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Interagency Steering Committee on Radiation Standards

Final Report

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

ISCORS Technical Report 2004-03

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

Developed by the Sewage Sludge Subcommittee

United States Nuclear Regulatory Commission

United States Department of Energy

United States Environmental Protection Agency

State of New Jersey Department of Environmental Protection

Middlesex County Utilities Authority

Northeast Ohio Regional Sewer District

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ABSTRACT

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 sewage 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 sewage 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 sewage 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 sewage sludge. Then, the RESRAD multi-pathway environmental transport model generated sewage 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.

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This NUREG contains information collection requirements that are subject to the Paperwork Reduction Act of 1995 (44 U.S.C. 3501 et seq.). These information collections were approved by the Office of Management and Budget, approval numbers 3150-0014 and 3150-0189.

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ACKNOWLEDGMENTS

The Sewage Sludge Subcommittee of the Federal ISCORS (1) conducted a survey to collect information concerning radioactive materials in sewage sludge and ash from POTWs; (2) performed dose modeling to help with the interpretation of the results of the survey; and (3) developed a guidance on radioactive materials in sewage sludge and ash for POTW owners and operators. Subcommittee members who actively participated in the development of the three reports associated with this project include the following (listed alphabetically):

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EXECUTIVE SUMMARY

INTRODUCTION

The processing of municipal sewage at publicly owned treatment works (POTWs) leads to the production of considerable amounts of residual waste materials known as sewage sludge or biosolids. In addition, some POTWs incinerate sewage sludge onsite, producing a dry ash residual.

Sewage sludge contains detectable amounts of radioactive materials. In addition, sewage flowing into a POTW can include anthropogenic materials exempt from regulatory control, such as excreta from individuals undergoing medical diagnosis or therapy, and discharges of limited quantities of radioactive materials from some licensees of the U.S. Nuclear Regulatory Commission (NRC) and NRC Agreement State licensees. NRC estimates that of the more than 22,000 regulated users of Atomic Energy Act (AEA) radioactive materials, about 9,000 have the potential to release radioactive materials to municipal sewer systems.

Other sources of radioactive materials that may enter sewage collection systems include: storm water runoff, groundwater, surface water, residuals from drinking water treatment plants, and waste streams from certain industries (e.g., ceramics, electronics, optics, mining, petroleum, foundries, and pulp/paper mills). All of these waste streams may contain naturally occurring radioactive materials (NORM), including naturally occurring radioactive materials whose radionuclide content, or the potential for exposure to humans and the environment, has been technologically enhanced by human activities (TENORM). Federal and State regulations limit the amounts of anthropogenic sources and some sources of TENORM that could otherwise be intentionally disposed of in the sewage systems. These regulations, however, do not apply to all sources of NORM and TENORM.

Sewage treatment processes include filtration, precipitation, and other techniques for removing solids and associated trace heavy metals from the wastewater prior to discharge. These same processes, however, will inadvertently cause radioactive materials that entered the sewer system to become concentrated in the sewage sludge, and POTW workers managing the sludge will be exposed to small amounts of radiation from these materials.

Treated sewage sludge is often applied to land as a source of organic material or nutrients as a part of agricultural and land reclamation operations. As a result, equipment operators who apply the sewage sludge, farmers, consumers of the farm products, or those who spend time on reclaimed land, will be exposed to small amounts of radiation from radioactive materials in the sewage sludge. The current Federal regulation at 40 CFR Part 503, which applies to the use or disposal of sewage sludge, limits levels of heavy metals and pathogens. At present, however, there are no Federal regulations in place that limit levels of radioactive materials in sewage sludge or ash.

There have been no identified situations in the U.S. where radioactive materials in sewage sludge have posed a significant threat to the health and safety of POTW workers or the general public.

There are, however, a number of facilities where elevated levels of radioactive materials have been detected. Also, some states have identified cases where radium from drinking water treatment residuals has been concentrated in sewage sludge. These situations made clear the need to assess the levels of radionuclides present in sewage sludge and ash around the country, and to assess the potential for human exposure to such materials.

In response to that need, and to Congressional interest, the Federal Interagency Steering Committee on Radiation Standards (ISCORS) formed a Sewage Sludge Subcommittee to assess the levels of radioactivity in sewage sludge and ash nationwide, and to determine whether there is a public health problem that needs to be addressed[1]. The Subcommittee conducted a limited, voluntary survey involving samples from 313 POTWs across the United States, and has used the results of that survey to evaluate potential human exposure to radiation from radioactive materials in sewage sludge and ash. In a *Federal Register* notice published on November 26, 2003 (68 FR 66503), ISCORS announced the availability of a final report entitled *ISCORS Assessment of Radioactivity in Sewage Sludge: Radiological Survey Results and Analysis* (ISCORS 2003-02). That report has also been posted on the ISCORS website (http://www.iscors.org), along with the associated survey data base.

The *Federal Register* notice also requested public comments on two associated documents. The present document, *ISCORS Assessment of Radioactivity in Sewage Sludge: Modeling to Assess Radiation Doses* (ISCORS 2004-03), is the final version of a report on the dose modeling conducted by ISCORS. It contains revisions made in response both to a formal scientific peer review and to valuable comments from the public. The report is intended to be complete, such that when used in conjunction with the RESRAD family of environmental pathway modeling codes, every result in it can be independently reproduced by other modelers.

The other document was a draft report, now finalized as *ISCORS Assessment of Radioactivity in Sewage Sludge: Recommendations on Management of Radioactive Materials in Sewage Sludge and Ash at Publicly Owned Treatment Works* (ISCORS 2004-04).

GENERAL APPROACH TO THE MODELING

The Subcommittee undertook this analysis of possible doses to POTW workers and members of the general public for two primary purposes: (1) to assist in interpreting the survey results and assessing the potential exposures, and (2) to support development of recommendations to POTW operators.

The general approach of the study consisted of two steps. First, a suitable number of generic scenarios, encompassing multiple environmental transport and exposure pathways, were

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1 ISCORS is co-chaired by the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC), and also has representatives from the U.S. Departments of Energy (DOE), Department of Defense (DOD), Health and Human Services (DHHS), and Labor (DOL), and observers from White House Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), and various states. Subcommittee members are representatives of EPA, NRC, DOE, the State of New Jersey, the Middlesex County Utilities Authority, and the Northeast Ohio Regional Sewer District.

designed so as to represent situations in which POTW workers or members of the public are most likely to be exposed to sewage sludge through typical sludge management practices. Then, assuming a reference specific activity (1 picocurie per gram of dry sewage sludge, or 37 Becquerel per kilogram, in SI units) of a single radionuclide, a widely-accepted, stochastic, multi-pathway environmental transport model (RESRAD) was employed to obtain a radionuclide-specific sludge concentration-to-dose conversion factor for every scenario.

The selection of radionuclides for consideration was based primarily on the results of the ISCORS survey of sewage sludge and ash at various POTWs, and the selected radionuclides include manmade and naturally-occurring isotopes. The survey reported the detection of 8 radionuclides (Be-7, Bi-214, I-131, K-40, Pb-212, Pb-214, Ra-226, and Ra-228) in more than 200 samples. The dose modeling covers these radionuclides, along with others found by spectroscopy during the full ISCORS survey. Several radionuclides not identified in the POTW survey have been included in the analysis because they are either a parent or a daughter of a radionuclide that was found in the survey (e.g., Ac-227, Np-237, Pa-231, Po-210, Th-229, U-233, and Xe-131m).

The output of the modeling was a set of dose-to-source ratios (DSRs), one for each combination of radionuclide and scenario. DSRs are factors for converting specific activities (concentrations, in pCi/g or Bq/kg) of radionuclides in sewage sludge to the peak Total Effective Dose Equivalent (TEDE, in rems or sieverts) occurring over the 1000-year calculational period.

This dose modeling analysis was probabilistic. A probabilistic (also known as a stochastic or Monte Carlo) calculation allows study of the uncertainty in dose assessment caused by uncertain input parameters. The dose calculations were repeated multiple times as certain parameters randomly assume ranges of numbers to reflect the uncertainties in the parameter values; each of these calculations generates its own DSR. The results were presented in a cumulative distribution function table, which records the probability that the “true” DSR-value is at or below any specified value. The 95%-DSR value for some radionuclide and scenario, for example, is greater than 95% of the hundreds of DSR-values calculated in the analysis, and smaller than only 5% of them. In other words, in 95% of the situations that might be modeled in this manner, the “true” DSR would be less than its listed 95^{th}-percentile value, and in the majority of cases, it would be much less.

The dose modeling scenarios cover a wide range of typical exposure conditions found across the country, and they allow for considerable variability. Guided in part by examples from previous dose assessments by DOE, EPA, and NRC, ISCORS developed scenarios that are simple and generic (i.e., not based on the unique characteristics of any particular site or sites), and the scenarios are general enough to account for the most common sewage sludge and ash management practices. The scenarios represent a variety of different uses or disposal options for sewage sludge, and consider those situations where radiation exposures are most likely to occur. For each scenario, all the standard environmental transport and exposure pathways were incorporated: direct exposure to gamma rays resuspension of dust; inhalation of dust and indoor and outdoor radon; leaching into groundwater; and ingestion of well and surface water, vegetables, fruit, meat, milk, and fish, any of which are obtained or produced onsite—along with ingestion of small amounts of soil. The seven scenarios are:

Exposure Onsite

1. Residents of a house built on a former agricultural field where sewage sludge was applied
2. Recreational visitors to a park where sewage sludge has been used in land reclamation

Exposure on Neighboring Site

3. Residents of a town near a sewage sludge land-application site
4. Neighbors of a landfill that contains sewage sludge or ash
5. Neighbors of an operating sludge incinerator

Occupational Exposure

6. Workers who operate equipment to apply sewage sludge to agricultural lands
7. Workers at a POTW involved in sewage sludge sampling, transport, or loading operations.

These scenarios were designed to form the basis for performing conservative but realistic assessments of the doses of ionizing radiation associated with typical sewage sludge management practices. They were ***not*** intended to represent 'worst case' scenarios.

After a number of computer-based environmental pathway models were considered for use in this effort, the RESRAD family of codes, including RESRAD version 6.0, RESRAD-BUILD version 3.0, and RESRAD-OFFSITE version 1.0, was selected largely because of its flexibility in scenario development (RESRAD 2000). RESRAD contains the necessary data on most relevant radionuclides. Other radionuclides were added for this effort. While all transport and exposure pathways of interest are included, the codes employ a manageable number of parameters (about 140 for RESRAD, 300 for RESRAD-OFFSITE, and 40 for RESRAD-BUILD) and contain built-in sensitivity and probabilistic uncertainty analysis modules. RESRAD is widely used, well documented, and user-friendly, so that the calculations can be readily replicated or modified by others.[2]

Because Scenarios 1, 2, and 6 involve only onsite receptors, their doses can be estimated using RESRAD Version 6. Scenarios 3, 4, and 5 are complicated by offsite transport and are examined with the RESRAD-OFFSITE code; as part of the calculation, the CAP88-PC code accounts for airborne transport of radioactive material away from the source. Some workers at the POTW

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2 RESRAD-OFFSITE is a recent addition to this family of codes. It implements the same general approach that is used in many other codes for simple offsite transport problems, and should be generally acceptable to experts in the field for relatively simple generic calculations, but it is not yet well documented or extensively used.

(Scenario 7) spend a considerable amount of time indoors, requiring the use of the RESRAD-BUILD code.

For nearly all the modeling parameters, a set of baseline parameter values and distributions, which do not change from scenario to scenario, were selected for application to all seven scenarios. Many of these parameter values and distributions are RESRAD default values, and others appear in EPA's *Exposure Factors Handbook* (EPA 1997), NRC's NUREG/CR-6697 (NRC 2000b), and similar compilations. Human metabolic and behavioral data, such as inhalation and ingestion rates under various conditions, were based on national databases that are generally accepted by regulatory agencies such as EPA and NRC. On those few occasions that standard generic and default values and distributions were not adopted, explanations are provided.

The relatively small number of parameter values and distributions that are scenario-specific and distinguish the scenarios from one another may be thought of as variations from the baseline. These have been tabulated explicitly for each scenario.

The computation of soil concentration is complicated by radionuclide decay and ingrowth, and by leaching and erosion. This is especially true for Scenarios 1, 3, 5, and 6, for which there are multiple sewage sludge applications over a period of years. RESRAD does not currently compute out Monte Carlo calculations that involve more than one sewage sludge application. To extrapolate from single-year (obtained with a probabilistic calculation) to multiple-year application, approximate scaling factors have been developed and presented in tables, as described in the report.

EXPOSURE SCENARIOS AND ASSOCIATED MODELING PARAMETERS

The assessment for every exposure scenario starts off with the creation of a conceptual model of the site. This model describes the spatial and temporal distribution of sewage sludge/ash in surface soil (the source term), the characteristics of the sub-surface soil, the occurrence of surface and ground water, the abundance of vegetation, and the presence of farm animals. Also crucial are the environmental transport and human exposure pathways potentially at work, such as the blowing of dust by wind, irrigation of fodder with groundwater, and the behavioral patterns of the humans who may be exposed.

The description of each scenario is then expressed, to the extent possible, as a specific set of parameter values and distributions chosen as inputs to the relevant RESRAD code. The selection of a particular model (with its built-in assumptions and approximations) and a set of parameter values and distributions (baseline plus any that are site-specific) completely defines the characteristics of the site and of the exposed population for the dose calculation.

The scenario description and the associated set of input parameters establish the degree of conservatism of the modeling. The scenarios in this study were modeled using "realistic" distributions and values for most pathway and exposure parameters. The objective was to estimate doses to the individuals most likely to be exposed to radioactive material from sewage sludge (i.e., "members of the critical group") for each scenario, and 95^{th}-percentile DSR values were adopted for the assessment. The critical group consists of the sub-population with relatively high exposure to sewage sludge; the scenarios represent reasonably conservative conditions for calculating doses.

The Seven Exposure Scenarios

1. In risk assessments, the resident farmer family is often modeled as a reasonable but bounding case study. But many new houses are now constructed on former farmlands near urban areas; so the report considers the similar, but much more common, situation of *Onsite Residents* who inhabit a home built on land previously used for farming, and who ingest some water and food obtained onsite. The source of radioactive material is a farm-field that was amended with sludge-based fertilizer either one time recently, or annually for the past 5 years, 20 years, 50 years, or 100 years. (Very few land application sites in the country are known to have applied sewage sludge annually for more than 20 years; the 50- and 100-year computations were included primarily for consistency with the technical support for EPA's *Standards for the Use or Disposal of Sewage Sludge* at 40 CFR 503, as a check on the data analysis methodology, and to assist POTW operators in their consideration of future sewage sludge management practices.)

2. A *Recreational User* occasionally spends time on land that was severely disturbed by mining or excavation, followed by a reclamation effort that included a single large application of sewage sludge and other soil additives. Three years after a sludge application, when a sustainable vegetative cover is in place, the site is opened to the public, but exclusively for hiking, camping, picnicking, boating, hunting, fishing, and other recreational uses.

3. The *Nearby-Town Resident* scenario assesses the doses to members of the critical group who live in a town, the proximal edge of which is located about 0.8 km (0.5 mile) downwind and downstream (for both ground- and surface-water) from an agricultural field where sludge has been applied for one or more years. All exposure pathways involve physical transport (and dilution) of radionuclides from the source field to the town or to neighboring fields, mainly through airborne transport of contaminated dust.

4. Two sub-cases for the *Landfill/Surface Impoundment Neighbor* scenario were designed for the study of the near-surface burial of sludge and ash: (1) a 1-hectare (about 2 acres), 2-meter-deep municipal solid waste (MSW) landfill; and (2) a surface impoundment of the same dimensions. Either form of disposal could affect someone who lives in a house sited 150 meters from the boundary, does some gardening, and raises a few animals for personal consumption.

5. The *Incinerator Neighbor* scenario considers the potential for exposure of a member of the public residing near a typical sewage sludge incineration facility. The incinerator burns de-watered sludge on an ongoing basis, and the resulting particulate-containing exhaust gas is released from the top of a stack as a plume, some of which settles onto the neighbor's property. An exposed individual resides on a small farm located at the downwind point of

maximum average radionuclide air-concentration at ground level, and receives dose from external exposure, inhalation, and ingestion.

6. A *Sludge Application Worker* typically drives or works on a truck, tractor, or other vehicle that dispenses liquid, de-watered, or dried sludge at a constant rate on fields. The sources of exposure will be the field itself and, to a lesser extent, the sludge loaded on the truck, but the vehicle itself provides distance and some shielding from the source material. These exposures are calculated both for the sludge being applied at the time as well as sludge applied from previous applications (for 5 years, 20 years, 50 yeasr, and 100 years).

7. There is a high degree of variability in the jobs that *POTW Workers* perform when treating and handling sludge. Still, there appear to be at least three tasks that are representative and that may give rise to relatively high exposures to the sludge. These involve sludge sampling and sample transport to the lab for analysis, sludge transport on an open conveyor belt, and biosolids loading operations (e.g., filling trucks with sludge using a front-end loader). For all three sub-scenarios, exposures are due primarily to direct gamma exposure and radon (if radon precursors are present). For biosolids loading, dust inhalation also is a possible exposure pathway.

RADIATION DOSES CORRESPONDING TO THE ISCORS SURVEY RESULTS

Given a set of measured radionuclide activities in a real sewage sludge or ash sample from the POTW Survey, the computed DSRs for each of the seven hypothetical scenarios can be used to estimate the corresponding doses that potentially would be imparted to members of the critical population group.

For every scenario and radionuclide combination, the dose was calculated, using the 95^{th}-percentile DSR, for every sludge and ash sample from the ISCORS national survey. The results were ordered as an increasing sequence of dose values; the 95^{th}-percentile dose is that which exceeds 95% of the set of calculated doses. The median and the 95^{th}-percentile values were tabulated and presented in this report.

The only non-POTW scenario of potential concern is the onsite resident who, as expected, received the highest dose. The greatest contributors to dose are NORM or TENORM sources, and the pathway of greatest importance is that of indoor radon-222 and its daughters. Radon is responsible for 65%–75% of the calculated doses, and direct gamma ray exposure from radium for another 20%.

For some long-lived radionuclides that do not percolate rapidly through soil (in particular, Ra-226), doses scale approximately linearly with number of applications. But when interpreting the dose to the On-site Resident for 100, or even 50, applications, one should bear in mind that these two long-term subscenarios were ***not*** included in the modeling out of any expectation that many such sites will exist in the foreseeable future.

The most exposed POTW employee is the Loading Worker. NORM and TENORM are again the primary source, and indoor radon is dominant, with Rn-220 and Rn-222 and their daughters responsible for 94% of the total calculated dose. As with the Onsite Resident, however, the radon dose for this subscenario is highly dependent on the particular characteristics of the site, in this case, on the details of the air-exchange rate and the size of the room that contains the sludge.

