 | 3.14e-11 | 3.39e-11 | 3.67e-11 | 3.94e-11 | 4.30e-11 | 4.66e-11 | 5.11e-11 | 5.83e-11 | 7.39e-11 | 3.44e-11 |
| Sr-89 | 1.14e-10 | 1.31e-10 | 1.50e-10 | 1.66e-10 | 1.86e-10 | 2.06e-10 | 2.21e-10 | 2.40e-10 | 2.57e-10 | 2.75e-10 | 2.97e-10 | 3.18e-10 | 3.40e-10 | 3.65e-10 | 3.88e-10 | 4.16e-10 | 4.55e-10 | 5.02e-10 | 5.70e-10 | 3.00e-10 |
| Sr-90 | 3.77e-09 | 4.92e-09 | 5.93e-09 | 6.93e-09 | 7.81e-09 | 8.68e-09 | 9.44e-09 | 1.02e-08 | 1.12e-08 | 1.23e-08 | 1.34e-08 | 1.50e-08 | 1.70e-08 | 1.91e-08 | 2.15e-08 | 2.48e-08 | 3.09e-08 | 4.05e-08 | 5.76e-08 | 1.99e-08 |
| Th-228 | 3.39e-04 | 3.39e-04 | 3.39e-04 | 3.39e-04 | 3.39e-04 | 3.40e-04 | 3.41e-04 | 3.40e-04 |
| Th-229 | 3.22e-06 | 3.97e-06 | 4.57e-06 | 5.13e-06 | 5.60e-06 | 6.22e-06 | 6.82e-06 | 7.33e-06 | 7.90e-06 | 8.40e-06 | 8.81e-06 | 9.32e-06 | 9.93e-06 | 1.05e-05 | 1.15e-05 | 1.25e-05 | 1.41e-05 | 1.63e-05 | 1.92e-05 | 9.27e-06 |
| Th-230 | 1.46e-06 | 2.52e-06 | 3.93e-06 | 6.21e-06 | 8.69e-06 | 1.17e-05 | 1.46e-05 | 1.81e-05 | 2.24e-05 | 2.50e-05 | 2.80e-05 | 3.09e-05 | 3.34e-05 | 3.55e-05 | 3.76e-05 | 3.96e-05 | 4.08e-05 | 4.17e-05 | 4.30e-05 | 2.34e-05 |

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Table E.3 Nearby Town DSR Percentiles (One Year of Application) (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 1.17e-04 | 2.00e-04 | 2.46e-04 | 2.79e-04 | 2.99e-04 | 3.11e-04 | 3.21e-04 | 3.27e-04 | 3.31e-04 | 3.35e-04 | 3.37e-04 | 3.39e-04 | 3.41e-04 | 3.42e-04 | 3.43e-04 | 3.44e-04 | 3.45e-04 | 3.47e-04 | 3.51e-04 | 3.02e-04 |
| Ti-201 | 2.77e-12 | 3.47e-12 | 4.16e-12 | 4.79e-12 | 5.36e-12 | 5.95e-12 | 6.71e-12 | 7.43e-12 | 8.22e-12 | 9.30e-12 | 1.04e-11 | 1.18e-11 | 1.30e-11 | 1.47e-11 | 1.66e-11 | 1.96e-11 | 2.32e-11 | 2.99e-11 | 4.49e-11 | 1.45e-11 |
| Ti-202 | 1.32e-11 | 1.67e-11 | 2.00e-11 | 2.31e-11 | 2.59e-11 | 2.87e-11 | 3.24e-11 | 3.60e-11 | 3.99e-11 | 4.51e-11 | 5.03e-11 | 5.72e-11 | 6.32e-11 | 7.14e-11 | 8.07e-11 | 9.55e-11 | 1.13e-10 | 1.46e-10 | 2.19e-10 | 7.06e-11 |
| U-233 | 1.95e-07 | 2.44e-07 | 2.92e-07 | 3.26e-07 | 3.67e-07 | 4.01e-07 | 4.35e-07 | 4.67e-07 | 5.04e-07 | 5.44e-07 | 5.76e-07 | 6.12e-07 | 6.67e-07 | 7.18e-07 | 7.90e-07 | 8.82e-07 | 9.97e-07 | 1.19e-06 | 1.50e-06 | 6.46e-07 |
| U-234 | 1.86e-07 | 2.30e-07 | 2.63e-07 | 2.95e-07 | 3.27e-07 | 3.60e-07 | 3.91e-07 | 4.21e-07 | 4.51e-07 | 4.82e-07 | 5.18e-07 | 5.48e-07 | 5.77e-07 | 6.10e-07 | 6.59e-07 | 7.14e-07 | 8.21e-07 | 9.41e-07 | 1.15e-06 | 5.39e-07 |
| U-235 | 1.76e-07 | 2.22e-07 | 2.53e-07 | 2.84e-07 | 3.17e-07 | 3.50e-07 | 3.80e-07 | 4.13e-07 | 4.37e-07 | 4.65e-07 | 4.96e-07 | 5.27e-07 | 5.58e-07 | 5.94e-07 | 6.44e-07 | 7.19e-07 | 8.32e-07 | 9.77e-07 | 1.19e-06 | 5.43e-07 |
| U-238 | 1.68e-07 | 2.03e-07 | 2.37e-07 | 2.67e-07 | 2.95e-07 | 3.19e-07 | 3.45e-07 | 3.76e-07 | 4.05e-07 | 4.34e-07 | 4.60e-07 | 4.83e-07 | 5.15e-07 | 5.48e-07 | 5.82e-07 | 6.39e-07 | 7.14e-07 | 8.77e-07 | 1.04e-06 | 4.84e-07 |
| Xe-131m | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Zn-65 | 4.69e-10 | 6.16e-10 | 7.76e-10 | 9.07e-10 | 1.04e-09 | 1.15e-09 | 1.30e-09 | 1.43e-09 | 1.56e-09 | 1.70e-09 | 1.90e-09 | 2.12e-09 | 2.34e-09 | 2.61e-09 | 2.94e-09 | 3.35e-09 | 3.84e-09 | 4.57e-09 | 5.64e-09 | 2.23e-09 |

Table E-4a Landfill (Municipal Solid Waste) Neighbor

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 4.16e-13 | 7.69e-12 | 1.37e-11 | 1.66e-11 | 1.86e-11 | 2.01e-11 | 2.13e-11 | 2.25e-11 | 2.35e-11 | 2.47e-11 | 2.57e-11 | 2.67e-11 | 2.80e-11 | 2.94e-11 | 3.08e-11 | 3.26e-11 | 3.45e-11 | 3.76e-11 | 4.77e-11 | 1.28e-10 |
| Am-241 | 2.01e-07 | 1.44e-06 | 1.98e-06 | 2.26e-06 | 2.50e-06 | 2.76e-06 | 2.98e-06 | 3.29e-06 | 3.64e-06 | 4.01e-06 | 4.51e-06 | 5.05e-06 | 5.71e-06 | 6.50e-06 | 7.92e-06 | 1.02e-05 | 1.34e-05 | 1.85e-05 | 3.72e-05 | 1.04e-05 |
| Be-7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C-14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.30e-07 | 4.81e-05 | 1.12e-04 |
| Ce-141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Co-57 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Co-60 | 2.78e-33 | 3.19e-32 | 5.41e-32 | 7.53e-32 | 9.99e-32 | 1.26e-31 | 1.55e-31 | 1.89e-31 | 2.23e-31 | 2.67e-31 | 3.24e-31 | 3.89e-31 | 4.87e-31 | 6.26e-31 | 7.45e-31 | 9.77e-31 | 1.25e-30 | 1.72e-30 | 2.95e-30 | 1.45e-23 |
| Cr-51 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cs-134 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8.14e-41 |
| Cs-137 | 2.50e-12 | 7.30e-12 | 1.08e-11 | 1.50e-11 | 1.87e-11 | 2.32e-11 | 2.84e-11 | 3.31e-11 | 3.76e-11 | 4.36e-11 | 5.15e-11 | 6.17e-11 | 7.33e-11 | 8.56e-11 | 9.74e-11 | 1.20e-10 | 1.49e-10 | 1.88e-10 | 2.76e-10 | 3.78e-10 |
| Eu-154 | 6.55e-25 | 1.04e-23 | 1.62e-23 | 1.99e-23 | 2.26e-23 | 2.50e-23 | 2.78e-23 | 3.03e-23 | 3.30e-23 | 3.65e-23 | 4.20e-23 | 5.00e-23 | 5.78e-23 | 6.77e-23 | 7.99e-23 | 1.01e-22 | 1.28e-22 | 1.71e-22 | 2.70e-22 | 2.15e-17 |
| Fe-59 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| H-3 | 0 | 0 | 0 | 0 | 0 | 9.16e-41 | 3.79e-35 | 5.87e-30 | 1.26e-24 | 3.30e-21 | 1.97e-18 | 1.22e-16 | 1.06e-14 | 5.32e-13 | 1.91e-11 | 3.44e-10 | 4.65e-09 | 3.54e-08 | 3.01e-07 | 6.59e-08 |
| I-125 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| I-131 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| In-111 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| K-40 | 7.43e-14 | 3.96e-13 | 1.12e-12 | 2.55e-12 | 4.80e-12 | 8.36e-12 | 1.41e-11 | 2.18e-11 | 3.77e-11 | 5.68e-11 | 8.50e-11 | 1.31e-10 | 1.91e-10 | 2.64e-10 | 4.32e-10 | 7.96e-10 | 8.22e-09 | 8.26e-07 | 9.19e-06 | 1.32e-06 |
| La-138 | 1.88e-36 | 1.07e-27 | 9.30e-22 | 2.05e-17 | 1.36e-14 | 1.47e-12 | 3.48e-11 | 4.06e-10 | 1.68e-09 | 5.36e-09 | 1.36e-08 | 2.37e-08 | 3.54e-08 | 4.82e-08 | 7.23e-08 | 1.17e-07 | 6.78e-07 | 4.88e-05 | 7.72e-04 | 1.99e-04 |
| Np-237 | 2.87e-10 | 8.81e-10 | 5.50e-09 | 4.48e-08 | 2.68e-07 | 7.80e-07 | 1.70e-06 | 2.97e-06 | 4.97e-06 | 6.69e-06 | 8.78e-06 | 1.07e-05 | 1.40e-05 | 1.87e-05 | 2.56e-05 | 5.12e-05 | 3.43e-04 | 1.53e-02 | 1.37e-01 | 3.22e-02 |
| Pa-231 | 7.46e-09 | 2.69e-06 | 1.51e-05 | 4.06e-05 | 6.13e-05 | 7.91e-05 | 9.40e-05 | 1.03e-04 | 1.11e-04 | 1.18e-04 | 1.26e-04 | 1.33e-04 | 1.40e-04 | 1.50e-04 | 1.59e-04 | 1.70e-04 | 1.81e-04 | 2.01e-04 | 2.44e-04 | 1.68e-03 |
| Pb-210 | 3.12e-12 | 5.60e-12 | 8.04e-12 | 1.07e-11 | 1.39e-11 | 1.74e-11 | 2.07e-11 | 2.51e-11 | 2.94e-11 | 3.51e-11 | 4.16e-11 | 4.94e-11 | 5.89e-11 | 7.01e-11 | 8.52e-11 | 1.05e-10 | 1.30e-10 | 1.74e-10 | 2.54e-10 | 7.27e-11 |
| Po-210 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pu-238 | 4.27e-08 | 5.29e-08 | 5.84e-08 | 6.31e-08 | 6.80e-08 | 7.17e-08 | 7.58e-08 | 8.13e-08 | 8.81e-08 | 9.48e-08 | 1.04e-07 | 1.13e-07 | 1.27e-07 | 1.47e-07 | 1.74e-07 | 2.05e-07 | 2.59e-07 | 3.27e-07 | 5.10e-07 | 1.79e-07 |
| Pu-239 | 4.80e-06 | 6.10e-06 | 7.02e-06 | 7.69e-06 | 8.27e-06 | 8.89e-06 | 9.50e-06 | 1.05e-05 | 1.12e-05 | 1.21e-05 | 1.31e-05 | 1.45e-05 | 1.61e-05 | 1.84e-05 | 2.10e-05 | 2.51e-05 | 2.97e-05 | 3.80e-05 | 5.58e-05 | 1.88e-05 |
| Ra-226 | 1.27e-03 | 1.32e-03 | 1.34e-03 | 1.35e-03 | 1.36e-03 | 1.36e-03 | 1.37e-03 | 1.38e-03 | 1.39e-03 | 1.40e-03 | 1.41e-03 | 1.42e-03 | 1.44e-03 | 1.46e-03 | 1.49e-03 | 1.53e-03 | 1.59e-03 | 1.67e-03 | 1.95e-03 | 1.47e-03 |
| Ra-228 | 5.33e-28 | 6.12e-28 | 6.79e-28 | 7.53e-28 | 8.13e-28 | 8.83e-28 | 9.63e-28 | 1.05e-27 | 1.15e-27 | 1.25e-27 | 1.40e-27 | 1.54e-27 | 1.74e-27 | 2.01e-27 | 2.26e-27 | 2.65e-27 | 3.22e-27 | 4.17e-27 | 5.93e-27 | 1.97e-27 |
| Sm-153 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sr-89 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sr-90 | 2.57e-18 | 1.25e-15 | 1.79e-14 | 1.15e-13 | 3.62e-13 | 7.56e-13 | 1.04e-12 | 1.36e-12 | 1.67e-12 | 2.07e-12 | 2.50e-12 | 3.10e-12 | 3.70e-12 | 4.61e-12 | 5.84e-12 | 7.04e-12 | 9.22e-12 | 1.40e-11 | 3.06e-11 | 1.08e-08 |
| Th-228 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Th-229 | 6.31e-06 | 2.29e-05 | 2.81e-05 | 3.18e-05 | 3.43e-05 | 3.66e-05 | 3.89e-05 | 4.12e-05 | 4.38e-05 | 4.67e-05 | 5.01e-05 | 5.49e-05 | 6.13e-05 | 6.99e-05 | 7.97e-05 | 9.32e-05 | 1.16e-04 | 1.15e-04 | 2.25e-04 | 7.34e-05 |
| Th-230 | 2.11e-04 | 3.77e-04 | 4.88e-04 | 5.43e-04 | 5.64e-04 | 5.75e-04 | 5.81e-04 | 5.87e-04 | 5.93e-04 | 6.01e-04 | 6.08e-04 | 6.17e-04 | 6.29e-04 | 6.43e-04 | 6.55e-04 | 6.89e-04 | 7.22e-04 | 7.78e-04 | 8.95e-04 | 6.04e-04 |

Table E-4a Landfill (Municipal Solid Waste) Neighbor (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 1.52e-03 | 4.81e-03 | 6.48e-03 | 7.18e-03 | 7.41e-03 | 7.55e-03 | 7.64e-03 | 7.69e-03 | 7.72e-03 | 7.74e-03 | 7.75e-03 | 7.76e-03 | 7.77e-03 | 7.78e-03 | 7.78e-03 | 7.80e-03 | 7.82e-03 | 7.85e-03 | 7.93e-03 | 7.01e-03 |
| Tl-201 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tl-202 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| U-233 | 2.15e-07 | 4.19e-07 | 6.77e-07 | 1.26e-06 | 1.79e-06 | 2.71e-06 | 3.61e-06 | 4.27e-06 | 4.84e-06 | 5.29e-06 | 5.80e-06 | 6.34e-06 | 6.80e-06 | 7.45e-06 | 8.46e-06 | 9.79e-06 | 1.19e-05 | 1.46e-05 | 2.46e-05 | 1.46e-04 |
| U-234 | 2.55e-07 | 4.20e-07 | 6.57e-07 | 1.07e-06 | 1.57e-06 | 2.15e-06 | 2.71e-06 | 3.25e-06 | 3.76e-06 | 4.16e-06 | 4.47e-06 | 4.70e-06 | 4.94e-06 | 5.16e-06 | 5.35e-06 | 5.58e-06 | 5.83e-06 | 6.28e-06 | 7.32e-06 | 4.52e-05 |
| U-235 | 9.70e-08 | 1.87e-07 | 3.41e-07 | 6.22e-07 | 1.03e-06 | 1.49e-06 | 1.85e-06 | 2.26e-06 | 2.66e-06 | 3.12e-06 | 3.47e-06 | 3.81e-06 | 4.17e-06 | 4.55e-06 | 4.95e-06 | 5.43e-06 | 5.95e-06 | 6.64e-06 | 8.23e-06 | 1.38e-04 |
| U-238 | 4.21e-10 | 1.13e-09 | 1.12e-08 | 1.20e-07 | 3.08e-07 | 6.03e-07 | 8.94e-07 | 1.11e-06 | 1.28e-06 | 1.44e-06 | 1.54e-06 | 1.66e-06 | 1.81e-06 | 1.93e-06 | 2.07e-06 | 2.19e-06 | 2.39e-06 | 2.65e-06 | 3.71e-06 | 3.70e-05 |
| Xe-131m | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Zn-65 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table E-4b Landfill (Surface Impoundment) Neighbor