The TEDE results (both with and without the indoor radon contribution) for the 95th-percentile concentration values from the ISCORS survey are summarized in Table ES-1.

CONCLUSION

This report describes the methodology and the results of computations undertaken to assess the potential radiation exposures associated with the handling, and the disposal or beneficial use, of sewage sludge that contains naturally occurring or man-made radioactive materials. A primary objective of the study has been to provide perspective on the levels of radionuclides detected in the ISCORS POTW Survey, taking into account typical sludge management practices.

The scenarios are intended to represent realistic situations that are likely to lead to conservative, but not worst-case, radiation exposure assessments. While it has not been feasible to consider a large number of distinct hypothetical situations, great effort has been made to ensure that the scenarios constructed and analyzed here represent a reasonable range of exposure conditions, without being overly conservative. In unique or unusual circumstances, real site-specific exposures may be greater.[3]

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3 Application of the modeling framework described here, but with site-specific values and distributions for sensitive parameters, may provide a helpful preliminary analysis for the POTW operator who seeks to evaluate levels of radioactive materials detected in sludge or ash. A comprehensive site assessment, however, might require adoption of a more detailed, site-specific model to account for actual site conditions.

Table ES.1 Calculated Total Peak Dose from Survey Samples: Summary Results With and Without Indoor Radon Contribution (mrem/year)

Scenario	Subscenario	95% sample		Dominant Radionuclide(s) [pathways]
		TEDE (mrem/yr)	TEDE w/o Rn (mrem/yr)	
S1—Onsite Resident	1 year of appl.	3	1	Ra-226 [indoor radon]
	5	14	4.9	
	20	55	16	
	50 *	130	37	
	100 *	260	69	
S2—Recreational User	N/A	0.22	--	Ra-226 [external]
S3—Nearby Town	1 yr of appl.	3.2e-03	--	Ra-226 [outdoor radon]
	5	0.014	--	
	20	0.045	--	
	50 *	0.094	--	
	100 *	0.17	--	
S4—Landfill	MSW - Sludge	0.027	0.01	Ra-226 [indoor radon]
	MSW - Ash	0.041	0.014	Ra-226 [indoor radon]
	Impoundment	1.2	0.36	Ra-226 [indoor radon]
S5—Incinerator	N/A	7.7	--	multiple [multiple]
S6—Sludge Application Worker	1 yr of appl.	0.15	--	Ra-226 [external]
	5	0.77	--	
	20	3	--	
	50 *	7.4	--	
	100 *	15	--	
S7—POTW Workers	Sampling (mrem/sample)	4.9e-07	--	Ra-226 [external]
	Transport (mrem/hr)	1.9e-04	5.6e-05	Th-228 [indoor radon, external]
	Loading	17–70§	13	Ra-226, Th-228 [indoor radon]

Notes:

* There are very few land application sites in the country that are known to have applied sewage sludge annually for more than 20 years; the 50- and 100-year computations were included as a check on the data analysis methodology, and for the information of POTW operators in their consideration of future sludge management practices.

§ Range represents results from the nine combinations of air exchange rate and room height (see Section 4.7.3).

– 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.

– N/A denotes Not Applicable.

– MSW denotes Municipal Solid Waste.

– POTW and sludge applications workers perform tasks that lead to potentially significant exposures 1,000 hours per year.

This study utilizes an existing, well-established model and relatively simple, generalized scenarios that make possible an overall assessment without need for a large amount of site-specific data. There are many factors—such as fracture flow, soluble and colloidal transport, the impact of the POTW sludge de-watering operations on the transport and bio-availability of radionuclides, year-to-year and seasonal changes in environmental conditions—that would impact individual, real-site assessments but are not included here. Others, such as indoor air exchange rates, room sizes, and the number of hours each year that workers are exposed, have been modified based on peer review and comments from the general public.

The computations have been carried out with probabilistic versions of three members of a widely-employed family of environmental transport codes: RESRAD, RESRAD-OFFSITE, and RESRAD-BUILD. The principal outputs are the tables of Dose-to-Source Ratios (DSR) for the relevant radionuclides and the estimated doses, for seven hypothetical sludge-management scenarios.

As expected, the DSR values range widely within each scenario for the various radionuclides, and there are significant variances among the scenarios. These differences, however, are meaningful only when considered in the context of the concentrations in sludge actually found in the POTW Survey. Combining the computed DSRs with the survey measurements indicates that most scenarios and radionuclides give rise to very low doses, but there are a few low-probability radionuclide-scenario combinations that might be of health concern.

If agricultural land application of treated sewage sludge that contains elevated levels of radioactive materials is carried out annually for many years (decades), then the potential exists for future significant radiation exposure to a future onsite resident, primarily due to indoor radon from NORM and TENORM. Additionally, when POTW workers are in a room with large quantities of sludge (e.g., for storage or loading) and the air exchange rate is unusually low, there exists the potential for significant exposure, again attributable mainly to radon. Recommendations addressing these situations are provided in the companion final report, *ISCORS Assessment of Radioactivity in Sewage Sludge: Recommendations on Management of Radioactive Materials in Sewage Sludge and Ash at Publicly Owned Treatment Works* (ISCORS 2004-04).

1 INTRODUCTION

1.1 BACKGROUND

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

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

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

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

In response to this need, the Interagency Steering Committee on Radiation Standards (ISCORS)[1] formed a Sewage Sludge Subcommittee (Subcommittee)[2] to coordinate, evaluate, and resolve issues regarding radioactive materials in sewage sludge and ash. To provide a reasonable bound on the amounts of radionuclides that actually occur in sewage sludge and ash, EPA and NRC, in consultations with this Subcommittee, have conducted a limited survey of radioactivity in sludge and ash across the United States. Concurrently, the Dose Modeling Workgroup of the Subcommittee has undertaken a dose assessment to help assess the potential threat that these materials may pose to human health. This report describes the methodology and results of that dose modeling effort.

1.2 PREVIOUS DOSE ASSESSMENTS OF RADIONUCLIDES IN SEWAGE SLUDGE

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

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

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

The PNNL study concluded that although concentration of radionuclides in sewage sludge was likely to occur, more information on the physical and chemical processes was necessary before reliable quantitative dose estimates could be made. The calculated doses were based on

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1 ISCORS is co-chaired by the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC), and ISCORS 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 Subcommittee 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.

estimated rather than measured concentrations of radionuclides. In addition, a relatively small number of radionuclides were considered.

Table 1.1 Hypothetical Maximum Doses (mrem/year) 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.

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

1.4 GENERAL APPROACH

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

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

1.5 ORGANIZATION OF THIS REPORT

This report provides a complete description of the dose assessment process conducted by the Dose Modeling Work Group of the Subcommittee. Chapter 2 provides an overview of the scenarios developed for the assessment and the rationale for the dose modeling approach. Chapter 3 discusses the sources of radioactive material considered in the dose assessment for each scenario. Chapter 4 describes each of the scenarios and presents detailed information on

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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 TEDE based on the methodology in ICRP Reports No. 26 and No. 30 (ICRP 1977 and 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.

input parameters used and assumptions made in constructing each scenario. Chapter 5 presents analyses conducted to assess uncertainty and variability in the scenarios and to identify sensitive parameters and assumptions. Chapter 6 (with additional detail in Appendix E) presents the results of the dose assessment: the dose-to-source ratios for each radionuclide in each scenario. Chapter 7 presents dose calculations combining these dose-to-source ratios with measured radionuclide concentrations, including some discussion of indoor radon and non-radon components. Conclusions of this dose assessment are presented Chapter 8, and references are listed in Chapter 9.

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 this Subcommittee on specific input parameters and assumptions in each scenario, such as the use of the 95^{th} percentile Dose-to-Source Ratios for calculating doses, and to extend the modeling out to 1,000 years following application of sludge in an attempt to assure that the peak dose is obtained.

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.

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

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

Scenarios 1 through 3 consider different kinds of intentional land application of sewage sludge. For the first two, people are exposed while living on a site of former application, and are said to be "onsite." The residents of the nearby town, by contrast, are not located at a site where sludge actually has been or is being applied, but rather are exposed to radionuclides that are transferred "offsite." Scenarios 4 and 5 treat two other kinds of sewage sludge or ash disposal for which the exposed populations are also offsite. The distinction is important because dose assessment for offsite populations is more complex than for onsite, and requires more sophisticated modeling. The last two scenarios consider possible exposure of agricultural and POTW workers.

2.3 SELECTION OF THE MODEL CODE

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

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

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

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

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

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

A description of the RESRAD family of codes, including references to how the calculations are 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	×			

Notes:

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.

Table 2.2 Scenarios and Models in this Assessment

Scenario	Exposed Individual*	Multiple Applications	Model Code
Land Application			
1. Onsite residents	on-site	T	RESRAD Version 6
2. Recreational users—reclamation	on-site	T	RESRAD Version 6
3. Residents of nearby town	off-site	T	RESRAD-OFFSITE/ CAP-88
Landfill Disposal			
4. Landfill neighbors—sub-scenarios for MSW and impoundment	off-site	T	RESRAD-OFFSITE/ CAP-88
Incineration			
5. POTW incinerator neighbors	off-site	T	RESRAD-OFFSITE/ CAP-88
Occupational Exposure			
6. Agricultural sludge application worker	on-site	T	RESRAD Version 6
7. Indoor POTW worker—subscenarios for different POTW operations	on-site		RESRAD-BUILD Version 3

Note:

* "Site" refers to the area where sludge is originally applied or, for Scenario 7, produced.

2.4 PARAMETER VALUES AND DISTRIBUTIONS

2.4.1 FIXED VALUE AND DISTRIBUTIONS FOR MODELING PARAMETERS

Each scenario must be translated from a qualitative narrative and a list of potential transport and exposure pathways into a specific set of parameter values suitable for use in a particular model. Since probabilistic calculations are needed to assess the uncertainty and variability of the DSR values quantitatively, distributions are generally appropriate for the most sensitive parameters. For parameters that are somehow found to be less sensitive, single parameter values may be used.

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

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

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

Because many of these parameter values and distributions do not change from scenario to scenario, a set of "baseline" parameter values and distributions have been defined for each RESRAD code and listed in tabular form in Appendix A. The relatively small number of scenario-specific parameter values that distinguish the scenarios from one another may thus be thought of as variations from the baseline, and these are addressed individually in each scenario description. For baseline parameters for which values or distributions are not available, the RESRAD default values are used, unless another value is clearly indicated. In all cases, the default RESRAD values are listed for reference (in parentheses if not used). They are intended to be as broadly representative as is reasonably achievable, but there may be real situations to which they do not apply.

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 $j = 1, 2, \ldots, J$. 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. RESRAD then computes the dose, $\mathrm{dsr}_j(t)$, as a function of time. The program then searches for the global maximum in $\mathrm{dsr}_j(t)$, which we call DSR_j, for every realization. (The maxima in $\mathrm{dsr}_j(t)$ 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 analyses in these dose assessments rely to a large extent on previous work in analyzing parameter sensitivities of the RESRAD codes. For RESRAD and RESRAD-BUILD, the categorization and ranking of parameter sensitivities are documented in NRC (2000ab). Additional sensitivity analyses were performed in some cases and is described in Chapter 5.

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

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

A unique source of uncertainty arises in dealing with multiple years of application. RESRAD, in its current configuration, can carry out a Monte Carlo analysis only for the case of a single application of sludge. Approximate scaling factors were therefore developed, employing only deterministic calculations, to handle scenarios with multiple years of agricultural application. It is acknowledged that this approach, described in the next chapter, introduces an error that ISCORS believes is small and insignificant to the overall uncertainty.

2.7 ASSESSMENT OF CONTRIBUTIONS FROM INDOOR RADON PATHWAY

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

2.8 LIMITATIONS OF THE CURRENT ASSESSMENT

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

2.8.1 SOURCES

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

2.8.2 SCENARIOS

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

2.8.3 MODELS

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

3 SOURCE ANALYSES AND RELATED ISSUES

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

3.1 RADIONUCLIDES CONSIDERED IN THE DOSE ASSESSMENT

The principal objective of this dose calculation study is to assist in the analysis of the results of the ISCORS POTW survey and to support the Subcommittee in preparing guidance for POTW operators. As such, it covers all radionuclides identified in the pilot survey conducted in 1997, revised in May 1999 (EPA 1999a), and any additional radionuclides found by spectrometry analysis during the full survey. These radionuclides are listed in Tables 3.1 and 3.2. Information on daughters for radionuclides included in standard RESRAD is presented by the RESRAD manual in Tables 3.1 and 3.2 (Yu et al., 2001).

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

The radiation dose calculated for a radionuclide listed in Table 3.1 includes the contributions into the future of *all* the daughter radionuclides (principal and associated) in the decay chain from decay of the listed nuclide. This assumption ensures that the assessment does not underestimate the potential impact of that radionuclide. As a naturally occurring radioactive material in fertilizers and food products, potassium-40 may concentrate in sewage sludge or ash and, as such, is of concern for this analysis. However, exposure to K-40 is only of potential concern for external exposures. Internal exposures do not result in increased dose because of the equilibrium of K-40 in the body. Iodine-131 is included because it is a licensed medical isotope which is discharged to the sewer system and can contribute to radiation dose, despite its short half-life.

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

Radio-nuclide	Major Radiations	Half-life	Radio-nuclide	Major Radiations	Half-life
Ac-227[c]	alpha, beta, gamma	22 years	Po-210[b]	alpha	138 days
Ac-228[d]	beta, gamma	6 hours	Pu-238	alpha	88 years
Am-241	alpha, gamma	432 years	Pu-239	alpha	24×10^3 years
Be-7[a]	gamma	53 days	Ra-223[d]	alpha, gamma	11 days
Bi-212[d]	alpha, beta, gamma	61 minutes	Ra-224[d]	alpha, gamma	4 days
Bi-214[d]	beta, gamma	20 minutes	Ra-226	alpha, gamma	1600 years
C-14	beta	5,730 years	Ra-228	beta	6 years
Ce-141	beta, gamma	33 days	Rn-219[d]	alpha, gamma	4 seconds
Co-57	gamma	271 days	Sm-153[a]	beta, gamma	47 hours
Co-60	beta, gamma	5 years	Sr-89	beta	51 days
Cr-51[a]	gamma	28 days	Sr-90	beta	29 years
Cs-134	beta, gamma	2 years	Th-227[d]	alpha, gamma	19 days
Cs-137	beta, gamma	30 years	Th-228	alpha, gamma	2 years
Eu-154	beta, gamma	9 years	Th-229[b]	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[d]	beta, gamma	24 days
I-131[a]	beta, gamma	8 days	Tl-201[a]	gamma	3 days
In-111[a]	gamma	3 days	Tl-202[a]	gamma	12 days
K-40	beta, gamma	1.3×10^9 years	Tl-208[d]	beta, gamma	3 minutes
La-138[a]	beta, gamma	135×10^9 years	U-233[b]	alpha	158.5×10^3 years
I-131[a]	beta, gamma	8 days	Tl-201[a]	gamma	3 days
In-111[a]	gamma	3 days	Tl-202[a]	gamma	12 days

Table 3.1 Radionuclides Included in the Dose Assessment (continued)

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

Source: EPA 1999b.

Notes:

Information on daughters for standard RESRAD radionuclides is included in Tables 3.1and 3.2 of the RESRAD manual (Yu et al., 2001).

a. This radionuclide is not included in standard RESRAD, and it was added as input to the code specifically for this project.

b. 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.

c. 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.

d. 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.

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

3.2 LAND APPLICATION SCENARIOS

In the Onsite Resident (1), Land Reclamation (2), Nearby Town (3), and Agricultural Worker (6) scenarios, sludge is applied directly to agricultural or reclamation land and then mixed into the top fifteen centimeters through tilling and natural processes such as plant root action. Application may occur a single time or annually for 5 years, 20 years, 50 years, or 100 years. While very few land application sites in the country are known to have applied sludge annually for more than 20 years, the 50- and 100-year computations were included primarily for conssitency with the technical support for EPA's *Standards for the Use or Disposal of Sewage Sludge* in 40 CFR Part 503, as a check on the data analysis methodology, and to assist POTW operators in their consideration of future sludge management practices.

3.2.1 SPECIFIC ACTIVITY IN SOIL-SLUDGE MIXTURE

The activity concentration (i.e., specific activity) of the source term for RESRAD is that of the soil-sludge mixture, rather than of the sludge alone. The average concentration of a radionuclide in soil depends on its initial concentration in the sludge, the continuous processes of radionuclide decay and ingrowth, the amount of sludge deposited per application, the number of prior (annual) applications that have occurred, the extent of tillage, and other factors. A simple expression for it assumes that sludge of specific activity A_{sludge} [Bq/kg or pCi/g], is applied at a rate of S [metric tons/hectare], and mixed into the top d [m] of soil that has density r [kg/m^3]. The specific activity in soil (Equation 3.1a) is then

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

for a single land application.

The present dose assessment assumes for its calculations a reference initial specific activity in dry sludge (1 pCi/g or 37 Bq/kg) of any single radionuclide, and an assumed application rate of 10 metric tons dry sludge matter[5] per hectare per year, or 1 kg/m^2. (One metric ton is equal to 1,000 kg, and a hectare is 10,000 m^2.) Tillage depth is assumed to be 15 cm, and the soil density

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5 Annual applications for agricultural utilization are found to range from 2 metric tons/hectare to 70 metric tons/hectare (1 ton/acre to 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.

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

$$A_{\mathrm{soil}} = 0.16\ \mathrm{Bq/kg}\ \ (0.0044\ \mathrm{pCi/g})\ , \qquad \textbf{(3.1b)}$$

the value used here for direct agricultural application.

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

3.2.2 MULTIPLE YEARS OF APPLICATION AND WAITING PERIODS

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

To estimate the dose rate resulting from n annual sludge applications, one first carries out a single-application, probabilistic run at the time of the first application, $n = 1$, which yields the dose D_1^{prob}. In Equation 3.2, this is then scaled for multiple applications by means of a factor, F_n ,

$$D_n^{\mathrm{prob}} = D_1^{\mathrm{prob}} \times F_n \qquad \textbf{(3.2)}$$

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 sewage 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.

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

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

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

In Equation 3.3a, for a series of n annual applications, the dose at time t would be the sum of $D^{(}(t-j)$ from $j = 0$ to $n-1$:

$$D_n(t) = 3\ D^{(}(t-j) \quad , \ [\, j = 0, \dots , n-1 \,] \ , \qquad \textbf{(3.3a)}$$

where this expression is meaningful only with the constraint (Equation 3.3b)

$$t\ \$\ (n-1) \ . \qquad \textbf{(3.3b)}$$

Suppose that residents of the property, or the members of any other relevant critical population group, come into direct or indirect contact with the source r years after the last (the n-th) application, in year $(n-1+r)$. The dose from all applications combined is still given by Equation 3.4a,

$$\mathrm{D_n}(t) = 3\ D^{(}(t-j) \quad , \ [\, j = 0, \dots , n-1 \,] \ , \qquad \textbf{(3.4a)}$$

but Equation 3.3b is replaced by Equation 3.4b,

$$t\ \$\ (n-1+r) \ . \qquad \textbf{(3.4b)}$$

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

$$D_n(t_r) \;=\; 3 \;\; D^{(}(t_r + k)\,,\;\; [k = r, \ldots\;, r + n - 1]\;\; \text{, and }\; t_r \;\$\; 0\;. \qquad \textbf{(3.5)}$$

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 3.5 that was used to compute the scaling factors for all seven scenarios, with $n = 1$ year, 5 years, 20 years, 50 years, 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 in Equation 3.6a,

$$F_n = \max[D_n(t_r)] \,/\, \max[D^{(}(t)]\,, \qquad \textbf{(3.6a)}$$

or, defining t^{max} as the time where $D(t)$ is greatest as in Equation 3.6b, then

$$F_n \;=\; D_n(t_r^{max}) \,/\, D^{(}(t^{max})\,, \qquad \textbf{(3.6b)}$$

where F_n is independent of time.

When re-written so as to account for time, Equation 3.2 then becomes Equation 3.6c,

$$D_n^{\text{prob}} = D_1^{\text{prob}} \times D_n(t_r^{max}) \,/\, D^{(}(t_{max})\;\;. \qquad \textbf{(3.6c)}$$

A limitation is that thicknesses of the contaminated zone and unsaturated zone need to remain unchanged during the time period of interest ($t_r = 0$ years to 1,000 years). The contaminated zone erosion rate and the groundwater table drop rate were therefore set to zero. 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.

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

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

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

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

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

Isotope—Nearby Town	Deposition Velocity (m/s)	P/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}

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

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

3.3 LANDFILL/IMPOUNDMENT NEIGHBOR SCENARIO

Two subscenarios 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% of sewage sludge/ash by weight, thereby creating a dilution factor of approximately 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 kg/m^3 – 4700 kg/m^3
Porosity	0.671
Bulk Density (derived)	860 kg/m^3 – 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 P/Q go through a maximum at 150 meters, given in Table 3.4.

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

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

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

3.4 INCINERATOR NEIGHBOR SCENARIO

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

The emission source from the incinerator stack is determined by the activity concentration in the sludge, the feed rate of sludge, and the total control efficiency of the incineration system, accounting for any stack gas cleaning systems. With activity A_{sludge} and feed rate R_{feed}, the rate of radionuclide release from the incinerator stack, R_{release}, is given by Equation 3.7,

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

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

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

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

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

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

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

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

Isotope—Nearby Town	Deposition Velocity (m/s)	P/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}

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

Table 3.7 Decay Factor Adjustments for Incinerator Neighbor Scenario

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

3.5 SLUDGE/ASH MANAGEMENT SCENARIOS

3.5.1 SLUDGE APPLICATION WORKER SOURCE

The sources of exposure to a worker who is applying sewage sludge to a field will be the field itself and, to a lesser extent, the sewage sludge on the truck. The field will contain radioactivity applied not only this year, but also in prior years. The sludge applied is assumed to be dry, dusty material. 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 variability in procedures and type of equipment used, and the complexity of dose contributions coming from past applications as well as from the current one, it is necessary to simplify aspects of the problem. The cab of the truck is assumed to be simply a box. The sludge application rate and tilling depth are the same as for the onsite resident. Rather than performing a time-integral as the truck traverses the field in a raster or spiral patter, the driver is located at the center of the full field; both external and inhalation doses would come mainly from the immediate vicinity of the truck, and change little from place to place within the field—so the dose would almost entirely be determined only by the time the driver spends working there.

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) sewage 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, a certain amount of radioactivity may become concentrated in the sewage sludge and thereby be 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 in sewage sludge or ash.

Solid materials are initially removed from sewage sludge. 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 resulting produces may be"sludge cake," usually 15% to 20% solids, or dry sludge with even higher solids contents.

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

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

For POTW operations, three different worker exposure subscenarios have been designed, involving the sampling, processing, and loading of biosolids. For the first of these, the worker obtains and carries a 1-liter sample containing 95% water and 5% sludge solids by volume, with a sludge dry weight of about 0.075 kg (.165 lbs) (assuming sludge solids have a density of about 1.5 g/cm^3). Thus a sludge sample with unit activity concentration of 37 Bq/kg (1 pCi/g) will contain 2.8 Bq (75 pCi) of activity, and is considered a point source in this assessment.

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

For biosolids loading, the worker carries out tasks near a circular pile of de-watered sludge (porosity of 0.4 and dry bulk density 1520 kg/m^3) that is 100 m^2 (.0247 acres) in area and 0.5 m (1.64 ft) in thickness. 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%–60% solids, and it is much like an organic topsoil. This material can dry out further, but when placed in piles, the surface 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

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

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

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

4.1 ONSITE RESIDENT

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

In this scenario, the source farm-field was amended one or more times in the past with sewage sludge fertilizer that may have contained radionuclides, as discussed in Chapter 3. A house was completed on the land one year after the last deposition of sludge, and thereafter it is inhabited by people who are not professional farmers. It is conservatively assumed that they produce significant portions of their annual diet on-site in the same manner as the resident farmer. Radionuclide transport did occur over the year(s) before the new residents came onsite and continues after they arrive.

The relevant transport and exposure pathways assumed for this scenario are summarized in Table 4.1a. Family members are exposed directly to external gamma emissions from sludge-containing soil. They inhale resuspended dust and outdoor radon and, since the home is built on land where sludge has been applied in the past, indoor radon as well. Doses from indoor radon can vary greatly depending on the construction of a building's foundation. For residential homes, the three major foundation types for new construction are an enclosed crawl space, a slab, and a basement. A simple slab-on-grade without excavation of the upper soil layer was modeled in this assessment, since preliminary RESRAD calculations indicated that this allows more radon diffusion into the house than the basement. The RESRAD code was not designed to evaluate an enclosed crawl space foundation type, but it is plausible that (with a nearly airtight crawl space) radon concentrations might be higher in such a situation because of a "chimney" effect. In most situations, however, the crawl space is not airtight, so little radon is likely to move into the house. As for the basement, there would be a much lower concentration under and around the house post-excavation than for a slab construction house. In real houses, of course, radon concentration depends strongly on the specifics of the design and construction, but that level of detail is neither practicable nor appropriate for the generic scenario modeled here.

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

Table 4.1b lists those parameter values or distributions that differ, for the Onsite Resident, from the baseline, as indicated in Tables A.7, A.9, and A.11 of Appendix A. In nearly all cases (with the exception of the POTW Workers), the baseline was set specifically *for* the Onsite Resident, so almost no entries are needed in Table 4.1b.

The interpretation of some of the parameter entries in Appendix A requires a thorough knowledge of RESRAD. Consider, for example, the assertion that 50% of leafy vegetables are grown onsite. The baseline vegetable consumption value and distribution are presented in Table A.7 in the subsection labeled *Ingestion Pathway Dietary Data*. The RESRAD Default Value of -1 under *Contaminated Fractions* instructs the model to base its selection on the size of the site; for the Onsite Resident site, with a baseline area of 404,685 m^2, the -1 flag leads RESRAD to accept a contaminated fraction for vegetables, fruits and grains (or, equivalently, the fraction of consumed vegetables, fruits and grains that are produced onsite) of 50%. Likewise, the Contaminated Fractions for fodder, meat and milk are 100%. While 100% for these last two may seem high, it was determined that cutting them significantly, such as in half, would lead to a very small change in the DSRs in nearly all cases — so the RESRAD default values have been retained. There are a few radionuclides that are exceptions, in which the meat pathway contributes more then 30% to the total dose; these include Sr-89 and Sr-90 (~55%), I-125 (~80%), Pb-210 (~70%), Po-210 (~90%), U-233, U-234, and U-238 (~55%), and Zn-65 (~30%). No radionuclides contribute more than 15% to the milk pathway.

Six sub-scenarios are used to investigate the dependence of calculated dose on the number of years of application of sludge, given in Table 4.1b. The first sub-scenario performs a complete probabilistic analysis for one year of application, making use of all the currently available parameter distributions and sampling capability of RESRAD Version 6, apart from field size. Sub-scenario two also considers only a single application, but it is fully deterministic; it serves as a baseline for the deterministic computations for multiple years of application (as discussed in Section 3.2.2) that follow. Sub-scenarios three through six use deterministic calculations to examine the impacts of five, twenty, fifty, and one hundred years of accumulation of sludge onsite, respectively. While very few land application sites in the country are known to have applied sludge annually for more than 20 years, the 50- and 100-year computations were included primarily for consistency with the technical support for EPA's *Standards for the Use or Disposal of Sewage Sludge* at 40 CFR 503, as a check on the data analysis methodology, and to assist POTW operators in their consideration of future sludge management practices. As discussed in connection with Equations 3.6a and 3.6b, the factor F_n (the ratio of the *n*-year deterministic to the 1-year deterministic doses) is used to scale the single-year probabilistic results of sub-scenario 1 for multiple years of application.

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

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 dust		Yes	Mass loading represents an average value; dust from top 15 cm (mixture region)
	Indoor radon		Yes	House sits on contaminated zone surface; diffusion in through slab foundation; exchange with outdoor air; 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	Irrigation water	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 *not* considered.

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

Subscenario	Parameter	Value/Distribution	Comments
1 (Uncertainty)		Appendix A Baseline distributions, values, except...	Probabilistic, except land area
1	Years of application	1	All other parameter values and distributions are baseline from Table A.7.
2–6 (Deterministic)		Appendix A Baseline 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 sustainable vegetative cover is in place (and after short-lived isotopes have largely decayed away), the site is opened to the general public for hiking, camping, picnicking, boating, hunting, fishing, and other residential uses. No residential homes are constructed, nor is there any agriculture.

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

Also included in the modeling are external exposure, inhalation of contaminated dust, and soil ingestion. The source and availability of water will vary from place to place. Some sites will have wells for drinking water and washing, while at others, users may have to rely on surface water. It is assumed here that people drink from a well, and wildlife drink surface water. The exposure pathways are summarized in Table 4.2a, and parameter distributions and values specific to this scenario (i.e., those that are not baseline) appear in Table 4.2b. Also not listed in Table 4.2b are those values that explicitly apply to indoor activities, or to irrigation, or to the consumption by humans of surface water, fruit, grain, leafy vegetables, or milk obtained onsite (since these pathways are considered to be not in operation). In cases where a pathway has been turned off in the model, some parameters have been left at their baseline values—which, of 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	

Table 4.2b Recreational User Scenario Parameters and Distributions

Parameter	Value/Distributions	Comments
Livestock (i.e., deer) water contamination fraction	1	
Plant food contamination fraction	0	
Meat (deer) contamination fraction	1	
Aquatic food contaminated fraction	1	
Livestock fodder intake 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)
Livestock water intake for meat (L/d)	7 L/d	From (EPA 1993b) Allometric Equations
Livestock intake of soil (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.
Groundwater fraction for livestock water	0	Deer drink only surface water.
Storage time for meat (d)	182.5	Deer meat consumed over 365 d.
Storage time for fish (d)	0	Fish eaten right away.
Meat transfer factor (pCi/kg per pCi/d)	Baseline values	Use cattle values and distributions as was done in the Part 503 rule.

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 (0.5 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. (Dust that settles on other fields and affects crops there—or is then resuspended and blows into the town—is assumed to be of much less consequence than dust from the primary field.)

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 are described in Table 4.3b.

Table 4.3a Nearby Town Resident Pathways

Human Exposure	Environmental Pathway		Pathway Included?	Comments
External radiation	Direct exposure		Yes	Contamination of surface soil in town; dust deposited by airborne transport from the field
Inhalation	Suspended dust		Yes	Atmospheric transport from contaminated field
	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.
	Outdoor radon		Yes	Air transport and radon emanation from deposition of contaminated dust
Ingestion of water	Groundwater		No	Town uses treated and monitored water, so actual radionuclide content would not exceed MCLs.
	Surface water		No	Town uses treated and monitored water.
Ingestion of plants	Irrigation water		No	Town uses treated and monitored water.
	Dust deposition		Yes	
	Root uptake		Yes	Root uptake from soil contaminated by atmospheric transport.
Ingestion of meat/ milk	Livestock water		No	Town uses treated and monitored water.
	Livestock soil		Yes	
	Fodder	Irrigation water	No	Town uses treated and monitored water.
		Dust deposition	Yes	
		Root uptake	Yes	
Ingestion of fish	Surface water		Yes	
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

Subscenario	Parameter	Value/Distribution	Comments
1 (Uncertainty)		Appendix A baseline values and distributions, except...	
1	Years of application	1 yr	
	Fraction of water from surface body – Household purposes – Beef cattle – Dairy cows – Irrigation for fruit, grain, non-leafy vegetable field – Irrigation for leafy vegetable field – Irrigation for livestock pasture and silage field – Irrigation for livestock grain field	0 0 0 0 0 0 0 0	Household water and irrigation water are not contaminated. They are not from a local well or surface water body.
	Fraction of water from well	0	Household water and irrigation water are not contaminated
	c/Q, all	see Table 3.2	
2–6 (Deterministic)		Appendix A baseline and Subscenario 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 yrs	
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 sewage sludge or ash 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-scenario 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[9] (i.e., the leachate is captured, treated and released) and that groundwater is monitored. The sludge is presumed to be moist, moreover, with little suspension of dust. 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 that 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 cm/yr to 16 cm/yr (0.0016 in./yr to 6.3 in./yr), with a typical value of 0.9 cm/yr (0.35 in./yr). Preliminary analyses using the HELP model showed that the infiltration rate can range from 3.3 cm/yr (1.3 in./yr) for a conservative case to 22 cm/yr (8.7 in./yr) for a very worst case, so a value of 3.3 cm/yr (1.3 in./yr) was used for the deterministic calculations. For the uncertainty calculation, the

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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/yr, which is considered negligible in the context of this generic assessment.

infiltration rate was assumed to have a uniform distribution with a range of from 3.3 cm/yr to 22 cm/yr (1.3 in./yr to 8.7 in./yr).

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

The other specific pathways and parameters, which are similar to those of the Onsite Resident 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	

Table 4.4b Landfill Neighbor Scenario Parameter and Distributions—Post-Monitoring Period

Parameter	Value / Distribution	Comments
Appendix A baseline values and distributions, except...		
Nuclide concentration (pCi/g)	Decay/ingrowth for 30 years Initial activity: Subscenarios 1 & 2 = 0.025 pCi/g; Subscenarios 3 & 4 = 1 pCi/g	See Chapter 3.
Primary Contamination Area Parameters		
Area of primary contamination (m^2)	10,000	About 2 acres (EPA, 1988b)
Length of contamination parallel to aquifer flow (m)	100	Square root of area
Depth of soil mixing layer (m)	0.15	Default plowing depth
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
Irrigation applied per year (m/yr)	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.
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 Table 3.3 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	The average value of the range as specified in Table 3.3 is 1.18.

Table 4.4b Landfill Neighbor Scenario Parameter and Distributions—Post-Monitoring Period (continued)

Parameter	Value / Distribution	Comments
Field capacity	0.292 for MSW landfill and 0.2 for surface impoundment	From Table 3.3 for MSW landfill, 0.2 is the 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	
c/Q, all	see Table 3.4	Adjusted CAP88PC value for a wind speed of 4.24 m/s at 150 m
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.

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

Table 4.5a Incinerator Neighbor Pathways

<table>
<tr><th>Exposure Pathway</th><th colspan="2">Environmental Pathway</th><th>Pathway Included?</th><th>Comments</th></tr>
<tr><td>External radiation</td><td colspan="2">Direct exposure</td><td>Yes</td><td>Plume submersion and groundshine</td></tr>
<tr><td rowspan="3">Inhalation</td><td colspan="2">Plume inhalation</td><td>Yes</td><td>Exposed individual placed in the sector with highest concentration</td></tr>
<tr><td colspan="2">Indoor radon</td><td>No</td><td></td></tr>
<tr><td colspan="2">Outdoor radon</td><td>Yes</td><td>In plume, and emanating from deposited radionuclides</td></tr>
<tr><td rowspan="2">Ingestion of water</td><td colspan="2">Groundwater</td><td>No</td><td></td></tr>
<tr><td colspan="2">Surface water</td><td>No</td><td></td></tr>
<tr><td rowspan="3">Ingestion of plants</td><td colspan="2">Irrigation water</td><td>No</td><td></td></tr>
<tr><td colspan="2">Dust deposition</td><td>Yes</td><td></td></tr>
<tr><td colspan="2">Root uptake</td><td>Yes</td><td>Surface deposition of transported nuclides</td></tr>
<tr><td rowspan="5">Ingestion of meat / milk</td><td colspan="2">Livestock water</td><td>No</td><td></td></tr>
<tr><td colspan="2">Livestock soil</td><td>Yes</td><td></td></tr>
<tr><td rowspan="3">Fodder</td><td>Irrigation water</td><td>No</td><td></td></tr>
<tr><td>Dust deposition</td><td>Yes</td><td></td></tr>
<tr><td>Root uptake</td><td>Yes</td><td></td></tr>
<tr><td>Ingestion of fish</td><td colspan="2">Surface Water</td><td>No</td><td></td></tr>
<tr><td>Ingestion of soil</td><td colspan="2">Surface soil</td><td>Yes</td><td>Deposition of transported effluent</td></tr>
</table>

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 Part 503 rule risk assessment
Stack Diameter (m)	1	Easterly incinerator
Stack Exit Velocity (m/sec)	1	Easterly incinerator
Appendix A baseline values and distributions, except ...		
Radiation Dose Calculation in RESRAD-Offsite		
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 water and irrigation water are not contaminated because there is no primary soil contamination source.
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	

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

Parameter	Value / Distributions	Comments
Fraction of water from well	0	Household water and irrigation water are not contaminated because there is no primary soil contamination source.
Distance from down gradient edge of contamination to – Well in the direction parallel to aquifer flow (m) – Surface water body in the direction parallel to aquifer flow (m)	 0 0	The value does not affect the dose results. However, to reduce the calculation time, a value of 0 was specified.
Distance from center of contamination to well in the direction perpendicular 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.
Fraction of time spent off-site, within the range of radiation emanating from primary contamination – Indoors – Outdoors	 0 0	No primary contamination source

4.6 SLUDGE APPLICATION WORKER SCENARIO

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

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

Table 4.6b presents the non-baseline parameter values.