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 4.63e-11 | 4.77e-10 | 7.32e-10 | 8.73e-10 | 9.67e-10 | 1.03e-09 | 1.08e-09 | 1.14e-09 | 1.19e-09 | 1.24e-09 | 1.29e-09 | 1.35e-09 | 1.41e-09 | 1.48e-09 | 1.57e-09 | 1.64e-09 | 1.75e-09 | 1.95e-09 | 2.48e-09 | 3.75e-08 |
| Am-241 | 2.09e-05 | 7.07e-05 | 8.62e-05 | 9.48e-05 | 1.04e-04 | 1.14e-04 | 1.22e-04 | 1.32e-04 | 1.44e-04 | 1.58e-04 | 1.73e-04 | 1.93e-04 | 2.25e-04 | 2.63e-04 | 3.11e-04 | 3.79e-04 | 5.24e-04 | 7.95e-04 | 1.90e-03 | 4.88e-04 |
| Be-7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C-14 | 1.45e-15 | 8.87e-13 | 1.51e-10 | 2.11e-09 | 8.83e-09 | 1.64e-08 | 2.41e-08 | 3.07e-08 | 3.74e-08 | 4.54e-08 | 5.52e-08 | 6.64e-08 | 8.57e-08 | 1.28e-07 | 2.41e-07 | 9.99e-07 | 8.09e-06 | 2.84e-05 | 6.02e-03 | 8.31e-03 |
| Ce-141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Co-57 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Co-60 | 4.15e-31 | 2.40e-30 | 3.71e-30 | 4.93e-30 | 6.15e-30 | 7.43e-30 | 8.98e-30 | 1.05e-29 | 1.30e-29 | 1.60e-29 | 1.87e-29 | 2.22e-29 | 2.59e-29 | 3.11e-29 | 3.78e-29 | 4.84e-29 | 6.62e-29 | 9.31e-29 | 1.68e-28 | 9.93e-25 |
| Cr-51 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cs-134 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cs-137 | 2.20e-10 | 4.11e-10 | 6.12e-10 | 8.34e-10 | 1.04e-09 | 1.27e-09 | 1.50e-09 | 1.71e-09 | 2.00e-09 | 2.33e-09 | 2.64e-09 | 3.07e-09 | 3.55e-09 | 4.23e-09 | 5.26e-09 | 6.21e-09 | 7.76e-09 | 1.01e-08 | 1.39e-08 | 4.24e-09 |
| Eu-154 | 1.48e-22 | 8.77e-22 | 1.22e-21 | 1.43e-21 | 1.59e-21 | 1.77e-21 | 1.93e-21 | 2.12e-21 | 2.31e-21 | 2.50e-21 | 2.74e-21 | 3.01e-21 | 3.34e-21 | 3.83e-21 | 4.52e-21 | 5.52e-21 | 7.03e-21 | 9.27e-21 | 1.42e-20 | 4.40e-21 |
| Fe-59 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| H-3 | 2.03e-35 | 1.51e-32 | 1.78e-30 | 4.49e-28 | 2.14e-26 | 2.22e-24 | 9.56e-23 | 3.95e-21 | 1.05e-19 | 1.63e-18 | 9.84e-17 | 2.51e-14 | 1.56e-12 | 6.68e-11 | 3.04e-09 | 2.57e-08 | 2.63e-07 | 1.89e-06 | 1.66e-05 | 3.39e-06 |
| I-125 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| I-131 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| In-111 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| K-40 | 2.01e-11 | 8.30e-11 | 2.44e-10 | 4.28e-10 | 7.43e-10 | 1.21e-09 | 1.75e-09 | 2.54e-09 | 3.59e-09 | 4.83e-09 | 6.30e-09 | 8.52e-09 | 1.14e-08 | 1.65e-08 | 2.32e-08 | 3.49e-08 | 2.47e-07 | 3.55e-05 | 4.26e-04 | 6.08e-05 |
| La-138 | 7.26e-36 | 9.45e-24 | 1.10e-18 | 2.79e-15 | 1.06e-11 | 8.84e-10 | 1.30e-08 | 6.16e-08 | 2.04e-07 | 5.33e-07 | 9.24e-07 | 1.47e-06 | 2.00e-06 | 2.79e-06 | 4.63e-06 | 8.51e-06 | 7.92e-05 | 3.25e-03 | 4.45e-02 | 1.09e-02 |
| Np-237 | 4.26e-08 | 1.07e-07 | 6.66e-07 | 6.01e-06 | 2.91e-05 | 5.87e-05 | 1.29e-04 | 2.01e-04 | 2.70e-04 | 3.42e-04 | 4.11e-04 | 4.85e-04 | 5.84e-04 | 7.76e-04 | 1.22e-03 | 2.66e-03 | 4.71e-02 | 1.13e+00 | 1.18e+01 | 2.51e+00 |
| Pa-231 | 2.06e-06 | 2.01e-04 | 1.06e-03 | 1.96e-03 | 2.89e-03 | 3.44e-03 | 3.92e-03 | 4.27e-03 | 4.58e-03 | 4.88e-03 | 5.12e-03 | 5.39e-03 | 5.73e-03 | 6.03e-03 | 6.36e-03 | 6.76e-03 | 7.30e-03 | 8.38e-03 | 1.04e-02 | 3.80e-02 |
| Pb-210 | 1.97e-10 | 3.18e-10 | 4.30e-10 | 5.88e-10 | 7.35e-10 | 8.98e-10 | 1.08e-09 | 1.31e-09 | 1.54e-09 | 1.82e-09 | 2.17e-09 | 2.53e-09 | 2.92e-09 | 3.62e-09 | 4.31e-09 | 5.28e-09 | 6.66e-09 | 9.18e-09 | 1.52e-08 | 3.96e-09 |
| Po-210 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pu-238 | 2.20e-06 | 2.59e-06 | 2.87e-06 | 3.11e-06 | 3.32e-06 | 3.56e-06 | 3.83e-06 | 4.13e-06 | 4.45e-06 | 4.80e-06 | 5.29e-06 | 5.80e-06 | 6.52e-06 | 7.42e-06 | 8.55e-06 | 1.00e-05 | 1.29e-05 | 1.65e-05 | 2.52e-06 | 8.45e-06 |
| Pu-239 | 1.90e-04 | 2.45e-04 | 2.80e-04 | 3.06e-04 | 3.31e-04 | 3.55e-04 | 3.81e-04 | 4.09e-04 | 4.37e-04 | 4.72e-04 | 5.25e-04 | 5.84e-04 | 6.52e-04 | 7.32e-04 | 8.47e-04 | 9.68e-04 | 1.20e-03 | 1.62e-03 | 2.37e-03 | 7.82e-04 |
| Ra-226 | 6.60e-02 | 6.80e-02 | 6.90e-02 | 6.94e-02 | 6.98e-02 | 7.00e-02 | 7.03e-02 | 7.06e-02 | 7.09e-02 | 7.12e-02 | 7.17e-02 | 7.23e-02 | 7.30e-02 | 7.39e-02 | 7.49e-02 | 7.64e-02 | 7.83e-02 | 8.18e-02 | 8.88e-02 | 7.38e-02 |
| Ra-228 | 2.67e-26 | 3.08e-26 | 3.43e-26 | 3.74e-26 | 4.14e-26 | 4.57e-26 | 4.96e-26 | 5.48e-26 | 6.08e-26 | 6.74e-26 | 7.53e-26 | 8.29e-26 | 9.23e-26 | 1.05e-25 | 1.18e-25 | 1.37e-25 | 1.62e-25 | 2.12e-25 | 3.24e-25 | 4.25e-21 |
| Sm-153 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sr-89 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sr-90 | 2.72e-16 | 3.51e-13 | 6.16e-12 | 1.84e-11 | 3.39e-11 | 5.08e-11 | 6.96e-11 | 8.56e-11 | 1.04e-10 | 1.25e-10 | 1.42e-10 | 1.71e-10 | 2.06e-10 | 2.60e-10 | 3.29e-10 | 4.33e-10 | 5.96e-10 | 8.27e-10 | 1.58e-09 | 2.06e-05 |
| Th-228 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Th-229 | 3.73e-04 | 9.62e-04 | 1.13e-03 | 1.27e-03 | 1.41e-03 | 1.51e-03 | 1.58e-03 | 1.68e-03 | 1.80e-03 | 1.91e-03 | 2.06e-03 | 2.21e-03 | 2.43e-03 | 2.73e-03 | 3.07e-03 | 3.57e-03 | 4.43e-03 | 5.88e-03 | 9.45e-03 | 3.12e-03 |
| Th-230 | 1.22e-02 | 2.28e-02 | 2.69e-02 | 2.91e-02 | 3.00e-02 | 3.04e-02 | 3.07e-02 | 3.09e-02 | 3.12e-02 | 3.15e-02 | 3.18e-02 | 3.22e-02 | 3.27e-02 | 3.33e-02 | 3.41e-02 | 3.50e-02 | 3.65e-02 | 3.87e-02 | 4.32e-02 | 3.13e-02 |

Table E-4b Landfill (Surface Impoundment) Neighbor (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 1.32e-01 | 2.92e-01 | 3.44e-01 | 3.75e-01 | 3.87e-01 | 3.92e-01 | 3.95e-01 | 3.96e-01 | 3.98e-01 | 3.98e-01 | 3.99e-01 | 3.99e-01 | 4.00e-01 | 4.00e-01 | 4.00e-01 | 4.01e-01 | 4.01e-01 | 4.03e-01 | 4.06e-01 | 3.65e-01 |
| Tl-201 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tl-202 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| U-233 | 8.89e-06 | 1.92e-05 | 3.41e-05 | 5.99e-05 | 9.35e-05 | 1.25e-04 | 1.56e-04 | 1.83e-04 | 2.01e-04 | 2.20e-04 | 2.37e-04 | 2.59e-04 | 2.83e-04 | 3.05e-04 | 3.36e-04 | 3.86e-04 | 4.50e-04 | 6.07e-04 | 9.33e-04 | 4.33e-03 |
| U-234 | 1.43e-05 | 2.37e-05 | 4.13e-05 | 6.04e-05 | 8.87e-05 | 1.13e-04 | 1.43e-04 | 1.67e-04 | 1.89e-04 | 2.05e-04 | 2.18e-04 | 2.28e-04 | 2.35e-04 | 2.43e-04 | 2.53e-04 | 2.65e-04 | 2.76e-04 | 3.00e-04 | 3.41e-04 | 5.00e-04 |
| U-235 | 1.50e-06 | 5.77e-06 | 1.35e-05 | 3.22e-05 | 4.76e-05 | 6.61e-05 | 8.46e-05 | 1.02e-04 | 1.17e-04 | 1.29e-04 | 1.45e-04 | 1.60e-04 | 1.73e-04 | 1.85e-04 | 2.01e-04 | 2.17e-04 | 2.36e-04 | 2.67e-04 | 3.36e-04 | 5.32e-03 |
| U-238 | 3.77e-09 | 9.81e-08 | 1.95e-06 | 7.84e-06 | 1.71e-05 | 2.70e-05 | 3.98e-05 | 4.65e-05 | 5.22e-05 | 5.87e-05 | 6.42e-05 | 6.85e-05 | 7.37e-05 | 7.78e-05 | 8.27e-05 | 8.78e-05 | 9.34e-05 | 1.06e-04 | 1.38e-04 | 2.02e-03 |
| Xe-131m | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Zn-65 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table E-5 Incinerator Neighbor