Table 4.6a Agricultural Application Worker Pathways

Exposure Pathway	Environmental Pathway		Pathway Included?	Comments
External radiation	Direct exposure		Yes	
Inhalation	Resuspended dust		Yes	
	Indoor radon		No	
	Outdoor radon		Yes	
Ingestion of water	Groundwater		No	
	Surface water		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	Assume industrial hygiene practices

Table 4.6b Agricultural Application Worker Scenario Parameters and Distributions

Subscenario	Parameter	Value / Distribution	Comments
1 (Uncertainty)		Appendix A baseline values, distribution	
	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/yr)	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/yr in the field.

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

Subscenario	Parameter	Value / Distribution	Comments
2 – 6 (Deterministic)		Appendix A baseline and Subscenario 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
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 (a) sludge sampling and sample transport to the lab for analysis, (b) sludge processing, and (c) 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 importance. But such accident conditions are rare, and they are not considered further in this report.) It is assumed that a 1-liter sample containing 5% by volume solids is a point source held for 5 minutes at waist level and at a distance of 0.5 m. The activity in the sample was derived in Chapter 3. Self-shielding by the sample container and water are neglected.

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

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

4.7.2 SLUDGE PROCESSING WITHIN PUBLICLY OWNED TREATMENT WORKS

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

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

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

4.7.3 BIOSOLIDS LOADING/STORAGE

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

RESRAD-BUILD is used to model the exposures for this scenario. Table 4.7b lists those parameters that differ from the baseline values. See Chapter 3 for source details.

It is conservatively assumed that during work in the area of the sludge pile, the worker stands at the edge of the slab source. Based on comments received on the draft report (see Appendix F), the previously used value of 2000-hours of exposure time per year appears unrealistically high. For the present report, a value of 1000-hours of exposure time per year has been used. This value of exposure time is known to be plausible at some POTWs, but it is more likely to be lower at most POTWs. Reductions (or increases) in exposure times at individual POTWs (all other conditions being equal) would result in proportionally lower (or higher) doses. DSRs, and thus doses, for all radionuclides have been recalculated accordingly. No shielding is included in the calculation.

The computed DSRs for radium-226 and Th-228 for the POTW loading worker, which are dominated by radon contributions, depend strongly on the room air exchange rate and the height of the room. Based on comments received on the draft report (see Appendix F), it appears that the values previously used for the building height and air exchange rate were unrealistically low. However, only limited data on these parameters specific to POTW facilities were available. Thus, for this present report, nine combinations of building height and air exchange rate have been used, with building heights of 2 m, 4 m, and 6 m, and air exchange rates of 1.5, 3, and 5 per hour. These parameters primarily affect the doses from inhalation of radon progeny, so recalculations of DSRs and doses have been performed only for Ra-226 and Th-228.

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

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

Subscenario	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 1 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

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

Subscenario	Parameter	Value / Distribution	Comments
2 - Processing (Deterministic)	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	
	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	0.114	To get a total exposure time of 1,000 hours in one year
4 - Biosolids loading (Deterministic)		Appendix A baseline values, except...	
	Indoor Fraction	0.114	To get a total exposure time of 1,000 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 Subcommittee, to be typical and 'reasonable.' There may exist, however, certain combinations of parameters that lead to radiation exposures that are greater or less than those calculated here. In exploring this variability, the Subcommittee noted, in particular, that the POTW worker scenarios display a broad array of site configurations and operations across the country. Thus, to partially address this variability, for the POTW worker loading scenario, calculations were performed for a number of different combinations of facility characteristics; this may provide a closer match to actual facilities.

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

5.3 PARAMETER UNCERTAINTY AND VARIABILITY

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

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

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

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

Table 5.1 Parameters and their Uncertainties and Variability

Parameter	Uncertainty Characterized by Distribution	Variability Characterized by Distribution
Hydrogeological parameters		
Distribution Coefficients	The possibility of rapid transport due to fracture flow and/or colloidal transport.	Variability of published measured or estimated values.
Total and Effective Porosities	—	Variability of published measured or estimated values based on national databases.
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.
Soil b parameter	—	Variability of published measured or estimated values.

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

Table 5.1 Parameters and their Uncertainties and Variability (continued)

Parameter	Uncertainty Characterized by Distribution	Variability Characterized by Distribution
Hydraulic Gradient	—	Variability of published measured or estimated values.
Unsaturated Zone Thickness	—	Variability across continental U.S.
Well pump intake depth	Uncertainty in actual intake depths	Variability in aquifer thicknesses.
Depth of Soil Mixing Layer	—	Variability in natural (wind, precipitation) and man-made processes (tillage).
Human Intake Parameters		
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.
Crops and Livestock Parameters		
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
Building Characteristics parameters		
Indoor dust filtration factor	—	Variability amongst different buildings, climates, and seasons.
External Gamma Shielding Factor	—	Variability amongst different home constructions
Other parameters		
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.		

Table 5.2 Parameter Uncertainty/Variability Results

Ratio of 95% DSR to 5% DSR								
Radio-nuclide	**Onsite Resident**	**Recrea-tional User**	**Nearby Town**	**Landfill (MSW) Neighbor**	**Landfill (Surface Impound-ment) 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	1.2	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	5.3	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	744.8	6.8	4.8E+08	2.8E+08	2.0	3.0	213.3
Pa-231	22.1	22.9	17.7	3.3E+04	5.0E+03	2.0	19.6	9.6
Pb-210	9.9	3.0	6.1	81.4	77.2	1.9	5.2	6.4
Po-210	20.2	7.8	4.8	1.0	1.0	2.5	12.2	99.1
Pu-238	7.0	1.2	6.1	11.9	1.1	2.0	12.6	187.5
Pu-239	6.8	1.2	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	1.0–1.8*
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	8.2	5.0	1.0	1.0	2.7	1.2	1.0
Sr-90	35.9	25.8	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	1.2–2.9*
Th-229	2.2	1.1	6.0	35.7	25.3	2.0	2.6	2.6
Th-230	62.6	46.7	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	150.8	7.7	114.4	104.9	2.0	18.6	88.3
U-234	19.2	112.6	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	14.5	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

* Range represents results from the nine combinations of air exchange rate and room height (see Section 4.7.3).

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/yr. 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/yr). For a "worst case" scenario under modern-day practices, the HELP model calculated an infiltration rate of 3.3 cm/yr out of 107 cm/yr 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/yr (again out of 107 cm/yr of precipitation), with leachate at about 25 cm/yr. 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 1,000-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, $\mathrm{dsr}_j(t), j = 1 \ldots J$, for every scenario and for every radionuclide (set at unit specific activity in dry sludge). As shown in Equation 6.1, each $\mathrm{dsr}_j(t)$ has a maximum value, called DSR_j,

$$\mathrm{DSR}_j = \mathrm{Max}[\mathrm{dsr}_j(t)] \ , \qquad \textbf{(6.1)}$$

and the set of these maximum values, $\{\mathrm{DSR}_j\}$, 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 (as discussed in Section 3.2.2), where appropriate. Table 6.1 presents the total DSRs, which include doses due to radon and other, non-radon exposure pathways, while Table 6.2 presents the DSRs for the radon pathway only. 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 very small (less than 0.001 mrem/yr per pCi/g). Indoor radon was only a significant component of the dose for the Onsite Resident with Ra-226 and Th-228. In the case of Ra-226, radon was the dominant pathway.

Table 6.1 Onsite Resident Scenario Total DSR Results (mrem/yr per pCi/g)

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 (mrem/yr per pCi/g) (continued)

Radio-nuclide	95% Peak Total DSR	Critical Pathway(s)	Scaling Factors				
			1	5	20	50	100
Pa-231	4.75e-02	Plant Ingestion and External	1.00e+00	5.00e+00	2.00e+01	4.94e+01	9.59e+01
Pb-210	1.88e-02	Meat	1.00e+00	4.83e+00	1.56e+01	2.65e+01	3.19e+01
Po-210	6.13e-03	Meat	1.59e-01	1.90e-01	1.90e-01	1.90e-01	0.19
Pu-238	1.23e-03	Plant and Soil Ingestion	9.91e-01	4.86e+00	1.82e+01	3.99e+01	6.51e+01
Pu-239	1.35e-03	Plant and Soil Ingestion	9.99e-01	4.98e+00	1.97e+01	4.84e+01	9.36e+01
Ra-226	1.94e-01	Radon *	1.00e+00	5.00e+00	2.00e+01	4.98e+01	9.83e+01
Ra-228	3.55e-02	External	1.00e+00	4.82e+00	1.16e+01	1.30e+01	1.30e+01
Sm-153	9.93e-06	External	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Sr-89	4.11e-04	Meat and Plant Ingestion	6.43e-03	6.47e-03	6.47e-03	6.47e-03	6.47e-03
Sr-90	3.23e-02	Meat and Plant Ingestion	9.40e-01	4.17e+00	1.11e+01	1.49e+01	1.56e+01
Th-228	2.36e-02	External *	6.96e-01	1.92e+00	2.29e+00	2.29e+00	2.29e+00
Th-229	5.71e-03	External	1.00e+00	5.00e+00	1.99e+01	4.96e+01	9.85e+01
Th-230	6.24e-02	Radon	1.00e+00	5.01e+00	2.01e+01	5.06e+01	1.03e+02
Th-232	5.28e-02	External	1.00e+00	5.00e+00	2.00e+01	4.99e+01	9.94e+01
Tl-201	1.88e-05	External	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
Tl-202	3.45e-04	External	1.00e-09	1.00e-09	1.00e-09	1.00e-09	1.00e-09
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 (mrem/yr per pCi/g) (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 (mrem/yr per pCi/g)

Radio-nuclide	95% Peak Non-Rn DSR	95% Peak Indoor Rn-only DSR		
		TEDE (mrem/yr per pCi/g)	WL (WL per pCi/g)	pCi/L (pCi/L per pCi/g)
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 (mrem/yr per pCi/g)

Radionuclide	95% Peak Total DSR	Critical Pathway(s)	Scaling Factor* 3 year waiting period
Ac-227	2.35E-03	External	9.06E-01
Am-241	1.82E-04	Soil	9.95E-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	5.98E-02
Co-60	1.10E-02	External	6.66E-01
Cr-51	1.49E-05	External	1.21E-12
Cs-134	6.41E-03	External	3.63E-01
Cs-137	2.86E-03	External	9.27E-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	8.62E-01
I-125	3.33E-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	8.55E-01
Pa-231	1.05E-02	External	1.00E+00
Pb-210	8.28E-04	Meat and Soil	9.75E-01
Po-210	4.15E-04	Meat	4.08E-03
Pu-238	1.29E-04	Soil	9.73E-01
Pu-239	1.45E-04	Soil	1.00E+00
Ra-226	8.72E-03	External	1.00E+00
Ra-228	7.37E-03	External	1.00E+00
Sm-153	2.77E-06	External	0.00E+00
Sr-89	1.51E-05	Meat and External	2.74E-07
Sr-90	1.45E-03	Meat	8.64E-01
Th-228	6.51E-03	External	3.37E-01
Th-229	1.52E-03	External	9.99E-01
Th-230	3.05E-03	External	1.00E+00

Table 6.3 Recreational User Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Radionuclide	95% Peak Total DSR	Critical Pathway(s)	Scaling Factor*
			3 year waiting period
Th-232	1.24E-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	Soil	9.78E-01
U-235	2.15E-03	External	9.79E-01
U-238	1.23E-03	External	9.79E-01
Xe-131m	8.19E-07	External	0.00E+00
Zn-65	2.35E-03	External	4.43E-02

Note:

* Scaling factors calculated to be less than 1e-27 were rounded to zero and listed as 0.00e+00.

Table 6.4 Nearby Town Scenario Total DSR Results (mrem/yr per pCi/g)

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

Table 6.4 Nearby Town Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Radio-nuclide	95% Peak Total DSR	Critical Pathway(s)	Scaling Factors				
			1	5	20	50	100
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
Ra-226	1.19e-04	Radon (outdoor)	1.00e+00	4.99e+00	1.99e+01	4.91e+01	9.64e+01
Ra-228	1.96e-04	Radon (outdoor)	1.00e+00	4.82e+00	1.25e+01	1.43e+01	1.43e+01
Sm-153	7.39e-11	Plant and Meat Ingestion	1.00e+00	1.00e+00	1.00e+00	1.00e+00	1.00e+00
Sr-89	5.70e-10	Inhalation and Meat Ingestion	1.00e+00	1.03e+00	1.03e+00	1.03e+00	1.03e+00
Sr-90	5.76e-08	Meat Ingestion	1.00e+00	4.98e+00	1.91e+01	3.75e+01	4.58e+01
Th-228	3.41e-04	Radon (outdoor)	1.00e+00	2.76e+00	3.29e+00	3.29e+00	3.29e+00
Th-229	1.92e-05	Inhalation	1.00e+00	5.00e+00	1.99e+01	4.97e+01	9.86e+01
Th-230	4.30e-05	Radon (outdoor)	1.00e+00	5.00e+00	1.99e+01	4.94e+01	9.75e+01
Th-232	3.51e-04	Radon (outdoor)	1.00e+00	5.00e+00	2.00e+01	4.98e+01	9.93e+01

Table 6.4 Nearby Town Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Radio-nuclide	95% Peak Total DSR	Critical Pathway(s)	Scaling Factors				
			1	5	20	50	100
Tl-201	4.49e-11	Meat Ingestion	1.00e+00	1.00e+00	1.00e+00	1.00e+00	1.00e+00
Tl-202	2.19e-10	Meat Ingestion	1.00e+00	1.01e+00	1.01e+00	1.01e+00	1.01e+00
U-233	1.50e-06	Inhalation	1.00e+00	4.92e+00	1.85e+01	4.13e+01	6.97e+01
U-234	1.15e-06	Inhalation	1.00e+00	4.90e+00	1.83e+01	3.98e+01	6.45e+01
U-235	1.19e-06	Inhalation	1.00e+00	4.91e+00	1.84e+01	4.06e+01	6.76e+01
U-238	1.04e-06	Inhalation	1.00e+00	4.90e+00	1.83e+01	3.98e+01	6.44e+01
Xe-131m	0.00e+00	Inhalation	1.00e+00	1.00e+00	1.00e+00	1.00e+00	1.00e+00
Zn-65	5.64e-09	Meat Ingestion	1.00e+00	2.43e+00	2.48e+00	2.48e+00	2.48e+00

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 subscenario, 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 (mrem/yr per pCi/g)

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

Table 6.5 Landfill Neighbor Scenario (Municipal Solid Waste) Total DSR Results (mrem/yr per pCi/g) (continued)

Radionuclide	95% Peak Total DSR	Critical Pathway(s)
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
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 (mrem/yr per pCi/g)

Radio-nuclide	95% Peak Non-Rn DSR	95% Peak Indoor Rn-only DSR		
		TEDE(mrem/yr per pCi/g)	WL (WL per pCi/g)	pCi/L (pCi/L per pCi/g)
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 (mrem/yr per pCi/g)

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

Table 6.7 Landfill Neighbor Scenario (Surface Impoundment) Total DSR Results (mrem/yr per pCi/g) (continued)

Radionuclide	95% Peak Total DSR	Critical Pathway(s)
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 *
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 (mrem/yr per pCi/g)

Radio-nuclide	95% Peak Non-Rn DSR	95% Peak Indoor Rn-only DSR		
		TEDE (mrem/yr per pCi/g)	WL (WL per pCi/g)	pCi/L (pCi/L per pCi/g)
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

Table 6.9 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 (mrem/yr per pCi/g)

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

Table 6.9 Incinerator Neighbor Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Radionuclide	95% Peak Total DSR	Critical Pathway(s)
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
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 (mrem/yr per pCi/g)

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

Table 6.10 Sludge Application Worker Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Radio-nuclide	95% Peak Total DSR	Critical Pathway(s)	Scaling Factors				
			1	5	20	50	100
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
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

Table 6.10 Sludge Application Worker Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Radio-nuclide	95% Peak Total DSR	Critical Pathway(s)	Scaling Factors				
			1	5	20	50	100
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

6.5.2 PUBLICLY OWNED TREATMENT WORKS WORKER SCENARIOS

For the POTW Worker Scenarios, the Loading subscenario had the highest DSRs, and the radionuclides Ra-226 and Th-228 had by far the highest DSRs in that subscenario. In the case of the Sampling Worker, even if samples were taken every hour for 2,000 hours a year, the DSRs would be significantly smaller than those for the Loading subscenario. Similarly, even in the case where the Transport Worker is in proximity to sewage sludge for 2,000 hours a year, the Loading subscenario would have the highest DSRs. Indoor radon contributed a significant portion of the dose for Ra-226 and Th-228 in the Transport and Loading subscenarios. For these scenarios, radon doses are also presented separately.

The computed DSRs for radium-226 and Th-228 for the POTW loading worker, which are dominated by radon contributions, depend strongly on the room air exchange rate and the height of the room. For this present report, nine combinations of building height and air exchange rate were used (see discussion in Section 4.7.3), with building heights of 2 m, 4 m, and 6 m, and air exchange rates of 1.5, 3, and 5 per hour. These parameters primarily affect the doses from inhalation of radon progeny. The impact of changes in air exchange rate and room height can be seen in Table 6.14b, which shows DSRs for the nine combinations of parameters.

Table 6.11 POTW Sampling Worker Scenario Total DSR Results (mrem/yr per pCi/g)

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		

Notes:

Only External pathway was evaluated in this subscenario. In addition, only deterministic calculations were performed.

Table 6.12 POTW Intra-POTW Transport Worker Scenario Total DSR Results (mrem/yr per pCi/g)

Radionuclide	Peak Total DSR	Critical Pathway(s)
Ac-227	4.20e-07	External
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

Table 6.12 POTW Intra-POTW Transport Worker Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Radionuclide	Peak Total DSR	Critical Pathway(s)
Th-232	9.37e-10	External
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 subscenario

Table 6.13 POTW Intra-POTW Transport Worker Scenario Indoor Radon DSR Results (mrem/yr per pCi/g)

Radionuclide	Peak Non-Rn DSR	Peak Indoor Rn-only DSR		
		TEDE (mrem/yr per pCi/g)	WL (WL per pCi/g)	pCi/L (PCi/L per pCi/g)
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 subscenario.

Table 6.14a POTW Biosolids Loading Worker Scenario Total DSR Results (mrem/yr per pCi/g)

Radionuclide	95% Peak Total DSR	Critical Pathway(s)
Ac-227	4.05E-01	Inhalation
Am-241	2.35E-02	Inhalation
Be-7	1.23E-02	External
C-14	5.60E-07	External
Ce-141	1.25E-02	External
Co-57	1.92E-02	External
Co-60	7.00E-01	External
Cr-51	7.40E-03	External
Cs-134	4.07E-01	External
Cs-137	1.46E-01	External
Eu-154	3.32E-01	External
Fe-59	3.31E-01	External
H-3	1.33E-03	Inhalation
I-125	6.00E-04	External
I-131	9.20E-02	External
In-111	8.05E-02	External
K-40	4.53E-02	External
La-138	3.46E-01	External
Np-237	2.89E-02	Inhalation
Pa-231	8.05E-02	Inhalation and External
Pb-210	1.33E-03	Inhalation and External
Po-210	4.35E-04	Inhalation
Pu-238	1.80E-02	Inhalation
Pu-239	2.38E-02	Inhalation
Ra-226	5.9E-01–2.7E+00*	Radon
Ra-226	5.9E-01–2.7E+00*	Radon
Ra-228	2.59E-01	External
Sm-153	5.80E-03	External
Sr-89	3.95E-04	External
Sr-90	1.05E-03	External
Th-228	2.2E+00–1.8E+01*	Radon
Th-229	1.74E-01	External

Table 6.14a POTW Biosolids Loading Worker Scenario Total DSR Results (mrem/yr per pCi/g) (continued)

Th-230	1.68E-02	Inhalation
Th-232	8.35E-02	Inhalation
Tl-201	1.01E-02	External
Tl-202	1.05E-01	External
U-233	7.55E-03	Inhalation
U-234	6.15E-03	Inhalation
U-235	3.68E-02	External
U-238	1.13E-02	External
Xe-131m	8.75E-04	External
Zn-65	1.60E-01	External

Note:

* Range represents results from the nine combinations of air exchange rate and room height (see Section 4.7.3). Individual results are shown in Table 6.14b.

Table 6.14b POTW Biosolids Loading Worker Scenario Total DSR Results (mrem/yr per pCi/g) for Ra-226 and Th-228

		95% Peak total DSR (mrem/y per pCi/g)	
Air exchange rate (h^{-1})	**Room height (m)**	**Ra-226**	**Th-228**
1.5	2	2.7	18
	4	1.6	9.4
	6	1.2	6.4
3	2	1.2	9.3
	4	0.85	4.9
	6	0.73	3.4
5	2	0.79	5.6
	4	0.64	3.0
	6	0.59	2.2

Table 6.15 POTW Biosolids Loading Worker Scenario Indoor Radon DSR Results (mrem.yr per pCi/g)

Radio-nuclide	95% Peak Non-Rn DSR	95% Peak Indoor Rn-only DSR*		
		TEDE (mrem/yr per pCi/g)	WL (WL per pCi/g)	pCi/L (pCi/yr per pCi/g)
Ra-226	0.48	0.10–2.2	2.3E-5 – 5.0E-4	0.026 – 0.32
Th-228	0.45	1.7–18	1.9E-3 – 2.0E-2	2.5 – 11

Note:

* Range represents results from the nine combinations of air exchange rate and room height (see Section 4.7.3).

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 shown in Equation 7.1,

$$D_s = \sum_r A_r \times \mathrm{DSR}_{rs} \ , \qquad \textbf{(7.1)}$$

where $\{\mathrm{DSR}_{rs}\}$ 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 sample[11] 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.

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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) subscenario uses both sewage sludge and ash samples, since municipal solid waste landfills tend to contain both materials; the source term for the surface impoundment subscenario, by contrast, considers only sludge samples.

Table 7.1 Calculated Total Peak Dose (Total Effective Dose Equivalent–TEDE) from Survey Samples: Summary Results With and Without Indoor Radon Contribution

Scenario	Subscenario	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	3.8–17 [2]	2.7	17–70[2]	13	Ra-226, Th-228 [indoor Rn]

Notes:

All values rounded to two significant figures. Note that 95% DSRs are used in all total peak dose calculations. A "–" denotes that indoor radon was not separately calculated.

1 There are very few land application sites in the country that are known to have applied sewage sludge annually for more than 20 years; the 50- and 100-year computations were included for the information of POTW operators in their consideration of future sludge management practices.

2 Range represents results from the nine combinations of air exchange rate and room height (see Sections 4.7.3 and 7.5 below).

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

Scenario	Subscenario	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

* Range represents results from the nine combinations of air exchange rate and room height (see Sections 4.73 and 7.5, below).

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 applications or even 50 applications; these two sub-scenarios were included in the modeling for consistency with the technical support for the 40 CFR Part 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 accord with 40 CFR 503, and therefore required to have 30 day waiting period prior to sale and application; only rarely is sludge treated to destroy pathogens and released as Class A sludge without a waiting period.

7.3 CALCULATED DOSES FOR LANDFILL/IMPOUNDMENT NEIGHBOR SCENARIO

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

7.4 CALCULATED DOSES FOR PUBLICLY OWNED TREATMENT WORKS INCINERATOR NEIGHBOR SCENARIO

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

7.5 CALCULATED DOSES FOR PUBLICLY OWNED TREATMENT WORKS SLUDGE/ASH WORKER SCENARIOS

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

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

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

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

Using a baseline exposure time of 1,000 hours per year, the following two expressions (Equations 7.2 and 7.3) are for the DSRs for Ra-226 and Th-228 (in mrem/yr per pCi/g) in terms of these four parameters alone and with all others held constant:[12]

$$DSR_{Ra\text{-}226} \approx 0.5 + 41.5\, \rho_{sludge} A_{sludge} \times (t_{exp}/1000 \text{ hours})/[\,(0.008 + \lambda_x) \times (2.69\, h_{room}^{-0.77} + \lambda_x)\, V_{room}] \;, \qquad \textbf{(7.2)}$$

$$DSR_{Th\text{-}228} \approx 0.45 + 2649\, \rho_{sludge} A_{sludge} \times (t_{exp}/1000 \text{ hours})/[\,(45 + \lambda_x) \times (1.25\, h_{room}^{-0.77} + \lambda_x)\, V_{room}] \;, \qquad \textbf{(7.3)}$$

These expressions reproduce RESRAD-BUILD runs to within about 10%.[13] The first term in each equation represents external exposure, and the second is for indoor radon exposure. Note that λ_x is the room air exchange rate in exchanges per hour; ρ_{sludge} the bulk density of the sludge in grams per cubic cm; V_{sludge} the total volume of sludge in the room in cubic meters; V_{room} the total volume of the room in cubic meters; h_{room} the height of the room in meters; A_{sludge} the surface area of the pile of sludge in the room in square meters; and t_{exp} is the exposure time (working time per year) in hours. The derivation of these fitting formulae, and additional discussion and motivation for their functional form, are contained in Appendix D.

For radon, the relationships among dose, progeny concentrations in working levels (WL), and exposures in working level months (WLM) are described in Appendix D.

7.6 UNCERTAINTY AND VARIABILITY IN CALCULATED DOSES

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

Table 7.3 summarizes the relative importance of parameter uncertainty/variability and source variability (which greatly exceeds source uncertainty) with respect to the calculated doses. As with Table 5-2, it presents the ratio of the 95-th percentile DSR to the 5% DSR. In the case of parameter uncertainty/variability, the 95% sample dose was calculated using both 95% and 5% DSRs, and this ratio captures the dose range due to changes in model parameters. In the case of

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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, $\rho_{sludge} = 1$ g/cm^3, $A_{sludge} = 6900$ m^2, $V_{sludge} = 13{,}800$ m^3, $V_{room} = 72{,}000$ m^3, 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 2.6 mrem/yr, whereas the approximate expression above gives 2.3 mrem/yr, a difference of only 12%.

source uncertainty, the ratio was taken between the 95% sample dose and 5% sample dose, for a fixed 95% DSR, thereby measuring the dose range due to different sludge and ash sample sources. Clearly, the source variability is a significantly greater cause of variance than the parameter uncertainty. Only in the cases of the POTW loading scenario are the magnitudes of parameter uncertainty and variability (for Ra-226 and Th-228) and the source variability comparable. In general, the source variability is greater by a factor of at least 10 or more.

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 operational life	36	2.3

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

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	16–19*	1.04–2.0*

Note:

* Range represents results from the nine combinations of air exchange rate and rom height (see Sections 4.7.3 and 7.5, below).

8 CONCLUSIONS

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

The computations have been undertaken using probabilistic versions of three members of a widely employed family of environmental transport codes: RESRAD, RESRAD-OFFSITE, and RESRAD BUILD. The principal outputs are the tables of Dose-to-Source Ratios (DSR) for the relevant radionuclides, under seven hypothetical sludge management scenarios, and the associated tables of multiplicative factors that correct for multiple years of sludge application. The 95th-percentile DSR value, for a particular radionuclide and scenario, relates the 95th-percentile level of dose, as determined in a Monte Carlo computation, to an average member of the critical population group that would result from the presence of unit activity concentration in sludge—that is, for 37 Bq per kilogram (1 pCi per gram) of dry sludge.

As expected, the DSR values range widely within each scenario, for the various radionuclides, and there is significant variance among the scenarios. These differences, however, are meaningful only when considered in the context of the concentrations in sludge actually found in the POTW Survey. Chapter 7 of this report combines the DSRs computed here with the Survey measurements, and makes it clear that while some scenarios and radionuclides give rise to very low doses, there are other radionuclide-scenario combinations that may be of concern. In particular, the calculated 95th-percentile sample dose for the Onsite Resident (with 50 years or 100 years of prior sludge application), and that for POTW Workers involved in sludge loading, exceed 1 mSv/yr (100 mrem/yr)[14]. Doses to the POTW incinerator neighbor (after 50 years of incineration) and the sludge application worker (after 50 years of field application), on the other hand, were below 0.1 mSv/yr (10 mrem/year), and those to the recreational user, residents of a nearby town, and neighbors of a landfill were all of little consequence.

The basic conclusions of this report are as follows:

- None of the non-POTW scenarios show a significant current widespread threat to public health. For instance, the scenarios with the largest potential critical groups—the Nearby Town and the Incinerator—show relatively small estimated doses.
- If agricultural land application is carried out for a long time into the future, then the potential exists for future radiation exposure primarily due to Radon. This is illustrated in the 50- and 100-year application subscenarios of the Onsite Resident.
- In specific cases of very high levels of radioactive materials (e.g., levels above the 95%), there is the potential for localized radiation exposure.

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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).

- Within the POTW, little exposure is expected for sampling and transport. Only when workers are in the same room with large quantities of sludge (e.g., for storage or loading) is there the potential for significant exposure, predominantly due to Radon. In this case, the degree of exposure is likely to depend highly on the configuration of the POTW in terms of room sizes, ventilation, etc.

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

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

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

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

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Appendix A

Baseline Parameter Values and Distributions

A.1 Introduction

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

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

A.2 Parameters Used in Multiple Codes

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

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

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**		
			:	F	exp(:)
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

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

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

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

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*		
			:	F	exp(:)
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}

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

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

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*		
			:	F	exp(:)
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}

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

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

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*		
			:	F	exp(:)
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}

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

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

Element of Interest	RESRAD 6.0 Default Value	Baseline Value as Geometric Mean of the Distribution	Disbribution from NUREG/CR-6697		
			Lognormal Distribution Parameters		
			:	F	exp(:)
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

A.3 Code-Specific Parameters

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

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

The following notation is used in the baseline tables:

* Mean value of the distribution.

** Geometric mean value of the distribution.

*** Not an input parameter in RESRAD.

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

N/A Not applicable.

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/yr)	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/yr)	(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/yr)	(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/yr)	1.0			
Irrigation (m/yr)	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/yr)	(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/yr)	(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/yr)	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/yr)	(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/yr)	(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/yr)	(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/yr)	(14)	22.667*	No distribution / Triangular (13, 25, 30)	Baseline distribution derived from EPA 1997 using methodology of NUREG/CR-6697.
Milk (L/yr)	(92)	120.67*	Triangular (60, 102, 200)	
Meat and Poultry (kg/yr)	(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/yr)	(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/yr)	(0.9)	0		No ocean fish.
Soil Ingestion (g/yr)	(36.5)	18.27*	Triangular (0, 18.3, 36.5)	
Drinking Water Intake (L/yr)	(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			

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
Aquatic food	(0.5)	0.463*	Triangular(0, 0.39, 1)	
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^3)	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)	

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
Groundwater Fractional Usage				
Drinking Water	1			
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/yr)	(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			

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
Translocation Factor	1			
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)	2×10^{-6}	N/A		No cover.
Bldg Foundation Thickness (m)	0.15			
Bldg Foundation Density (g/cm^3)	2.4			

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 Total Porosity	0.1			
Bldg Foundation Volumetric Water Content	0.03			
Bldg Foundation Radon Diffusion Coefficient (m^2/s)	3×10^{-7}			
Contaminated Radon Diffusion Coefficient (m^2/s)	2×10^{-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			

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
Storage Times Before Use Data				
Fruits, Non-leafy Vegetables and Grain (d)	14			
Leafy Vegetables (d)	1			
Milk (d)	1			
Meat (d)	20			
Fish (d)	7			
Crustacea and Molusks (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			

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
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			
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 Input					
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	
Intake to animal product 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
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)	
Water to aquatic food 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
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			
Leafy vegetables (d)		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**
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(1.445, 0.2419, 1.4, 13)	
Primary Contamination Area Parameters					
Contaminated zone and cover					
Area of primary contamination (m^2)		(10000)	404685 (100 acres)		
Length of contamination parallel to aquifer flow (m)		(100)	636 (equivalent to the square root of area).		

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 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/yr)		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 parameters is used to calculate the erosion rate.
Slope-length-steepness factor	v	1			The parameter is used to calculate the erosin rate.
Cropping management factor	v	0.11			The parameter is used to calculate the erosin rate.
Conservation practice factor	v	1			The parameter is used to calculate the erosion rate.
Contaminated zone					
Thickness (m)		(2)	0.15		Plowing depth.
Total porosity		(0.4)	0.426		Value calculated using the dry bulk density.

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/yr)		(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/yr)		(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		
Erosion rate (m/yr)		(0.0009856)	Not used		No cover material. The parameter value is calculated by RESRAD-Offsite using other input parameters.

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**
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(2.2926, 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.
Hydraulic conductivity (m/yr)		(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)	

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**
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/yr)		(100)	9.974**	BoundedLogN(2.3, 2.11, 0.004, 9250)	
Hydraulic gradient		(0.02)	0.00604**	BoundedLogN(-5.1 1, 1.77, 7e-5, 0.5)	
Longitudinal dispersivity (m)	v	10			
Horizontal lateral dispersivity (m)	v	3			
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/yr)		0.2	Not used		Vertical dispersion was selected.

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		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/yr)	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)	

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 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/yr)	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.
Conservation practice factor	v	1			The parameter is used to calculate the erosion rate.
Leafy vegetable field					
Area (m^2)	v	1000			

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 area directly over primary contamination	v	0			Scenario definition.
Irrigation applied per year (m/yr)	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.
Erosion rate (m/yr)	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.

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
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/yr)	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/yr)	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.
Grain field					
Area (m^2)	v	10000			
Fraction of area directly over primary contamination	v	0			
Irrigation applied per year (m/yr)	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)	

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 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/yr)	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.

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
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.
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					

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 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					
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			

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
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					
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/yr)		(510)	409.5 **	TruncLogN(6.015, 0.489, 0.001, 0.999)	

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 surface body		0			Assuming 90% of the drinking water is from a local well.
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/yr)	v	225			
Fraction of water from surface body		0			
Fraction of water from well		1			
Beef cattle					
Quantify (L/yr)		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/yr)		160			
Fraction of water from surface body	v	(0)	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
Fraction of water from well	v	(1)	0.5		
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/yr)	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/yr)	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/yr)	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/yr)	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/yr)		250			Value kept consistent with the baseline value used for RESRAD.
Well pumping rate needed to specified water use (m^3/yr)	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/yr)		(510)	409.5**	TruncLogN(6.015, 0.489, 0.001, 0.999)	
Fish (kg/yr)		(5.4)	155.6*	/ Triangular(2.0, 56.3, 408.5)	Baseline distribution from 1997 EPA Exposure Factors Handbook.
Other aquatic food (kg/yr)		(0.9)	0		Scenario definition. No ocean fish.
Fruit, grain, non-leafy vegetables (kg/yr)		(160)	210.33*	Triangular(135, 178, 318)	
Leafy vegetables (kg/yr)		(14)	22.667*	/ Triangular(13, 25, 30)	
Meat (kg/yr)		(63)	222.1*	/ Triangular(5.0, 72.6, 588.7)	
Milk (L/yr)		(92)	120.67*	Triangular(60, 102, 200)	
Soil (incidental) (g/yr)		(36.5)	18.27*	Triangular(0, 18.3, 36.5)	

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
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.
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.

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
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.
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.

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
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.
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".

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
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.
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".

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**
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.
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/yr)		(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)	
External Radiation Shape and Area Factors					
Shape of the plane of the primary contamination					
Circular?		Yes			
Polygonal?		No			

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
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.
Occupancy Factors					
Fraction of time spent on primary contamination (whether cultivated or not)					
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)					

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
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.
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.
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.

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
Radon Data					
Effective radon diffusion coefficient of cover (m^2/s)		2×10^{-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)		3×10^{-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.
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.

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**
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			
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)	

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 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.
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.
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.

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 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.
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.
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.

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 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.
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.
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.

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-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.
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)	
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)	

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 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			
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.

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
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			
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)	

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 Diffusion Coefficient (m^2/s)	2.0E-5			
Porosity	(0.1)	0.4		
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		
Humidity (g/m^3)	(8)	9.8*	Uniform (6.5, 13.1)	This distribution represents humidity inside the building

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
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

B.1 Introduction

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

The RESRAD code focuses on radioactive contaminants in soil and their transport in air, water, and biological media to a single receptor. Nine exposure pathways are considered in RESRAD: (1) direct exposure; inhalation of (2) particulates and (3) radon; and ingestion of (4) plant foods, (5) meat, (6) milk, (7) aquatic foods, (8) water, and (9) soil. Figure B.1 illustrates conceptually the exposure pathways considered in RESRAD. RESRAD calculates time-integrated annual dose, soil cleanup guidelines, radionuclide concentrations, and lifetime cancer risks as a function of time. The code estimates at which time the peak dose occurs for each radionuclide and for all radionuclides summed. The RESRAD code permits sensitivity analysis for various parameters. Graphics are used to show the sensitivity analysis and probabilistic results. Text reports are provided for users to view the deterministic and probabilistic analysis results through a text viewer.