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 5.79e+00 | 6.35e+00 | 6.78e+00 | 7.14e+00 | 7.46e+00 | 7.75e+00 | 8.01e+00 | 8.26e+00 | 8.49e+00 | 8.71e+00 | 8.95e+00 | 9.19e+00 | 9.46e+00 | 9.74e+00 | 1.00e+01 | 1.04e+01 | 1.08e+01 | 1.12e+01 | 1.18e+01 | 8.76e+00 |
| Am-241 | 3.94e-01 | 4.32e-01 | 4.60e-01 | 4.85e-01 | 5.06e-01 | 5.25e-01 | 5.43e-01 | 5.60e-01 | 5.75e-01 | 5.90e-01 | 6.06e-01 | 6.23e-01 | 6.39e-01 | 6.58e-01 | 6.79e-01 | 7.02e-01 | 7.29e-01 | 7.61e-01 | 7.99e-01 | 5.94e-01 |
| Bc-7 | 3.61e-07 | 3.88e-07 | 4.13e-07 | 4.34e-07 | 4.57e-07 | 4.76e-07 | 4.94e-07 | 5.15e-07 | 5.40e-07 | 5.63e-07 | 5.90e-07 | 6.11e-07 | 6.38e-07 | 6.71e-07 | 7.04e-07 | 7.50e-07 | 8.16e-07 | 9.04e-07 | 1.09e-06 | 6.15e-07 |
| C-14 | 1.95e-07 | 2.14e-07 | 2.28e-07 | 2.39e-07 | 2.51e-07 | 2.61e-07 | 2.69e-07 | 2.78e-07 | 2.86e-07 | 2.92e-07 | 3.01e-07 | 3.09e-07 | 3.18e-07 | 3.28e-07 | 3.38e-07 | 3.50e-07 | 3.63e-07 | 3.79e-07 | 3.99e-07 | 2.95e-07 |
| Ce-141 | 1.75e-06 | 1.86e-06 | 1.93e-06 | 2.01e-06 | 2.07e-06 | 2.13e-06 | 2.18e-06 | 2.23e-06 | 2.28e-06 | 2.33e-06 | 2.37e-06 | 2.42e-06 | 2.48e-06 | 2.54e-06 | 2.59e-06 | 2.69e-06 | 2.76e-06 | 2.86e-06 | 3.02e-06 | 2.35e-06 |
| Co-57 | 1.90e-05 | 2.11e-05 | 2.28e-05 | 2.44e-05 | 2.57e-05 | 2.72e-05 | 2.87e-05 | 2.99e-05 | 3.19e-05 | 3.38e-05 | 3.56e-05 | 3.86e-05 | 4.11e-05 | 4.50e-05 | 4.94e-05 | 5.36e-05 | 6.04e-05 | 7.35e-05 | 1.02e-04 | 4.38e-05 |
| Co-60 | 2.11e-03 | 2.38e-03 | 2.57e-03 | 2.75e-03 | 2.91e-03 | 3.12e-03 | 3.25e-03 | 3.43e-03 | 3.62e-03 | 3.82e-03 | 4.02e-03 | 4.20e-03 | 4.44e-03 | 4.65e-03 | 4.85e-03 | 5.24e-03 | 5.71e-03 | 6.50e-03 | 7.97e-03 | 4.29e-03 |
| Cr-51 | 1.98e-07 | 2.24e-07 | 2.49e-07 | 2.70e-07 | 2.84e-07 | 3.03e-07 | 3.20e-07 | 3.40e-07 | 3.61e-07 | 3.82e-07 | 4.08e-07 | 4.30e-07 | 4.64e-07 | 4.96e-07 | 5.33e-07 | 5.90e-07 | 6.44e-07 | 7.21e-07 | 8.78e-07 | 4.37e-07 |
| Cs-134 | 1.46e-03 | 1.66e-03 | 1.87e-03 | 2.01e-03 | 2.16e-03 | 2.29e-03 | 2.45e-03 | 2.61e-03 | 2.77e-03 | 2.96e-03 | 3.16e-03 | 3.38e-03 | 3.58e-03 | 3.89e-03 | 4.20e-03 | 4.50e-03 | 4.93e-03 | 5.56e-03 | 6.69e-03 | 3.40e-03 |
| Cs-137 | 2.74e-03 | 3.26e-03 | 3.57e-03 | 3.89e-03 | 4.15e-03 | 4.42e-03 | 4.73e-03 | 4.94e-03 | 5.23e-03 | 5.57e-03 | 5.90e-03 | 6.40e-03 | 6.83e-03 | 7.31e-03 | 7.81e-03 | 8.80e-03 | 9.78e-03 | 1.11e-02 | 1.43e-02 | 6.68e-03 |
| Eu-154 | 1.67e-03 | 1.80e-03 | 1.90e-03 | 2.01e-03 | 2.12e-03 | 2.19e-03 | 2.30e-03 | 2.40e-03 | 2.50e-03 | 2.61e-03 | 2.73e-03 | 2.86e-03 | 2.99e-03 | 3.14e-03 | 3.28e-03 | 3.45e-03 | 3.63e-03 | 3.92e-03 | 4.34e-03 | 2.74e-03 |
| Fe-59 | 8.17e-05 | 9.29e-05 | 1.03e-04 | 1.11e-04 | 1.20e-04 | 1.27e-04 | 1.34e-04 | 1.42e-04 | 1.50e-04 | 1.60e-04 | 1.71e-04 | 1.80e-04 | 1.94e-04 | 2.07e-04 | 2.26e-04 | 2.45e-04 | 2.65e-04 | 2.96e-04 | 3.54e-04 | 1.82e-04 |
| H-3 | 1.54e-06 | 1.70e-06 | 1.81e-06 | 1.90e-06 | 1.99e-06 | 2.07e-06 | 2.13e-06 | 2.20e-06 | 2.27e-06 | 2.32e-06 | 2.39e-06 | 2.45e-06 | 2.53e-06 | 2.61e-06 | 2.69e-06 | 2.78e-06 | 2.88e-06 | 3.01e-06 | 3.17e-06 | 2.34e-06 |
| I-125 | 1.16e-02 | 1.37e-02 | 1.56e-02 | 1.75e-02 | 2.00e-02 | 2.19e-02 | 2.38e-02 | 2.57e-02 | 2.78e-02 | 2.99e-02 | 3.18e-02 | 3.46e-02 | 3.74e-02 | 3.97e-02 | 4.28e-02 | 4.63e-02 | 5.07e-02 | 5.86e-02 | 6.99e-02 | 3.36e-02 |
| I-131 | 2.17e-03 | 2.56e-03 | 2.92e-03 | 3.29e-03 | 3.73e-03 | 4.08e-03 | 4.46e-03 | 4.81e-03 | 5.19e-03 | 5.57e-03 | 5.91e-03 | 6.42e-03 | 6.96e-03 | 7.40e-03 | 7.97e-03 | 8.60e-03 | 9.45e-03 | 1.09e-02 | 1.31e-02 | 6.26e-03 |
| In-111 | 4.78e-08 | 5.19e-08 | 5.51e-08 | 5.81e-08 | 6.12e-08 | 6.40e-08 | 6.66e-08 | 6.98e-08 | 7.45e-08 | 7.79e-08 | 8.30e-08 | 8.83e-08 | 9.50e-08 | 1.02e-07 | 1.12e-07 | 1.29e-07 | 1.46e-07 | 1.78e-07 | 2.42e-07 | 1.04e-07 |
| K-40 | 1.03e-04 | 1.25e-04 | 1.38e-04 | 1.51e-04 | 1.65e-04 | 1.78e-04 | 1.89e-04 | 2.02e-04 | 2.15e-04 | 2.27e-04 | 2.40e-04 | 2.55e-04 | 2.72e-04 | 2.95e-04 | 3.17e-04 | 3.38e-04 | 3.71e-04 | 4.16e-04 | 4.81e-04 | 2.51e-04 |
| La-138 | 1.97e-03 | 2.23e-03 | 2.40e-03 | 2.56e-03 | 2.73e-03 | 2.87e-03 | 3.05e-03 | 3.29e-03 | 3.53e-03 | 3.84e-03 | 4.36e-03 | 5.05e-03 | 5.64e-03 | 6.19e-03 | 6.73e-03 | 7.28e-03 | 8.06e-03 | 9.14e-03 | 1.06e-02 | 4.94e-03 |
| Np-237 | 4.92e-01 | 5.38e-01 | 5.72e-01 | 6.03e-01 | 6.28e-01 | 6.51e-01 | 6.74e-01 | 6.92e-01 | 7.11e-01 | 7.31e-01 | 7.52e-01 | 7.73e-01 | 7.93e-01 | 8.17e-01 | 8.45e-01 | 8.72e-01 | 9.06e-01 | 9.40e-01 | 9.93e-01 | 7.37e-01 |
| Pa-231 | 1.17e+00 | 1.26e+00 | 1.35e+00 | 1.42e+00 | 1.48e+00 | 1.54e+00 | 1.59e+00 | 1.64e+00 | 1.68e+00 | 1.73e+00 | 1.78e+00 | 1.82e+00 | 1.87e+00 | 1.93e+00 | 1.99e+00 | 2.06e+00 | 2.13e+00 | 2.23e+00 | 2.35e+00 | 1.74e+00 |
| Pb-210 | 2.46e-02 | 2.67e-02 | 2.81e-02 | 2.89e-02 | 2.98e-02 | 3.08e-02 | 3.16e-02 | 3.23e-02 | 3.31e-02 | 3.39e-02 | 3.47e-02 | 3.54e-02 | 3.64e-02 | 3.74e-02 | 3.86e-02 | 3.98e-02 | 4.11e-02 | 4.31e-02 | 4.74e-02 | 3.47e-02 |
| Po-210 | 6.60e-03 | 7.15e-03 | 7.56e-03 | 7.88e-03 | 8.16e-03 | 8.43e-03 | 8.75e-03 | 8.98e-03 | 9.30e-03 | 9.58e-03 | 9.85e-03 | 1.01e-02 | 1.05e-02 | 1.09e-02 | 1.13e-02 | 1.20e-02 | 1.28e-02 | 1.41e-02 | 1.64e-02 | 1.02e-02 |
| Pu-238 | 3.48e-01 | 3.79e-01 | 4.05e-01 | 4.26e-01 | 4.44e-01 | 4.62e-01 | 4.77e-01 | 4.91e-01 | 5.06e-01 | 5.18e-01 | 5.33e-01 | 5.48e-01 | 5.64e-01 | 5.80e-01 | 5.99e-01 | 6.20e-01 | 6.41e-01 | 6.70e-01 | 7.04e-01 | 5.22e-01 |
| Pu-239 | 3.82e-01 | 4.17e-01 | 4.45e-01 | 4.68e-01 | 4.89e-01 | 5.08e-01 | 5.24e-01 | 5.40e-01 | 5.56e-01 | 5.70e-01 | 5.86e-01 | 6.03e-01 | 6.19e-01 | 6.37e-01 | 6.58e-01 | 6.81e-01 | 7.05e-01 | 7.36e-01 | 7.74e-01 | 5.74e-01 |
| Ra-226 | 2.97e-02 | 3.21e-02 | 3.40e-02 | 3.56e-02 | 3.70e-02 | 3.86e-02 | 4.00e-02 | 4.14e-02 | 4.29e-02 | 4.44e-02 | 4.59e-02 | 4.75e-02 | 4.92e-02 | 5.14e-02 | 5.35e-02 | 5.71e-02 | 6.27e-02 | 7.03e-02 | 8.80e-02 | 4.90e-02 |
| Ra-228 | 1.19e-02 | 1.27e-02 | 1.32e-02 | 1.37e-02 | 1.42e-02 | 1.46e-02 | 1.51e-02 | 1.56e-02 | 1.59e-02 | 1.63e-02 | 1.68e-02 | 1.72e-02 | 1.77e-02 | 1.81e-02 | 1.88e-02 | 1.93e-02 | 1.72e-02 | 2.21e-02 | 2.53e-02 | 1.72e-02 |
| Sm-153 | 5.34e-08 | 5.81e-08 | 6.12e-08 | 6.37e-08 | 6.65e-08 | 6.92e-08 | 7.17e-08 | 7.46e-08 | 7.73e-08 | 7.97e-08 | 8.44e-08 | 8.90e-08 | 9.52e-08 | 1.01e-07 | 1.09e-07 | 1.21e-07 | 1.34e-07 | 1.56e-07 | 2.03e-07 | 9.83e-08 |
| Sr-89 | 1.75e-05 | 1.91e-05 | 2.02e-05 | 2.12e-05 | 2.20e-05 | 2.28e-05 | 2.36e-05 | 2.46e-05 | 2.58e-05 | 2.70e-05 | 2.78e-05 | 2.90e-05 | 3.02e-05 | 3.16e-05 | 3.32e-05 | 3.50e-05 | 3.74e-05 | 4.12e-05 | 4.70e-05 | 2.88e-05 |
| Sr-90 | 4.29e-03 | 5.13e-03 | 5.84e-03 | 6.57e-03 | 7.19e-03 | 7.89e-03 | 8.50e-03 | 9.35e-03 | 1.01e-02 | 1.11e-02 | 1.21e-02 | 1.32e-02 | 1.48e-02 | 1.62e-02 | 1.79e-02 | 2.03e-02 | 2.34e-02 | 2.91e-02 | 3.86e-02 | 1.50e-02 |
| Th-228 | 2.56e-01 | 2.81e-01 | 2.99e-01 | 3.15e-01 | 3.30e-01 | 3.42e-01 | 3.53e-01 | 3.64e-01 | 3.74e-01 | 3.85e-01 | 3.95e-01 | 4.06e-01 | 4.17e-01 | 4.30e-01 | 4.44e-01 | 4.59e-01 | 4.76e-01 | 4.97e-01 | 5.23e-01 | 3.87e-01 |
| Th-229 | 1.89e+00 | 2.08e+00 | 2.22e+00 | 2.33e+00 | 2.44e+00 | 2.53e+00 | 2.62e+00 | 2.70e+00 | 2.77e+00 | 2.85e+00 | 2.92e+00 | 3.00e+00 | 3.09e+00 | 3.18e+00 | 3.29e+00 | 3.40e+00 | 3.52e+00 | 3.68e+00 | 3.87e+00 | 2.86e+00 |
| Th-230 | 2.85e-01 | 3.13e-01 | 3.34e-01 | 3.52e-01 | 3.68e-01 | 3.82e-01 | 3.95e-01 | 4.07e-01 | 4.18e-01 | 4.30e-01 | 4.41e-01 | 4.53e-01 | 4.66e-01 | 4.80e-01 | 4.96e-01 | 5.12e-01 | 5.31e-01 | 5.55e-01 | 5.85e-01 | 4.32e-01 |

Table E-5 Incinerator Neighbor (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 1.46e+00 | 1.60e+00 | 1.70e+00 | 1.79e+00 | 1.87e+00 | 1.95e+00 | 2.01e+00 | 2.08e+00 | 2.13e+00 | 2.18e+00 | 2.24e+00 | 2.30e+00 | 2.37e+00 | 2.44e+00 | 2.52e+00 | 2.61e+00 | 2.70e+00 | 2.82e+00 | 2.97e+00 | 2.20e+00 |
| Pt-201 | 1.99e-08 | 2.32e-08 | 2.66e-08 | 2.91e-08 | 3.21e-08 | 3.56e-08 | 3.89e-08 | 4.25e-08 | 4.67e-08 | 5.12e-08 | 5.72e-08 | 6.28e-08 | 7.13e-08 | 8.02e-08 | 9.34e-08 | 1.08e-07 | 1.28e-07 | 1.61e-07 | 2.31e-07 | 8.11e-08 |
| Pt-202 | 5.12e-07 | 5.93e-07 | 6.50e-07 | 7.16e-07 | 7.73e-07 | 8.35e-07 | 9.11e-07 | 9.82e-07 | 1.07e-06 | 1.15e-06 | 1.26e-06 | 1.38e-06 | 1.57e-06 | 1.72e-06 | 1.98e-06 | 2.27e-06 | 2.70e-06 | 3.36e-06 | 4.74e-06 | 1.75e-06 |
| U-233 | 1.19e-01 | 1.30e-01 | 1.39e-01 | 1.46e-01 | 1.52e-01 | 1.58e-01 | 1.64e-01 | 1.69e-01 | 1.73e-01 | 1.78e-01 | 1.83e-01 | 1.88e-01 | 1.93e-01 | 1.99e-01 | 2.06e-01 | 2.12e-01 | 2.20e-01 | 2.30e-01 | 2.43e-01 | 1.79e-01 |
| U-234 | 1.16e-01 | 1.27e-01 | 1.35e-01 | 1.43e-01 | 1.49e-01 | 1.55e-01 | 1.60e-01 | 1.65e-01 | 1.69e-01 | 1.74e-01 | 1.79e-01 | 1.84e-01 | 1.89e-01 | 1.95e-01 | 2.01e-01 | 2.08e-01 | 2.15e-01 | 2.25e-01 | 2.37e-01 | 1.75e-01 |
| U-235 | 1.09e-01 | 1.19e-01 | 1.27e-01 | 1.34e-01 | 1.39e-01 | 1.45e-01 | 1.50e-01 | 1.54e-01 | 1.59e-01 | 1.63e-01 | 1.67e-01 | 1.72e-01 | 1.77e-01 | 1.82e-01 | 1.88e-01 | 1.94e-01 | 2.01e-01 | 2.10e-01 | 2.22e-01 | 1.64e-01 |
| U-238 | 1.04e-01 | 1.14e-01 | 1.21e-01 | 1.28e-01 | 1.33e-01 | 1.38e-01 | 1.43e-01 | 1.48e-01 | 1.52e-01 | 1.56e-01 | 1.60e-01 | 1.64e-01 | 1.69e-01 | 1.74e-01 | 1.80e-01 | 1.86e-01 | 1.93e-01 | 2.01e-01 | 2.12e-01 | 1.57e-01 |
| Xe-131m | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Zn-65 | 3.06e-04 | 3.66e-04 | 4.20e-04 | 4.71e-04 | 5.30e-04 | 5.93e-04 | 6.41e-04 | 7.03e-04 | 7.78e-04 | 8.34e-04 | 9.03e-04 | 9.84e-04 | 1.07e-03 | 1.16e-03 | 1.28e-03 | 1.41e-03 | 1.55e-03 | 1.82e-03 | 2.28e-03 | 1.01e-03 |