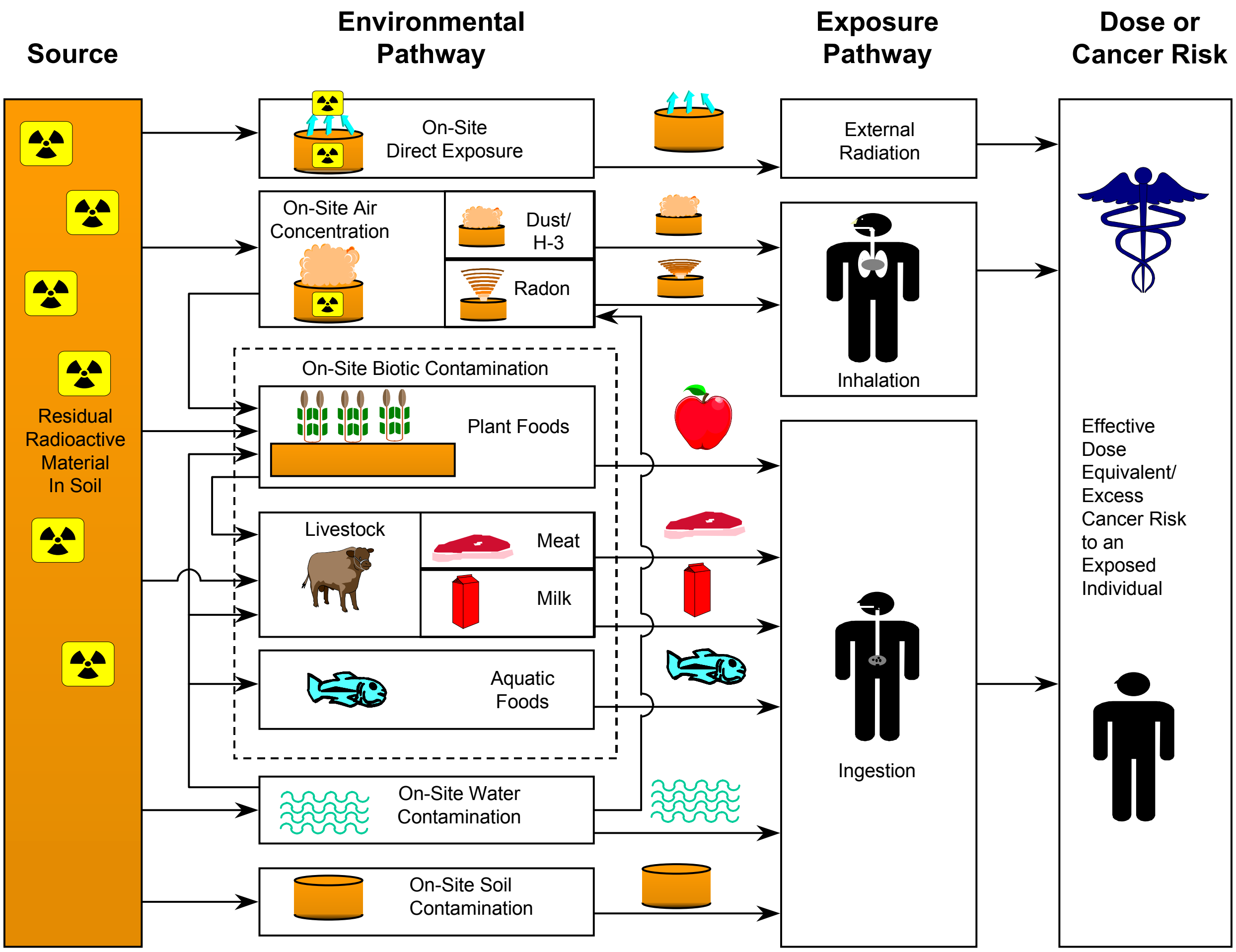

Figure B.1. Graphical Representation of Pathways Considered in RESRAD

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 B.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.

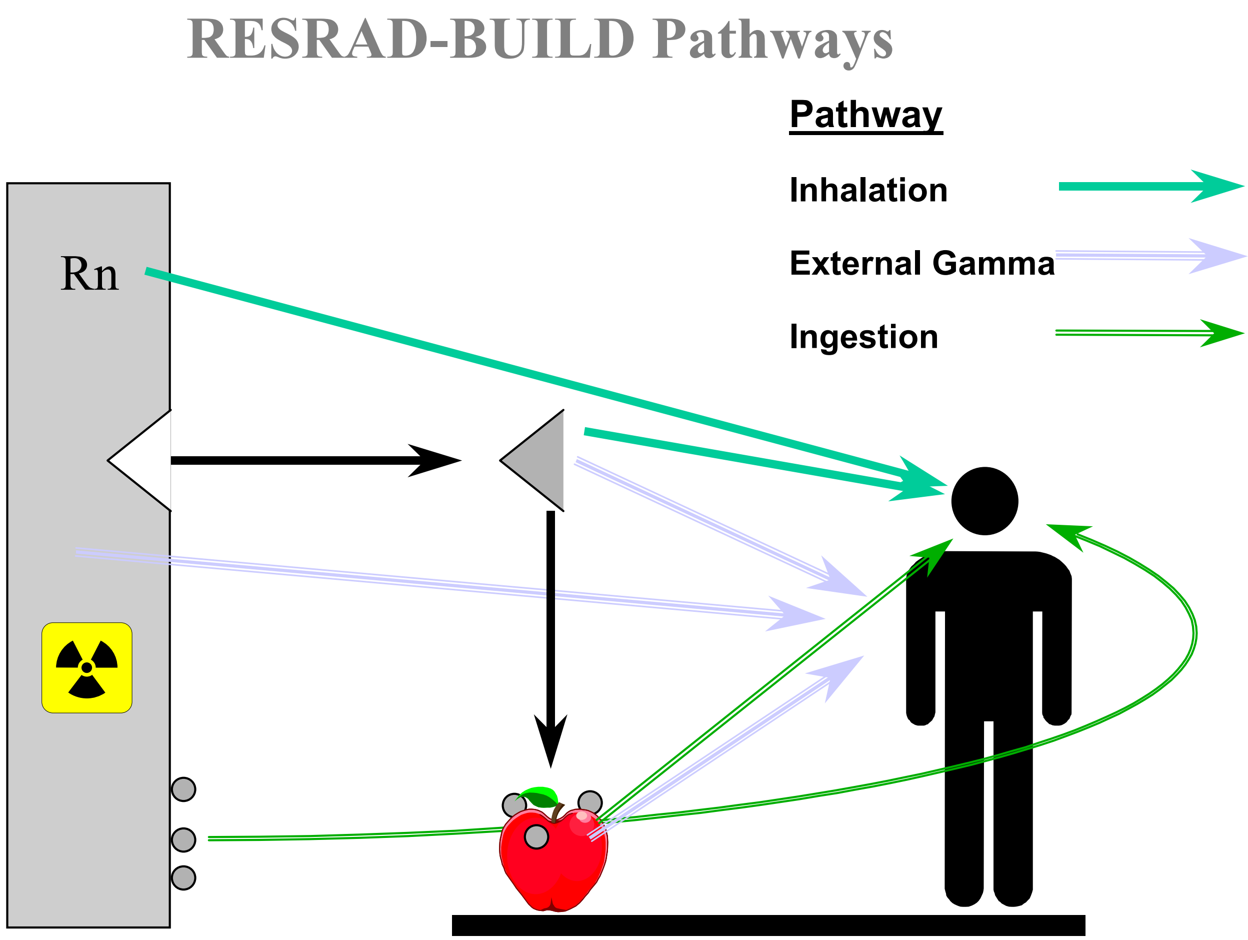

Figure B.2. Graphical Representation of Pathways Considered in RESRAD-BUILD

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

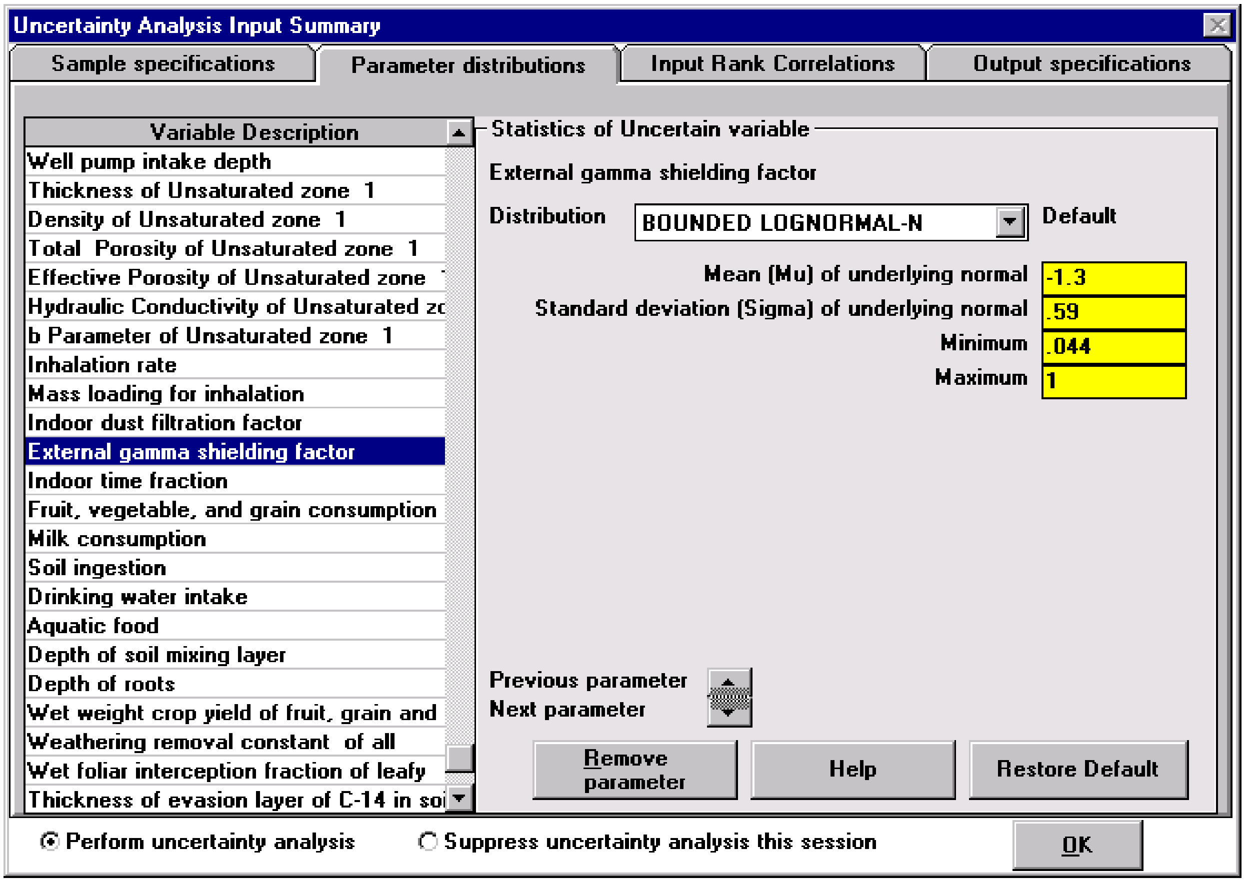

Figure B.3. Parameter Distribution Input Screen

B.2 Probabilistic Modules

B.2.1 Overview

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

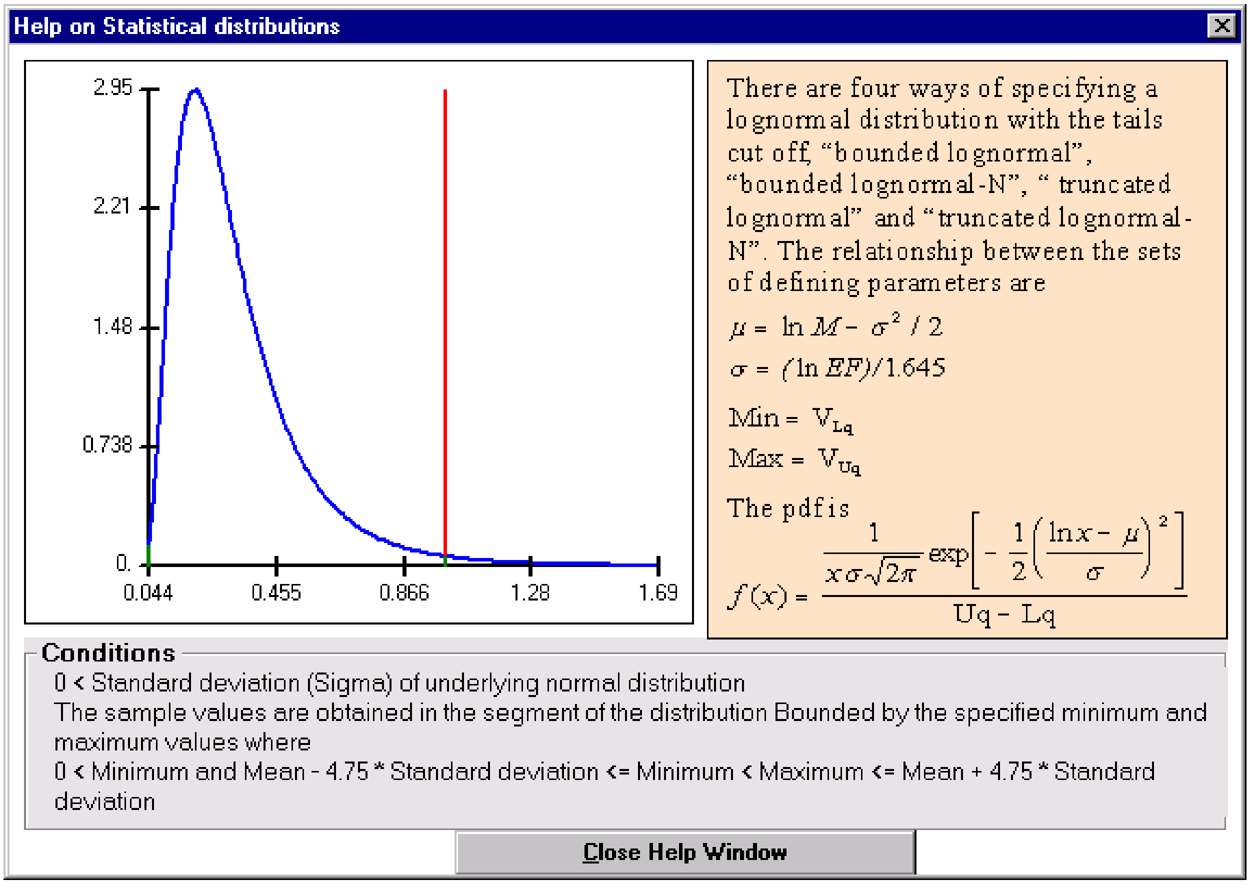

Figure B.4. Parameter Distribution Help Screen

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

B.2.2 Sampling Method

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

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

Input Data	Description
Sampling Parameters	
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.
Sampling Techniques	
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 is obtained at random from the whole distribution.
Grouping of Observations	
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 variable are grouped together at random. Some pairs of variables may be correlated just by chance.
Statistical Distributions	
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 B.5). The input interface will check that these are satisfied when the user completes inputting the parameters.
Input Rank Correlations	
Variable 1, Variable 2	Two variables for which rank correlation is specified
Rank Correlation Coefficient	The specified input rank correlation coefficient between two variables

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

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

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

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

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

Iman and Helton (1985) suggest ways of choosing the number of samples for a given situation. The minimum and maximum doses and risk vary with the number of samples chosen. The accuracies of the mean dose and of the dose values for a particular percentile are dependent on the percentile of interest and on the number of samples. The confidence interval or the (upper or lower) confidence limit of the mean can be determined from the results of a single set of samples. Distribution-free upper (u%, v%) statistical tolerance limits can be computed by using the SRS technique according to the methodology in IAEA Report No. 100 (IAEA, 1989).

B.2.3 Distribution of Parameters

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

B.2.4 Probabilistic Results

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

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

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

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

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

The probabilistic versions of the RESRAD and RESRAD-BUILD codes provide tools for studying the uncertainty in dose assessment caused by uncertainty in the input parameters. Although the codes are designed to be user-friendly, they must be used with caution, and it is important that users be properly trained and that sufficient site-specific (probabilistic) data be collected for input into the codes.

B.3 References

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Appendix C

Incinerator Control/Release Fractions

C.1 Introduction

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

C.2 Regulatory Values for Release Fraction

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

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

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

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

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

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

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

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

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

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

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

C.5 Part 503 Metals Partitioning Information

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

C.6 Summary

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

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

Nuclide	*Decontamination Factor*	*Release Fraction*
H-3	1.1	0.9
C-14	1.3	0.75
Cl-36	100	0.01
Tc-99	100	0.01
Ru-103	100	0.01
Ru-106	100	0.01
I-125	100	0.01
I-129	100	0.01
All others	400	0.0025

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

Element	*Bottom Ash or Slag*	*Fly Ash*	*Stack Emissions*
Cs	60-90	30-50	0.2
Sr	45-95	2-20	0.05
Zr	60-95	40-60	<1
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

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

Element	*Fly Ash*	*Slag*	*Stack*
H	0.1	0	0.9
Be	0.1	0.9	0.001
C	0.02	0.03	0.95
Na	0.1	0.9	0.001
P	0.13	0.85	0.02
S	0.65	0.3	0.05
Sc	0.05	0.95	0.0005
V	0.1	0.9	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	0.6	0.005
Zn	0.49	0.5	0.01
Ge	0.5	0.5	0.001
As	0.5	0.5	0.005
Se	0.8	0.1	0.1
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	0.5	0.4	0.1
Ru	0.59	0.4	0.01
Ag	0.2	0.8	0.001
Sn	0.02	0.98	0.001
Sb	0.43	0.55	0.02

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

Element	*Fly Ash*	*Slag*	*Stack*
Te	0.49	0.5	0.01
I	0.68	0.02	0.3
Cs	0.2	0.8	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	0.9	0.05	0.05
Bi	0.7	0.3	0.005
Ra	0.1	0.9	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

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

Element	*ACERC[1]*	*SWIFT[2]*	*EPA IRF[3]*	*APTUS[4]*
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

Notes:

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.

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

Element	*SWIFT*[1]	*EPA IRF*[2]	*APTUS*[3]
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

Notes:

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

Table C.6 Average Control Efficiencies for the Easterly, Southerly, and Westerly 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

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Appendix D

Conversion Between Radon Doses and Working Level Concentrations

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

This subsection describes the conversion between radon-pathway doses and Working Level concentration levels in the onsite resident and POTW loading worker scenarios. For Rn-220 and Rn-222 progeny, the conversion between the two dosimetric quantities committed effective dose equivalent (CEDE) and Working Level Months (WLM) used by RESRAD and RESRAD-BUILD is given by Equation D.1:

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

with the conversion factors listed in Table D.1.

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

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

The conversion between dose in WLM and the concentrations of radon progeny in Working Levels (WL) is given by the Equation D.2:

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

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

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

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

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

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

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

The first quantity calculated by RESRAD-BUILD is the air concentration of radon isotopes. For a unit concentration source, following fitting formulas (Equations D.3 and E.4) were derived for the CSR ratio, where the concentration is the activity in pCi/L of Rn-220 or Rn-222:

$$\mathrm{CSR}_{\mathrm{pCi\ Rn\text{-}220/l\ per\ pCi/g\ Th\text{-}228}} \cdot 720 \times (45 + 8_x)^{-1}\, r_{\mathrm{sludge}}\, A_{\mathrm{sludge}} / V_{\mathrm{room}} \qquad \textbf{(D.3)}$$

$$\mathrm{CSR}_{\mathrm{pCi\ Rn\text{-}222/l\ per\ pCi/g\ Ra\text{-}226}} \cdot 1.49 \times (0.008 + 8_x)^{-1}\, r_{\mathrm{sludge}}\, V_{\mathrm{sludge}} / V_{\mathrm{room}} \qquad \textbf{(D.4)}$$

Here 8_x is the room air exchange rate in exchanges per hour, r_{sludge} is the bulk density of the sludge in grams per cubic cm, V_{sludge} is the total volume of sludge in the room in cubic meters, and V_{room} is the total volume of the room in cubic meters, and A_{sludge} is the *surface area* of the pile of sludge in the room in square meters. The formulas are accurate to a few percent[1].

The following fitting formulas (Equations D.5 and D.6) were derived converting betwen concentrations in WL and concentrations in pCi/l were derived from sensitivity analyses of the baseline RESRAD-BUILD calculation:

$$C_{\mathrm{WL\ Rn\text{-}220}} \cdot C_{\mathrm{pCi\ Rn\text{-}220/l}} \times 0.00417 \times (1.25\, h_{\mathrm{room}}^{-0.77} + 8_x)^{-1} \qquad \textbf{(D.5)}$$

$$C_{\mathrm{WL\ Rn\text{-}222}} \cdot C_{\mathrm{pCi\ Rn\text{-}222/l}} \times 0.00625 \times (2.69\, h_{\mathrm{room}}^{-0.13} + 8_x)^{-1} \qquad \textbf{(D.6)}$$

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

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1 The motivation for the $(\text{constant} + 8_x)^{-1}$ formula 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.

Combining Equations D.3–D.6 leads to the following Concentration-to-Source-Ratios (Equations D.7 and D.8):

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

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

Furthermore, using Equation D.2 can be used to obtain Dose-to-Source in terms of WLM (Equations D.9 and D.10). We do this using the baseline expires time (annual working hours near the sludge) of 1,000 hours, and include the factor to correct for other exposure times t_{exp}:

$$DSR_{WLM\ Rn\text{-}220\ per\ pCi/g\ Th\text{-}228} \approx 17.6 \times (45 + \lambda_x)^{-1} \times (1.25\ h_{room}^{-0.77} + \lambda_x)^{-1} \times (r_{sludge}\ A_{sludge} / V_{room}) \times (t_{exp} / 1000\ \text{hours}) \quad \textbf{(D.9)}$$

$$DSR_{WLM\ Rn\text{-}222\ per\ pCi/g\ Ra\text{-}226} \approx 0.0547 \times (0.008 + \lambda_x)^{-1} \times (2.69\ h_{room}^{-0.13} + \lambda_x)^{-1} \times (r_{sludge}\ A_{sludge} / V_{room}) \times (t_{exp} / 1000\ \text{hours}) \quad \textbf{(D.10)}$$

Finally, using Equation D.1 leads to the radon dose formulas (Equations D.11 and D.12):

$$DSR_{mrem(radon)\ per\ pCi/g\ Th\text{-}228} \approx 2640 \times (45 + \lambda_x)^{-1} \times (1.25\ h_{room}^{-0.77} + \lambda_x)^{-1} \times (r_{sludge}\ A_{sludge} / V_{room}) \times (t_{exp} / 1000\ \text{hours}) \quad \textbf{(D.11)}$$

$$DSR_{mrem(radon)\ per\ pCi/g\ Ra\text{-}226} \approx 41.5 \times (0.008 + \lambda_x)^{-1} \times (2.69\ h_{room}^{-0.13} + \lambda_x)^{-1} \times (r_{sludge}\ A_{sludge} / V_{room}) \times (t_{exp} / 1000\ \text{hours}) \quad \textbf{(D.12)}$$

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

Appendix E

Probabilistic Percentiles for Dose-to-Source Ratios

This appendix contains the probabilistic results for the Dose-to-Source Ratios (mrem/yr per pCi/g) in sewage sludge for each scenario. Note that the scaling factors to account for multiple years of application and waiting periods were provided in Chapter 6.

Table E.1 Onsite Resident DSR Percentiles (mrem/yr per pCi/g in Sewage Sludge)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	3.64e-03	3.97e-03	4.67e-03	5.56e-03	6.87e-03	8.65e-03	1.06e-02	6.25e-03
Am-241	2.54e-04	2.93e-04	3.84e-04	5.26e-04	7.22e-04	1.07e-03	1.43e-03	7.60e-04
Be-7	7.44e-05	7.83e-05	8.70e-05	1.01e-04	1.21e-04	1.46e-04	1.63e-04	1.07e-04
C-14	3.18e-04	4.17e-04	7.07e-04	1.35e-03	3.45e-03	9.83e-03	2.42e-02	7.76e-03
Ce-141	5.51e-05	5.78e-05	6.40e-05	7.38e-05	8.83e-05	1.06e-04	1.19e-04	7.85e-05
Co-57	4.47e-04	4.76e-04	5.34e-04	6.24e-04	7.50e-04	9.13e-04	1.03e-03	6.66e-04
Co-60	1.78e-02	1.89e-02	2.13e-02	2.48e-02	2.98e-02	3.60e-02	4.06e-02	2.64e-02
Cr-51	2.41e-05	2.55e-05	2.83e-05	3.26e-05	3.91e-05	4.69e-05	5.26e-05	3.47e-05
Cs-134	1.13e-02	1.20e-02	1.35e-02	1.58e-02	1.93e-02	2.33e-02	2.63e-02	1.71e-02
Cs-137	5.07e-03	5.50e-03	6.27e-03	7.52e-03	9.36e-03	1.17e-02	1.35e-02	8.35e-03
Eu-154	8.49e-03	9.02e-03	1.00e-02	1.17e-02	1.40e-02	1.69e-02	1.88e-02	1.23e-02
Fe-59	1.57e-03	1.65e-03	1.84e-03	2.13e-03	2.55e-03	3.07e-03	3.43e-03	2.26e-03
H-3	1.35e-06	1.56e-06	2.10e-06	3.04e-06	5.08e-06	8.67e-06	1.20e-05	4.31e-06
I-125	4.75e-05	6.31e-05	9.88e-05	1.68e-04	2.86e-04	4.61e-04	6.09e-04	2.35e-04
I-131	1.13e-04	1.22e-04	1.40e-04	1.67e-04	2.04e-04	2.51e-04	2.79e-04	1.80e-04
In-111	5.46e-05	5.73e-05	6.34e-05	7.32e-05	8.76e-05	1.05e-04	1.18e-04	7.79e-05
K-40	1.05e-03	1.12e-03	1.25e-03	1.45e-03	1.75e-03	2.10e-03	2.34e-03	1.54e-03
La-138	2.22e-03	3.04e-03	6.55e-03	1.00e-02	1.27e-02	1.55e-02	1.78e-02	9.82e-03
Np-237	3.23e-03	4.12e-03	6.17e-03	1.11e-02	2.73e-02	1.03e-01	2.42e-01	6.26e-02
Pa-231	2.15e-03	3.11e-03	5.37e-03	8.79e-03	1.54e-02	3.06e-02	4.75e-02	1.62e-02
Pb-210	1.93e-03	2.50e-03	3.82e-03	5.93e-03	9.72e-03	1.50e-02	1.88e-02	7.73e-03
Po-210	3.03e-04	4.16e-04	7.18e-04	1.34e-03	2.59e-03	4.44e-03	6.13e-03	2.06e-03
Pu-238	1.76e-04	2.15e-04	3.02e-04	4.41e-04	6.34e-04	9.11e-04	1.23e-03	5.45e-04
Pu-239	1.99e-04	2.40e-04	3.39e-04	4.92e-04	7.16e-04	1.02e-03	1.35e-03	6.37e-04
Ra-226	1.65e-01	1.67e-01	1.69e-01	1.74e-01	1.80e-01	1.87e-01	1.94e-01	1.76e-01
Ra-228	1.45e-02	1.55e-02	1.75e-02	2.05e-02	2.46e-02	3.09e-02	3.55e-02	2.24e-02
Sm-153	4.62e-06	4.85e-06	5.36e-06	6.19e-06	7.38e-06	8.88e-06	9.93e-06	6.57e-06
Sr-89	1.46e-05	1.86e-05	3.21e-05	6.41e-05	1.34e-04	2.66e-04	4.11e-04	1.29e-04
Sr-90	9.00e-04	1.25e-03	2.34e-03	4.90e-03	1.04e-02	2.13e-02	3.23e-02	1.01e-02
Th-228	1.19e-02	1.25e-02	1.36e-02	1.55e-02	1.80e-02	2.13e-02	2.36e-02	1.62e-02
Th-229	2.54e-03	2.73e-03	3.10e-03	3.58e-03	4.27e-03	5.10e-03	5.71e-03	3.87e-03
Th-230	9.18e-04	2.88e-03	1.28e-02	3.63e-02	5.37e-02	6.01e-02	6.24e-02	3.37e-02
Th-232	1.35e-02	2.06e-02	2.64e-02	3.17e-02	3.82e-02	4.68e-02	5.28e-02	3.30e-02
Tl-201	8.44e-06	8.88e-06	9.91e-06	1.15e-05	1.38e-05	1.67e-05	1.88e-05	1.23e-05
Tl-202	1.57e-04	1.66e-04	1.85e-04	2.13e-04	2.56e-04	3.10e-04	3.45e-04	2.28e-04
U-233	5.77e-05	7.58e-05	1.17e-04	2.06e-04	3.76e-04	6.24e-04	1.09e-03	5.76e-04
U-234	5.30e-05	7.09e-05	1.13e-04	1.95e-04	3.34e-04	5.85e-04	1.02e-03	5.23e-04
U-235	8.61e-04	1.09e-03	1.28e-03	1.51e-03	1.82e-03	2.21e-03	2.53e-03	1.73e-03
U-238	2.13e-04	2.54e-04	3.07e-04	3.83e-04	4.94e-04	6.76e-04	1.00e-03	7.07e-04
Xe-131m	1.11e-06	1.19e-06	1.34e-06	1.55e-06	1.86e-06	2.25e-06	2.53e-06	1.65e-06
Zn-65	3.36e-03	3.82e-03	4.68e-03	6.08e-03	8.63e-03	1.40e-02	2.07e-02	8.34e-03

Table E.2 Recreational User DSR Percentiles (mrem/yr per pCi/g in Sewage Sludge)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	1.96E-03	2.05E-03	2.10E-03	2.15E-03	2.21E-03	2.29E-03	2.35E-03	2.17E-03
Am-241	1.53E-04	1.56E-04	1.59E-04	1.63E-04	1.68E-04	1.74E-04	1.82E-04	8.00E-04
Be-7	4.42E-05	4.53E-05	4.58E-05	4.58E-05	4.58E-05	4.58E-05	4.58E-05	4.55E-05
C-14	1.75E-04	2.28E-04	4.06E-04	9.30E-04	5.03E-03	3.81E-02	9.76E-02	2.56E-02
Ce-141	3.32E-05	3.33E-05	3.33E-05	3.33E-05	3.33E-05	3.33E-05	3.33E-05	3.33E-05
Co-57	2.45E-04	2.60E-04	2.67E-04	2.68E-04	2.70E-04	2.72E-04	2.76E-04	2.66E-04
Co-60	9.61E-03	1.04E-02	1.07E-02	1.08E-02	1.08E-02	1.09E-02	1.10E-02	1.06E-02
Cr-51	1.39E-05	1.44E-05	1.48E-05	1.48E-05	1.49E-05	1.49E-05	1.49E-05	1.47E-05
Cs-134	5.88E-03	6.02E-03	6.07E-03	6.11E-03	6.18E-03	6.30E-03	6.41E-03	6.12E-03
Cs-137	2.52E-03	2.56E-03	2.58E-03	2.62E-03	2.68E-03	2.77E-03	2.86E-03	2.64E-03
Eu-154	4.89E-03	5.19E-03	5.33E-03	5.36E-03	5.36E-03	5.36E-03	5.36E-03	5.26E-03
Fe-59	9.16E-04	9.47E-04	9.63E-04	9.66E-04	9.66E-04	9.67E-04	9.67E-04	9.56E-04
H-3	3.83E-07	4.72E-07	6.84E-07	1.13E-06	2.03E-06	3.40E-06	4.51E-06	1.64E-06
I-125	6.31E-06	7.45E-06	9.74E-06	1.36E-05	1.92E-05	2.73E-05	3.33E-05	1.62E-05
I-131	5.47E-05	5.59E-05	5.72E-05	5.81E-05	5.94E-05	6.10E-05	6.23E-05	5.84E-05
In-111	3.30E-05	3.30E-05	3.30E-05	3.30E-05	3.30E-05	3.30E-05	3.30E-05	3.30E-05
K-40	6.02E-04	6.24E-04	6.58E-04	6.83E-04	7.01E-04	7.12E-04	7.17E-04	6.75E-04
La-138	1.38E-03	1.84E-03	3.56E-03	5.23E-03	5.56E-03	5.59E-03	5.60E-03	4.66E-03
Np-237	8.15E-04	9.89E-04	1.10E-03	1.37E-03	3.48E-02	2.51E-01	6.07E-01	1.58E-01
Pa-231	4.58E-04	5.39E-04	1.05E-03	2.00E-03	2.54E-03	2.84E-03	1.05E-02	1.06E-02
Pb-210	2.79E-04	2.98E-04	3.42E-04	4.21E-04	5.39E-04	6.83E-04	8.28E-04	4.72E-04
Po-210	5.34E-05	6.23E-05	8.70E-05	1.31E-04	2.10E-04	3.22E-04	4.15E-04	1.70E-04
Pu-238	1.07E-04	1.09E-04	1.11E-04	1.15E-04	1.20E-04	1.25E-04	1.29E-04	1.17E-04
Pu-239	1.19E-04	1.21E-04	1.24E-04	1.28E-04	1.33E-04	1.40E-04	1.45E-04	1.79E-04
Ra-226	8.18E-03	8.19E-03	8.24E-03	8.31E-03	8.43E-03	8.58E-03	8.72E-03	8.53E-03
Ra-228	6.88E-03	7.05E-03	7.12E-03	7.18E-03	7.24E-03	7.32E-03	7.37E-03	7.15E-03
Sm-153	2.75E-06	2.75E-06	2.75E-06	2.76E-06	2.76E-06	2.76E-06	2.77E-06	2.76E-06
Sr-89	1.85E-06	2.02E-06	2.43E-06	3.34E-06	5.46E-06	9.89E-06	1.51E-05	5.38E-06
Sr-90	5.61E-05	7.04E-05	1.05E-04	1.84E-04	3.86E-04	8.41E-04	1.45E-03	7.68E-04
Th-228	6.14E-03	6.21E-03	6.26E-03	6.32E-03	6.38E-03	6.46E-03	6.51E-03	6.29E-03
Th-229	1.39E-03	1.40E-03	1.42E-03	1.44E-03	1.46E-03	1.50E-03	1.52E-03	1.93E-03
Th-230	6.53E-05	2.06E-04	8.15E-04	2.09E-03	2.75E-03	2.97E-03	3.05E-03	1.96E-03
Th-232	5.80E-03	8.35E-03	1.10E-02	1.19E-02	1.21E-02	1.23E-02	1.24E-02	1.13E-02
Tl-201	4.90E-06	4.90E-06	4.90E-06	4.91E-06	4.93E-06	4.97E-06	5.01E-06	4.93E-06
Tl-202	8.90E-05	9.20E-05	9.42E-05	9.45E-05	9.46E-05	9.50E-05	9.54E-05	9.38E-05
U-233	1.30E-05	1.49E-05	1.93E-05	3.62E-05	1.24E-04	3.68E-04	1.96E-03	7.66E-04
U-234	1.19E-05	1.32E-05	1.58E-05	2.10E-05	3.14E-05	2.39E-04	1.34E-03	9.51E-04
U-235	4.42E-04	5.58E-04	6.17E-04	6.27E-04	6.35E-04	8.02E-04	2.15E-03	1.39E-03
U-238	8.50E-05	1.07E-04	1.15E-04	1.19E-04	1.26E-04	2.62E-04	1.23E-03	1.33E-03
Xe-131m	6.38E-07	6.61E-07	6.97E-07	7.42E-07	7.78E-07	8.05E-07	8.19E-07	7.36E-07
Zn-65	1.31E-03	1.65E-03	1.71E-03	1.77E-03	1.89E-03	2.13E-03	2.35E-03	1.82E-03