Table E-6 Sludge Application Worker

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 1.71e-03 | 1.90e-03 | 2.06e-03 | 2.21e-03 | 2.35e-03 | 2.48e-03 | 2.64e-03 | 2.79e-03 | 2.96e-03 | 3.17e-03 | 3.36e-03 | 3.56e-03 | 3.83e-03 | 4.11e-03 | 4.40e-03 | 4.79e-03 | 5.32e-03 | 6.18e-03 | 7.62e-03 | 3.68e-03 |
| Am-241 | 5.08e-05 | 6.04e-05 | 6.97e-05 | 7.97e-05 | 8.89e-05 | 9.81e-05 | 1.08e-04 | 1.19e-04 | 1.31e-04 | 1.43e-04 | 1.57e-04 | 1.72e-04 | 1.88e-04 | 2.07e-04 | 2.32e-04 | 2.62e-04 | 2.98e-04 | 3.48e-04 | 4.42e-04 | 1.80e-04 |
| Be-7 | 3.79e-05 | 3.93e-05 | 3.97e-05 | 3.98e-05 | 3.99e-05 | 4.00e-05 | 4.00e-05 | 4.00e-05 | 3.95e-05 |
| C-14 | 3.66e-08 | 4.26e-08 | 4.70e-08 | 5.16e-08 | 5.66e-08 | 6.11e-08 | 6.61e-08 | 7.03e-08 | 7.53e-08 | 8.05e-08 | 8.58e-08 | 9.18e-08 | 9.89e-08 | 1.06e-07 | 1.13e-07 | 1.22e-07 | 1.32e-07 | 1.47e-07 | 1.71e-07 | 8.93e-08 |
| Ce-141 | 2.59e-05 | 2.60e-05 |
| Co-57 | 1.81e-04 | 1.94e-04 | 1.99e-04 | 2.01e-04 | 2.02e-04 | 2.03e-04 | 2.04e-04 | 2.04e-04 | 2.04e-04 | 2.04e-04 | 2.04e-04 | 2.05e-04 | 2.00e-04 |
| Co-60 | 8.55e-03 | 9.28e-03 | 9.54e-03 | 9.67e-03 | 9.74e-03 | 9.78e-03 | 9.81e-03 | 9.82e-03 | 9.84e-03 | 9.85e-03 | 9.85e-03 | 9.86e-03 | 9.86e-03 | 9.86e-03 | 9.87e-03 | 9.87e-03 | 9.87e-03 | 9.87e-03 | 9.87e-03 | 9.61e-03 |
| Cr-51 | 1.16e-05 | 1.22e-05 | 1.24e-05 | 1.25e-05 | 1.26e-05 | 1.26e-05 | 1.26e-05 | 1.27e-05 | 1.25e-05 |
| Cs-134 | 5.04e-03 | 5.22e-03 | 5.28e-03 | 5.31e-03 | 5.32e-03 | 5.33e-03 | 5.34e-03 | 5.34e-03 | 5.34e-03 | 5.35e-03 | 5.29e-03 |
| Cs-137 | 2.12e-03 | 2.19e-03 | 2.22e-03 | 2.23e-03 | 2.23e-03 | 2.24e-03 | 2.24e-03 | 2.24e-03 | 2.24e-03 | 2.25e-03 | 2.22e-03 |
| Eu-154 | 4.13e-03 | 4.54e-03 | 4.64e-03 | 4.68e-03 | 4.70e-03 | 4.71e-03 | 4.72e-03 | 4.72e-03 | 4.73e-03 | 4.62e-03 |
| Fe-59 | 8.19e-04 | 8.57e-04 | 8.68e-04 | 8.73e-04 | 8.76e-04 | 8.78e-04 | 8.79e-04 | 8.79e-04 | 8.80e-04 | 8.80e-04 | 8.80e-04 | 8.80e-04 | 8.81e-04 | 8.69e-04 |
| H-3 | 6.46e-08 | 7.67e-08 | 8.77e-08 | 9.62e-08 | 1.03e-07 | 1.12e-07 | 1.20e-07 | 1.30e-07 | 1.40e-07 | 1.49e-07 | 1.60e-07 | 1.71e-07 | 1.85e-07 | 1.99e-07 | 2.13e-07 | 2.32e-07 | 2.55e-07 | 2.85e-07 | 3.36e-07 | 1.68e-07 |
| I-125 | 1.11e-07 | 1.32e-07 | 1.45e-07 | 1.58e-07 | 1.69e-07 | 1.76e-07 | 1.82e-07 | 1.87e-07 | 1.91e-07 | 1.95e-07 | 1.97e-07 | 1.99e-07 | 2.00e-07 | 2.02e-07 | 2.02e-07 | 2.03e-07 | 2.04e-07 | 2.04e-07 | 2.05e-07 | 1.80e-07 |
| I-131 | 4.47e-05 | 4.61e-05 | 4.69e-05 | 4.75e-05 | 4.78e-05 | 4.81e-05 | 4.83e-05 | 4.84e-05 | 4.86e-05 | 4.87e-05 | 4.87e-05 | 4.88e-05 | 4.88e-05 | 4.89e-05 | 4.89e-05 | 4.89e-05 | 4.89e-05 | 4.89e-05 | 4.90e-05 | 4.80e-05 |
| In-111 | 2.73e-05 |
| K-40 | 5.27e-04 | 5.50e-04 | 5.64e-04 | 5.74e-04 | 5.83e-04 | 5.90e-04 | 5.97e-04 | 6.02e-04 | 6.07e-04 | 6.11e-04 | 6.15e-04 | 6.20e-04 | 6.24e-04 | 6.27e-04 | 6.32e-04 | 6.36e-04 | 6.40e-04 | 6.45e-04 | 6.51e-04 | 6.03e-04 |
| La-138 | 8.98e-04 | 1.23e-03 | 1.59e-03 | 2.03e-03 | 2.64e-03 | 3.20e-03 | 3.64e-03 | 4.01e-03 | 4.32e-03 | 4.56e-03 | 4.72e-03 | 4.83e-03 | 4.91e-03 | 4.98e-03 | 5.01e-03 | 5.04e-03 | 5.06e-03 | 5.07e-03 | 5.08e-03 | 3.78e-03 |
| Np-237 | 3.88e-04 | 5.49e-04 | 6.54e-04 | 7.10e-04 | 7.41e-04 | 7.61e-04 | 7.75e-04 | 7.89e-04 | 8.04e-04 | 8.18e-04 | 8.34e-04 | 8.55e-04 | 8.74e-04 | 8.98e-04 | 9.25e-04 | 9.56e-04 | 9.99e-04 | 1.06e-03 | 1.17e-03 | 8.20e-04 |
| Pa-231 | 3.27e-04 | 4.86e-04 | 6.36e-04 | 8.11e-04 | 1.02e-03 | 1.23e-03 | 1.45e-03 | 1.64e-03 | 1.84e-03 | 2.06e-03 | 2.29e-03 | 2.51e-03 | 2.74e-03 | 3.03e-03 | 3.40e-03 | 3.79e-03 | 4.34e-03 | 5.06e-03 | 6.41e-03 | 2.50e-03 |
| Pb-210 | 4.46e-06 | 4.97e-06 | 5.46e-06 | 5.94e-06 | 6.38e-06 | 6.86e-06 | 7.34e-06 | 7.84e-06 | 8.38e-06 | 8.95e-06 | 9.54e-06 | 1.03e-05 | 1.10e-05 | 1.20e-05 | 1.31e-05 | 1.45e-05 | 1.65e-05 | 1.89e-05 | 2.34e-05 | 1.08e-05 |
| Po-210 | 3.40e-07 | 4.46e-07 | 5.41e-07 | 6.33e-07 | 7.30e-07 | 8.19e-07 | 9.17e-07 | 1.02e-06 | 1.12e-06 | 1.24e-06 | 1.36e-06 | 1.51e-06 | 1.67e-06 | 1.86e-06 | 2.08e-06 | 2.35e-06 | 2.72e-06 | 3.22e-06 | 4.16e-06 | 1.62e-06 |
| Pu-238 | 2.98e-05 | 3.91e-05 | 4.76e-05 | 5.62e-05 | 6.48e-05 | 7.29e-05 | 8.19e-05 | 9.14e-05 | 1.01e-04 | 1.11e-04 | 1.23e-04 | 1.36e-04 | 1.50e-04 | 1.68e-04 | 1.88e-04 | 2.14e-04 | 2.48e-04 | 2.91e-04 | 3.75e-04 | 1.46e-04 |
| Pu-239 | 3.27e-05 | 4.24e-05 | 5.14e-05 | 6.15e-05 | 7.10e-05 | 7.95e-05 | 8.85e-05 | 9.98e-05 | 1.12e-04 | 1.25e-04 | 1.37e-04 | 1.52e-04 | 1.68e-04 | 1.86e-04 | 2.09e-04 | 2.39e-04 | 2.74e-04 | 3.24e-04 | 4.16e-04 | 1.59e-04 |
| Ra-226 | 7.37e-03 | 7.38e-03 | 7.39e-03 | 7.39e-03 | 7.39e-03 | 7.39e-03 | 7.39e-03 | 7.39e-03 | 7.40e-03 | 7.40e-03 | 7.40e-03 | 7.41e-03 | 7.41e-03 | 7.39e-03 |
| Ra-228 | 6.15e-03 | 6.37e-03 | 6.43e-03 | 6.46e-03 | 6.47e-03 | 6.48e-03 | 6.50e-03 | 6.51e-03 | 6.52e-03 | 6.53e-03 | 6.54e-03 | 6.55e-03 | 6.57e-03 | 6.58e-03 | 6.60e-03 | 6.62e-03 | 6.64e-03 | 6.68e-03 | 6.74e-03 | 6.49e-03 |
| Sm-153 | 1.78e-06 |
| Sr-89 | 9.58e-07 | 1.04e-06 | 1.08e-06 | 1.10e-06 | 1.12e-06 | 1.13e-06 | 1.13e-06 | 1.14e-06 | 1.14e-06 | 1.14e-06 | 1.15e-06 | 1.11e-06 |
| Sr-90 | 1.02e-05 | 1.25e-05 | 1.39e-05 | 1.46e-05 | 1.50e-05 | 1.53e-05 | 1.55e-05 | 1.56e-05 | 1.58e-05 | 1.58e-05 | 1.59e-05 | 1.59e-05 | 1.60e-05 | 1.60e-05 | 1.61e-05 | 1.62e-05 | 1.63e-05 | 1.64e-05 | 1.67e-05 | 1.51e-05 |
| Th-228 | 5.68e-03 | 5.77e-03 | 5.80e-03 | 5.82e-03 | 5.84e-03 | 5.85e-03 | 5.87e-03 | 5.88e-03 | 5.90e-03 | 5.91e-03 | 5.93e-03 | 5.94e-03 | 5.96e-03 | 5.99e-03 | 6.01e-03 | 6.04e-03 | 6.08e-03 | 6.13e-03 | 6.23e-03 | 5.90e-03 |
| Th-229 | 1.20e-03 | 1.25e-03 | 1.30e-03 | 1.35e-03 | 1.39e-03 | 1.44e-03 | 1.49e-03 | 1.54e-03 | 1.60e-03 | 1.66e-03 | 1.72e-03 | 1.79e-03 | 1.86e-03 | 1.96e-03 | 2.06e-03 | 2.19e-03 | 2.41e-03 | 2.68e-03 | 3.15e-03 | 1.84e-03 |
| Th-230 | 1.00e-04 | 1.82e-04 | 2.86e-04 | 4.05e-04 | 5.47e-04 | 7.30e-04 | 9.22e-04 | 1.14e-03 | 1.37e-03 | 1.58e-03 | 1.77e-03 | 1.94e-03 | 2.11e-03 | 2.22e-03 | 2.31e-03 | 2.40e-03 | 2.48e-03 | 2.56e-03 | 2.63e-03 | 1.46e-03 |

E-14

Table E-6 Sludge Application Worker (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 4.79e-03 | 7.32e-03 | 8.72e-03 | 9.56e-03 | 1.01e-02 | 1.04e-02 | 1.07e-02 | 1.08e-02 | 1.09e-02 | 1.10e-02 | 1.11e-02 | 1.12e-02 | 1.13e-02 | 1.14e-02 | 1.15e-02 | 1.16e-02 | 1.18e-02 | 1.20e-02 | 1.25e-02 | 1.03e-02 |
| Tl-201 | 3.27e-06 | 3.28e-06 |
| Tl-202 | 7.30e-05 | 7.71e-05 | 7.87e-05 | 7.95e-05 | 7.98e-05 | 8.00e-05 | 8.01e-05 | 8.02e-05 | 8.03e-05 |
| U-233 | 1.07e-05 | 1.51e-05 | 1.91e-05 | 2.27e-05 | 2.65e-05 | 3.09e-05 | 3.52e-05 | 4.07e-05 | 4.59e-05 | 5.22e-05 | 5.92e-05 | 6.64e-05 | 7.54e-05 | 8.66e-05 | 9.92e-05 | 1.15e-04 | 1.32e-04 | 1.58e-04 | 1.99e-04 | 7.34e-05 |
| U-234 | 9.31e-06 | 1.23e-05 | 1.51e-05 | 1.78e-05 | 2.06e-05 | 2.34e-05 | 2.62e-05 | 2.93e-05 | 3.28e-05 | 3.64e-05 | 3.98e-05 | 4.37e-05 | 4.84e-05 | 5.39e-05 | 6.00e-05 | 6.76e-05 | 7.85e-05 | 9.50e-05 | 1.23e-04 | 4.70e-05 |
| U-235 | 2.94e-04 | 4.19e-04 | 4.73e-04 | 4.92e-04 | 4.99e-04 | 5.04e-04 | 5.07e-04 | 5.10e-04 | 5.14e-04 | 5.17e-04 | 5.21e-04 | 5.26e-04 | 5.31e-04 | 5.37e-04 | 5.43e-04 | 5.52e-04 | 5.63e-04 | 5.79e-04 | 6.08e-04 | 5.05e-04 |
| U-238 | 7.18e-05 | 8.93e-05 | 9.38e-05 | 9.68e-05 | 9.95e-05 | 1.02e-04 | 1.05e-04 | 1.08e-04 | 1.11e-04 | 1.14e-04 | 1.17e-04 | 1.21e-04 | 1.26e-04 | 1.31e-04 | 1.36e-04 | 1.44e-04 | 1.54e-04 | 1.67e-04 | 1.94e-04 | 1.21e-04 |
| Xe-131m | 3.37e-07 | 3.48e-07 | 3.57e-07 | 3.64e-07 | 3.70e-07 | 3.75e-07 | 3.80e-07 | 3.84e-07 | 3.89e-07 | 3.93e-07 | 3.96e-07 | 4.00e-07 | 4.04e-07 | 4.08e-07 | 4.12e-07 | 4.17e-07 | 4.22e-07 | 4.28e-07 | 4.35e-07 | 3.90e-07 |
| Zn-65 | 9.59e-04 | 1.33e-03 | 1.45e-03 | 1.49e-03 | 1.50e-03 | 1.51e-03 | 1.51e-03 | 1.52e-03 | 1.45e-03 |

Table E-7 POTW Worker: Biosolids Loading

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ac-227 | 1.70e-01 | 1.74e-01 | 1.78e-01 | 1.83e-01 | 1.89e-01 | 1.97e-01 | 2.04e-01 | 2.12e-01 | 2.22e-01 | 2.34e-01 | 2.50e-01 | 2.70e-01 | 2.91e-01 | 3.19e-01 | 3.53e-01 | 3.95e-01 | 4.65e-01 | 6.13e-01 | 8.10e-01 | 3.47e-01 |
| Am-241 | 3.16e-03 | 3.44e-03 | 3.75e-03 | 4.11e-03 | 4.59e-03 | 5.03e-03 | 5.53e-03 | 6.10e-03 | 6.81e-03 | 7.70e-03 | 8.86e-03 | 1.01e-02 | 1.18e-02 | 1.36e-02 | 1.57e-02 | 1.87e-02 | 2.40e-02 | 3.47e-02 | 4.69e-02 | 1.55e-02 |
| Be-7 | 2.45e-02 |
| C-14 | 8.78e-07 | 8.79e-07 | 8.81e-07 | 8.82e-07 | 8.84e-07 | 8.87e-07 | 8.89e-07 | 8.92e-07 | 8.95e-07 | 9.00e-07 | 9.04e-07 | 9.11e-07 | 9.20e-07 | 9.30e-07 | 9.43e-07 | 9.60e-07 | 9.83e-07 | 1.02e-06 | 1.12e-06 | 9.35e-07 |
| Ce-141 | 2.50e-02 |
| Co-57 | 3.84e-02 |
| Co-60 | 1.40e+00 |
| Cr-51 | 1.48e-02 |
| Cs-134 | 8.13e-01 |
| Cs-137 | 2.92e-01 |
| Eu-154 | 6.63e-01 |
| Fe-59 | 6.62e-01 |
| H-3 | 1.41e-04 | 2.01e-04 | 2.35e-04 | 2.90e-04 | 3.28e-04 | 3.72e-04 | 4.27e-04 | 4.74e-04 | 5.42e-04 | 6.12e-04 | 6.89e-04 | 7.77e-04 | 8.71e-04 | 1.02e-03 | 1.17e-03 | 1.34e-03 | 1.53e-03 | 1.85e-03 | 2.65e-03 | 9.24e-04 |
| I-125 | 1.20e-03 |
| I-131 | 1.84e-01 |
| In-111 | 1.61e-01 |
| K-40 | 9.05e-02 |
| La-138 | 6.90e-01 | 6.91e-01 | 6.90e-01 |
| Np-237 | 2.71e-04 | 5.95e-04 | 1.01e-03 | 1.57e-03 | 2.00e-03 | 2.56e-03 | 3.32e-03 | 4.03e-03 | 4.76e-03 | 5.66e-03 | 6.72e-03 | 8.26e-03 | 1.02e-02 | 1.27e-02 | 1.50e-02 | 1.90e-02 | 2.54e-02 | 3.53e-02 | 5.78e-02 | 1.50e-02 |
| Pa-231 | 1.68e-02 | 1.75e-02 | 1.82e-02 | 1.94e-02 | 2.03e-02 | 2.19e-02 | 2.34e-02 | 2.50e-02 | 2.75e-02 | 3.01e-02 | 3.29e-02 | 3.61e-02 | 4.11e-02 | 4.71e-02 | 5.48e-02 | 6.30e-02 | 7.91e-02 | 9.80e-02 | 1.61e-01 | 5.14e-02 |
| Pb-210 | 4.17e-04 | 4.32e-04 | 4.45e-04 | 4.63e-04 | 4.82e-04 | 5.09e-04 | 5.35e-04 | 5.65e-04 | 6.01e-04 | 6.46e-04 | 6.98e-04 | 7.57e-04 | 8.39e-04 | 9.25e-04 | 1.05e-03 | 1.22e-03 | 1.46e-03 | 1.90e-03 | 2.66e-03 | 1.00e-03 |
| Po-210 | 8.77e-06 | 1.28e-05 | 1.75e-05 | 2.52e-05 | 3.24e-05 | 4.13e-05 | 5.09e-05 | 6.16e-05 | 7.58e-05 | 9.51e-05 | 1.11e-04 | 1.30e-04 | 1.56e-04 | 1.90e-04 | 2.45e-04 | 3.08e-04 | 3.98e-04 | 5.40e-04 | 8.69e-04 | 2.22e-04 |
| Pu-238 | 1.92e-04 | 4.13e-04 | 6.47e-04 | 9.54e-04 | 1.31e-03 | 1.70e-03 | 2.22e-03 | 2.78e-03 | 3.48e-03 | 4.33e-03 | 5.09e-03 | 5.99e-03 | 7.43e-03 | 9.22e-03 | 1.15e-02 | 1.40e-02 | 1.76e-02 | 2.38e-02 | 3.60e-02 | 1.03e-02 |
| Pu-239 | 1.89e-04 | 4.33e-04 | 7.09e-04 | 1.06e-03 | 1.51e-03 | 1.96e-03 | 2.36e-03 | 3.02e-03 | 3.78e-03 | 4.49e-03 | 5.59e-03 | 7.02e-03 | 8.52e-03 | 1.03e-02 | 1.24e-02 | 1.54e-02 | 2.05e-02 | 3.12e-02 | 4.76e-02 | 1.19e-02 |
| Ra-226 | 1.27e+00 | 1.47e+00 | 1.67e+00 | 1.92e+00 | 2.18e+00 | 2.47e+00 | 2.74e+00 | 3.08e+00 | 3.53e+00 | 3.90e+00 | 4.49e+00 | 5.15e+00 | 5.91e+00 | 6.89e+00 | 7.94e+00 | 9.42e+00 | 1.16e+01 | 1.53e+01 | 2.28e+01 | 6.90e+00 |
| Ra-228 | 5.17e-01 | 5.18e-01 | 5.18e-01 | 5.17e-01 |
| Sm-153 | 1.16e-02 |
| Sr-89 | 7.86e-04 | 7.87e-04 | 7.88e-04 | 7.88e-04 | 7.88e-04 | 7.90e-04 | 7.87e-04 |
| Sr-90 | 1.97e-03 | 1.97e-03 | 1.98e-03 | 1.99e-03 | 1.99e-03 | 1.99e-03 | 2.00e-03 | 2.00e-03 | 2.01e-03 | 2.02e-03 | 2.03e-03 | 2.05e-03 | 2.09e-03 | 2.01e-03 |
| Th-228 | 6.71e+00 | 8.48e+00 | 9.91e+00 | 1.12e+01 | 1.28e+01 | 1.44e+01 | 1.62e+01 | 1.80e+01 | 2.01e+01 | 2.24e+01 | 2.49e+01 | 2.76e+01 | 3.04e+01 | 3.42e+01 | 3.88e+01 | 4.41e+01 | 5.07e+01 | 6.10e+01 | 8.30e+01 | 3.04e+01 |
| Th-229 | 1.32e-01 | 1.34e-01 | 1.35e-01 | 1.37e-01 | 1.39e-01 | 1.42e-01 | 1.44e-01 | 1.47e-01 | 1.51e-01 | 1.55e-01 | 1.60e-01 | 1.65e-01 | 1.74e-01 | 1.82e-01 | 1.95e-01 | 2.12e-01 | 2.37e-01 | 2.77e-01 | 3.48e-01 | 1.90e-01 |
| Th-230 | 2.35e-04 | 4.11e-04 | 6.04e-04 | 9.04e-04 | 1.17e-03 | 1.50e-03 | 1.90e-03 | 2.45e-03 | 3.06e-03 | 3.68e-03 | 4.56e-03 | 5.52e-03 | 6.68e-03 | 8.12e-03 | 9.94e-03 | 1.26e-02 | 1.55e-02 | 2.22e-02 | 3.35e-02 | 8.97e-03 |

Table E-7 POTW Worker: Biosolids Loading (continued)

| Radio-nuclide | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | mean | |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Th-232 | 7.61e-04 | 1.75e-03 | 2.73e-03 | 4.10e-03 | 5.89e-03 | 7.57e-03 | 9.50e-03 | 1.19e-02 | 1.44e-02 | 1.76e-02 | 2.17e-02 | 2.60e-02 | 3.20e-02 | 4.09e-02 | 5.11e-02 | 6.28e-02 | 8.10e-02 | 1.12e-01 | 1.67e-01 | 4.42e-02 | |
| Pt-201 | 2.02e-02 |
| Pt-202 | 2.10e-01 |
| U-233 | 1.71e-04 | 2.48e-04 | 3.35e-04 | 4.45e-04 | 5.88e-04 | 7.29e-04 | 8.56e-04 | 1.06e-03 | 1.30e-03 | 1.52e-03 | 1.87e-03 | 2.32e-03 | 2.79e-03 | 3.36e-03 | 4.00e-03 | 4.96e-03 | 6.57e-03 | 9.93e-03 | 1.51e-02 | 3.85e-03 | |
| U-234 | 9.39e-05 | 1.70e-04 | 2.49e-04 | 3.56e-04 | 4.78e-04 | 6.17e-04 | 8.02e-04 | 1.00e-03 | 1.23e-03 | 1.55e-03 | 1.78e-03 | 2.14e-03 | 2.62e-03 | 3.24e-03 | 4.01e-03 | 4.92e-03 | 6.26e-03 | 8.33e-03 | 1.23e-02 | 3.59e-03 | |
| U-235 | 6.04e-02 | 6.04e-02 | 6.05e-02 | 6.07e-02 | 6.08e-02 | 6.09e-02 | 6.11e-02 | 6.12e-02 | 6.14e-02 | 6.16e-02 | 6.18e-02 | 6.22e-02 | 6.26e-02 | 6.32e-02 | 6.37e-02 | 6.46e-02 | 6.61e-02 | 6.83e-02 | 7.35e-02 | 6.37e-02 | |
| U-238 | 1.15e-02 | 1.15e-02 | 1.16e-02 | 1.17e-02 | 1.18e-02 | 1.19e-02 | 1.21e-02 | 1.23e-02 | 1.25e-02 | 1.27e-02 | 1.30e-02 | 1.34e-02 | 1.38e-02 | 1.45e-02 | 1.51e-02 | 1.59e-02 | 1.72e-02 | 1.91e-02 | 2.26e-02 | 1.45e-02 | |
| Xe-131m | 1.75e-03 | |
| Zn-65 | 3.20e-01 | |

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The treatment of municipal sewage at publicly-owned treatment works (POTWs) leads to the production of considerable amounts of residual solid material known as sewage sludge, which is widely used in agriculture and land reclamation. Elevated levels of naturally-occurring and man-made radionuclides have been found in sludge samples, suggesting the possible radiation exposure of POTW workers and members of the public. The Interagency Steering Committee on Radiation Standards (ISCORS) therefore conducted a limited survey of radioactivity in sludge across the United States. Concurrently, to assess the levels of the associated doses to people, it undertook to model the transport of the relevant radionuclides from sludge into the local environment. The modeling work consisted of two steps: First, seven general scenarios were constructed to represent typical situations in which members of the public or POTW workers may be exposed to sludge. Then, the RESRAD multi-pathway environmental transport model generated sludge concentration-to-dose conversion factors. This Report describes the results of this dose modeling effort, and provides a complete description and justification of the dose assessment methodology.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Interagency Steering Committee on Radiation Standards, ISCORS, Sewage Sludge Subcommittee, SSS, dose modeling, sewage sludge, dose assessment, model selection criterion, ash management, scenarios, exposure scenarios, sludge application worker, municipal sewage, publicly owned treatment works, dose assessment methodology

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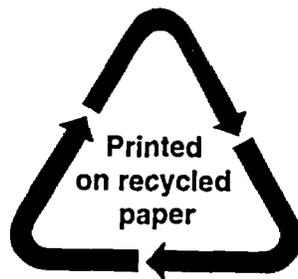
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