Table E.3 Nearby Town DSR Percentiles (mrem/yr per pCi/g in Sewage Sludge) (One Year of Application)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	9.55e-06	1.17e-05	1.69e-05	2.45e-05	3.31e-05	4.96e-05	5.94e-05	2.74e-05
Am-241	6.62e-07	8.12e-07	1.18e-06	1.68e-06	2.27e-06	3.49e-06	4.22e-06	1.90e-06
Be-7	8.82e-13	1.06e-12	1.50e-12	2.27e-12	3.29e-12	4.66e-12	6.43e-12	2.76e-12
C-14	2.55e-07	2.79e-07	3.28e-07	3.83e-07	4.42e-07	4.96e-07	5.22e-07	3.86e-07
Ce-141	1.70e-11	2.01e-11	2.67e-11	3.96e-11	5.56e-11	6.59e-11	7.12e-11	4.15e-11
Co-57	2.34e-11	2.94e-11	4.56e-11	7.33e-11	1.17e-10	2.01e-10	2.98e-10	1.00e-10
Co-60	1.42e-09	1.83e-09	2.73e-09	4.21e-09	6.63e-09	1.02e-08	1.36e-08	5.53e-09
Cr-51	1.99e-12	2.48e-12	3.82e-12	6.08e-12	9.49e-12	1.45e-11	1.80e-11	7.41e-12
Cs-134	1.52e-09	1.97e-09	3.05e-09	5.27e-09	9.93e-09	1.91e-08	2.84e-08	8.80e-09
Cs-137	2.87e-09	3.63e-09	5.50e-09	8.80e-09	1.49e-08	2.71e-08	4.28e-08	1.42e-08
Eu-154	9.18e-10	1.19e-09	1.78e-09	2.72e-09	4.13e-09	5.94e-09	7.50e-09	3.24e-09
Fe-59	8.27e-11	1.03e-10	1.63e-10	2.59e-10	4.16e-10	6.10e-10	7.44e-10	3.19e-10
H-3	1.37e-07	1.63e-07	2.05e-07	2.79e-07	3.65e-07	4.64e-07	5.32e-07	2.97e-07
I-125	1.80e-09	2.21e-09	3.27e-09	5.31e-09	8.46e-09	1.25e-08	1.55e-08	6.54e-09
I-131	2.46e-09	3.03e-09	4.48e-09	7.27e-09	1.16e-08	1.72e-08	2.12e-08	8.96e-09
In-111	5.86e-12	7.00e-12	1.03e-11	1.63e-11	2.41e-11	3.56e-11	4.54e-11	2.00e-11
K-40	5.78e-11	7.01e-11	1.07e-10	1.62e-10	2.42e-10	3.64e-10	4.94e-10	1.99e-10
La-138	1.83e-09	2.24e-09	3.27e-09	5.20e-09	8.20e-09	1.68e-08	2.69e-08	9.74e-09
Np-237	7.36e-07	8.89e-07	1.28e-06	1.96e-06	2.69e-06	3.88e-06	5.00e-06	3.10e-06
Pa-231	2.99e-06	4.50e-06	8.19e-06	1.59e-05	2.74e-05	4.16e-05	5.30e-05	2.02e-05
Pb-210	6.67e-08	8.06e-08	1.16e-07	1.65e-07	2.22e-07	3.28e-07	4.04e-07	1.86e-07
Po-210	2.00e-08	2.36e-08	3.12e-08	4.67e-08	6.50e-08	8.22e-08	9.68e-08	5.13e-08
Pu-238	5.97e-07	7.42e-07	1.05e-06	1.53e-06	2.08e-06	3.00e-06	3.62e-06	1.71e-06
Pu-239	6.79e-07	8.29e-07	1.17e-06	1.67e-06	2.28e-06	3.40e-06	3.95e-06	1.88e-06
Ra-226	1.19e-04	1.19e-04	1.19e-04	1.19e-04	1.19e-04	1.19e-04	1.19e-04	1.19e-04
Ra-228	1.72e-04	1.87e-04	1.93e-04	1.95e-04	1.96e-04	1.96e-04	1.96e-04	1.90e-04
Sm-153	1.15e-11	1.36e-11	1.97e-11	2.94e-11	4.30e-11	5.83e-11	7.39e-11	3.44e-11
Sr-89	1.14e-10	1.31e-10	1.86e-10	2.75e-10	3.88e-10	5.02e-10	5.70e-10	3.00e-10
Sr-90	3.77e-09	4.92e-09	7.81e-09	1.23e-08	2.15e-08	4.05e-08	5.76e-08	1.99e-08
Th-228	3.39e-04	3.39e-04	3.39e-04	3.40e-04	3.40e-04	3.40e-04	3.41e-04	3.40e-04
Th-229	3.22e-06	3.97e-06	5.60e-06	8.40e-06	1.15e-05	1.63e-05	1.92e-05	9.27e-06
Th-230	1.46e-06	2.52e-06	8.69e-06	2.50e-05	3.76e-05	4.17e-05	4.30e-05	2.34e-05
Th-232	1.17e-04	2.00e-04	2.99e-04	3.35e-04	3.43e-04	3.47e-04	3.51e-04	3.02e-04
Tl-201	2.77e-12	3.47e-12	5.36e-12	9.30e-12	1.66e-11	2.99e-11	4.49e-11	1.45e-11
Tl-202	1.32e-11	1.67e-11	2.59e-11	4.51e-11	8.07e-11	1.46e-10	2.19e-10	7.06e-11
U-233	1.95e-07	2.44e-07	3.67e-07	5.44e-07	7.90e-07	1.19e-06	1.50e-06	6.46e-07
U-234	1.86e-07	2.30e-07	3.27e-07	4.82e-07	6.59e-07	9.41e-07	1.15e-06	5.39e-07
U-235	1.76e-07	2.22e-07	3.17e-07	4.65e-07	6.44e-07	9.77e-07	1.19e-06	5.43e-07
U-238	1.68e-07	2.03e-07	2.95e-07	4.34e-07	5.82e-07	8.77e-07	1.04e-06	4.84e-07
Xe-131m	0	0	0	0	0	0	0	0
Zn-65	4.69e-10	6.16e-10	1.04e-09	1.70e-09	2.94e-09	4.57e-09	5.64e-09	2.23e-09

Table E.4a Landfill (Municipal Solid Waste) Neighbor (mrem/yr per pCi/g in Sewage Sludge)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	4.16e-13	7.69e-12	1.86e-11	2.47e-11	3.08e-11	3.76e-11	4.77e-11	1.28e-10
Am-241	2.01e-07	1.44e-06	2.50e-06	4.01e-06	7.92e-06	1.85e-05	3.72e-05	1.04e-05
Be-7	0	0	0	0	0	0	0	0
C-14	0	0	0	0	0	1.30e-07	4.81e-05	1.12e-04
Ce-141	0	0	0	0	0	0	0	0
Co-57	0	0	0	0	0	0	0	0
Co-60	2.78e-33	3.19e-32	9.99e-32	2.67e-31	7.45e-31	1.72e-30	2.95e-30	1.45e-23
Cr-51	0	0	0	0	0	0	0	0
Cs-134	0	0	0	0	0	0	0	8.14e-41
Cs-137	2.50e-12	7.30e-12	1.87e-11	4.36e-11	9.74e-11	1.88e-10	2.76e-10	3.78e-10
Eu-154	6.55e-25	1.04e-23	2.26e-23	3.65e-23	7.99e-23	1.71e-22	2.70e-22	2.15e-17
Fe-59	0	0	0	0	0	0	0	0
H-3	0	0	0	3.30e-21	1.91e-11	3.54e-08	3.01e-07	6.59e-08
I-125	0	0	0	0	0	0	0	0
I-131	0	0	0	0	0	0	0	0
In-111	0	0	0	0	0	0	0	0
K-40	7.43e-14	3.96e-13	4.80e-12	5.68e-11	4.32e-10	8.26e-07	9.19e-06	1.32e-06
La-138	1.88e-36	1.07e-27	1.36e-14	5.36e-09	7.23e-08	4.88e-05	7.72e-04	1.99e-04
Np-237	2.87e-10	8.81e-10	2.68e-07	6.69e-06	2.56e-05	1.53e-02	1.37e-01	3.22e-02
Pa-231	7.46e-09	2.69e-06	6.13e-05	1.18e-04	1.59e-04	2.01e-04	2.44e-04	1.68e-03
Pb-210	3.12e-12	5.60e-12	1.39e-11	3.51e-11	8.52e-11	1.74e-10	2.54e-10	7.27e-11
Po-210	0	0	0	0	0	0	0	0
Pu-238	4.27e-08	5.29e-08	6.80e-08	9.48e-08	1.74e-07	3.27e-07	5.10e-07	1.79e-07
Pu-239	4.80e-06	6.10e-06	8.27e-06	1.21e-05	2.10e-05	3.80e-05	5.58e-05	1.88e-05
Ra-226	1.27e-03	1.32e-03	1.36e-03	1.40e-03	1.49e-03	1.67e-03	1.95e-03	1.47e-03
Ra-228	5.33e-28	6.12e-28	8.13e-28	1.25e-27	2.26e-27	4.17e-27	5.93e-27	1.97e-27
Sm-153	0	0	0	0	0	0	0	0
Sr-89	0	0	0	0	0	0	0	0
Sr-90	2.57e-18	1.25e-15	3.62e-13	2.07e-12	5.84e-12	1.40e-11	3.06e-11	1.08e-08
Th-228	0	0	0	0	0	0	0	0
Th-229	6.31e-06	2.29e-05	3.43e-05	4.67e-05	7.97e-05	1.15e-04	2.25e-04	7.34e-05
Th-230	2.11e-04	3.77e-04	5.64e-04	6.01e-04	6.55e-04	7.78e-04	8.95e-04	6.04e-04
Th-232	1.52e-03	4.81e-03	7.41e-03	7.74e-03	7.78e-03	7.85e-03	7.93e-03	7.01e-03
Tl-201	0	0	0	0	0	0	0	0
Tl-202	0	0	0	0	0	0	0	0
U-233	2.15e-07	4.19e-07	1.79e-06	5.29e-06	8.46e-06	1.46e-05	2.46e-05	1.46e-04
U-234	2.55e-07	4.20e-07	1.57e-06	4.16e-06	5.35e-06	6.28e-06	7.32e-06	4.52e-05
U-235	9.70e-08	1.87e-07	1.03e-06	3.12e-06	4.95e-06	6.64e-06	8.23e-06	1.38e-04
U-238	4.21e-10	1.13e-09	3.08e-07	1.44e-06	2.07e-06	2.65e-06	3.71e-06	3.70e-05
Xe-131m	0	0	0	0	0	0	0	0
Zn-65	0	0	0	0	0	0	0	0

Table E.4b Landfill (Surface Impoundment) Neighbor (mrem/yr per pCi/g in Sewage Sludge)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	4.63e-11	4.77e-10	9.67e-10	1.24e-09	1.57e-09	1.95e-09	2.48e-09	3.75e-08
Am-241	2.09e-05	7.07e-05	1.04e-04	1.58e-04	3.11e-04	7.95e-04	1.90e-03	4.88e-04
Be-7	0	0	0	0	0	0	0	0
C-14	1.45e-15	8.87e-13	8.83e-09	4.54e-08	2.41e-07	2.84e-05	6.02e-03	8.31e-03
Ce-141	0	0	0	0	0	0	0	0
Co-57	0	0	0	0	0	0	0	0
Co-60	4.15e-31	2.40e-30	6.15e-30	1.60e-29	3.78e-29	9.31e-29	1.68e-28	9.93e-25
Cr-51	0	0	0	0	0	0	0	0
Cs-134	0	0	0	0	0	0	0	0
Cs-137	2.20e-10	4.11e-10	1.04e-09	2.33e-09	5.26e-09	1.01e-08	1.39e-08	4.24e-09
Eu-154	1.48e-22	8.77e-22	1.59e-21	2.50e-21	4.52e-21	9.27e-21	1.42e-20	4.40e-21
Fe-59	0	0	0	0	0	0	0	0
H-3	2.03e-35	1.51e-32	2.14e-26	1.63e-18	3.04e-09	1.89e-06	1.66e-05	3.39e-06
I-125	0	0	0	0	0	0	0	0
I-131	0	0	0	0	0	0	0	0
In-111	0	0	0	0	0	0	0	0
K-40	2.01e-11	8.30e-11	7.43e-10	4.83e-09	2.32e-08	3.55e-05	4.26e-04	6.08e-05
La-138	7.26e-36	9.45e-24	1.06e-11	5.33e-07	4.63e-06	3.25e-03	4.45e-02	1.09e-02
Np-237	4.26e-08	1.07e-07	2.91e-05	3.42e-04	1.22e-03	1.13e+00	1.18e+01	2.51e+00
Pa-231	2.06e-06	2.01e-04	2.89e-03	4.88e-03	6.36e-03	8.38e-03	1.04e-02	3.80e-02
Pb-210	1.97e-10	3.18e-10	7.35e-10	1.82e-09	4.31e-09	9.18e-09	1.52e-08	3.96e-09
Po-210	0	0	0	0	0	0	0	0
Pu-238	2.20e-06	2.59e-06	3.32e-06	4.80e-06	8.55e-06	1.65e-05	2.52e-06	8.45e-06
Pu-239	1.90e-04	2.45e-04	3.31e-04	4.72e-04	8.47e-04	1.62e-03	2.37e-03	7.82e-04
Ra-226	6.60e-02	6.80e-02	6.98e-02	7.12e-02	7.49e-02	8.18e-02	8.88e-02	7.38e-02
Ra-228	2.67e-26	3.08e-26	4.14e-26	6.74e-26	1.18e-25	2.12e-25	3.24e-25	4.25e-21
Sm-153	0	0	0	0	0	0	0	0
Sr-89	0	0	0	0	0	0	0	0
Sr-90	2.72e-16	3.51e-13	3.39e-11	1.25e-10	3.29e-10	8.27e-10	1.58e-09	2.06e-05
Th-228	0	0	0	0	0	0	0	0
Th-229	3.73e-04	9.62e-04	1.41e-03	1.91e-03	3.07e-03	5.88e-03	9.45e-03	3.12e-03
Th-230	1.22e-02	2.28e-02	3.00e-02	3.15e-02	3.41e-02	3.87e-02	4.32e-02	3.13e-02
Th-232	1.32e-01	2.92e-01	3.87e-01	3.98e-01	4.00e-01	4.03e-01	4.06e-01	3.65e-01
Tl-201	0	0	0	0	0	0	0	0
Tl-202	0	0	0	0	0	0	0	0
U-233	8.89e-06	1.92e-05	9.35e-05	2.20e-04	3.36e-04	6.07e-04	9.33e-04	4.33e-03
U-234	1.43e-05	2.37e-05	8.87e-05	2.05e-04	2.53e-04	3.00e-04	3.41e-04	5.00e-04
U-235	1.50e-06	5.77e-06	4.76e-05	1.29e-04	2.01e-04	2.67e-04	3.36e-04	5.32e-03
U-238	3.77e-09	9.81e-08	1.71e-05	5.87e-05	8.27e-05	1.06e-04	1.38e-04	2.02e-03
Xe-131m	0	0	0	0	0	0	0	0
Zn-65	0	0	0	0	0	0	0	0

Table E.5 Incinerator Neighbor (mrem/yr per pCi/g in Sewage Sludge)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	5.79e+00	6.35e+00	7.46e+00	8.71e+00	1.00e+01	1.12e+01	1.18e+01	8.76e+00
Am-241	3.94e-01	4.32e-01	5.06e-01	5.90e-01	6.79e-01	7.61e-01	7.99e-01	5.94e-01
Be-7	3.61e-07	3.88e-07	4.57e-07	5.63e-07	7.04e-07	9.04e-07	1.09e-06	6.15e-07
C-14	1.95e-07	2.14e-07	2.51e-07	2.92e-07	3.38e-07	3.79e-07	3.99e-07	2.95e-07
Ce-141	1.75e-06	1.86e-06	2.07e-06	2.33e-06	2.59e-06	2.86e-06	3.02e-06	2.35e-06
Co-57	1.90e-05	2.11e-05	2.57e-05	3.38e-05	4.94e-05	7.35e-05	1.02e-04	4.38e-05
Co-60	2.11e-03	2.38e-03	2.91e-03	3.82e-03	4.85e-03	6.50e-03	7.97e-03	4.29e-03
Cr-51	1.98e-07	2.24e-07	2.84e-07	3.82e-07	5.33e-07	7.21e-07	8.78e-07	4.37e-07
Cs-134	1.46e-03	1.66e-03	2.16e-03	2.96e-03	4.20e-03	5.56e-03	6.69e-03	3.40e-03
Cs-137	2.74e-03	3.26e-03	4.15e-03	5.57e-03	7.81e-03	1.11e-02	1.43e-02	6.68e-03
Eu-154	1.67e-03	1.80e-03	2.12e-03	2.61e-03	3.28e-03	3.92e-03	4.34e-03	2.74e-03
Fe-59	8.17e-05	9.29e-05	1.20e-04	1.60e-04	2.26e-04	2.96e-04	3.54e-04	1.82e-04
H-3	1.54e-06	1.70e-06	1.99e-06	2.32e-06	2.69e-06	3.01e-06	3.17e-06	2.34e-06
I-125	1.16e-02	1.37e-02	2.00e-02	2.99e-02	4.28e-02	5.86e-02	6.99e-02	3.36e-02
I-131	2.17e-03	2.56e-03	3.73e-03	5.57e-03	7.97e-03	1.09e-02	1.31e-02	6.26e-03
In-111	4.78e-08	5.19e-08	6.12e-08	7.79e-08	1.12e-07	1.78e-07	2.42e-07	1.04e-07
K-40	1.03e-04	1.25e-04	1.65e-04	2.27e-04	3.17e-04	4.16e-04	4.81e-04	2.51e-04
La-138	1.97e-03	2.23e-03	2.73e-03	3.84e-03	6.73e-03	9.14e-03	1.06e-02	4.94e-03
Np-237	4.92e-01	5.38e-01	6.28e-01	7.31e-01	8.45e-01	9.40e-01	9.93e-01	7.37e-01
Pa-231	1.17e+00	1.26e+00	1.48e+00	1.73e+00	1.99e+00	2.23e+00	2.35e+00	1.74e+00
Pb-210	2.46e-02	2.67e-02	2.98e-02	3.39e-02	3.86e-02	4.31e-02	4.74e-02	3.47e-02
Po-210	6.60e-03	7.15e-03	8.16e-03	9.58e-03	1.13e-02	1.41e-02	1.64e-02	1.02e-02
Pu-238	3.48e-01	3.79e-01	4.44e-01	5.18e-01	5.99e-01	6.70e-01	7.04e-01	5.22e-01
Pu-239	3.82e-01	4.17e-01	4.89e-01	5.70e-01	6.58e-01	7.36e-01	7.74e-01	5.74e-01
Ra-226	2.97e-02	3.21e-02	3.70e-02	4.44e-02	5.35e-02	7.03e-02	8.80e-02	4.90e-02
Ra-228	1.19e-02	1.27e-02	1.42e-02	1.63e-02	1.88e-02	2.21e-02	2.53e-02	1.72e-02
Sm-153	5.34e-08	5.81e-08	6.65e-08	7.97e-08	1.09e-07	1.56e-07	2.03e-07	9.83e-08
Sr-89	1.75e-05	1.91e-05	2.20e-05	2.70e-05	3.32e-05	4.12e-05	4.70e-05	2.88e-05
Sr-90	4.29e-03	5.13e-03	7.19e-03	1.11e-02	1.79e-02	2.91e-02	3.86e-02	1.50e-02
Th-228	2.56e-01	2.81e-01	3.30e-01	3.85e-01	4.44e-01	4.97e-01	5.23e-01	3.87e-01
Th-229	1.89e+00	2.08e+00	2.44e+00	2.85e+00	3.29e+00	3.68e+00	3.87e+00	2.86e+00
Th-230	2.85e-01	3.13e-01	3.68e-01	4.30e-01	4.96e-01	5.55e-01	5.85e-01	4.32e-01
Th-232	1.46e+00	1.60e+00	1.87e+00	2.18e+00	2.52e+00	2.82e+00	2.97e+00	2.20e+00
Tl-201	1.99e-08	2.32e-08	3.21e-08	5.12e-08	9.34e-08	1.61e-07	2.31e-07	8.11e-08
Tl-202	5.12e-07	5.93e-07	7.73e-07	1.15e-06	1.98e-06	3.36e-06	4.74e-06	1.75e-06
U-233	1.19e-01	1.30e-01	1.52e-01	1.78e-01	2.06e-01	2.30e-01	2.43e-01	1.79e-01
U-234	1.16e-01	1.27e-01	1.49e-01	1.74e-01	2.01e-01	2.25e-01	2.37e-01	1.75e-01
U-235	1.09e-01	1.19e-01	1.39e-01	1.63e-01	1.88e-01	2.10e-01	2.22e-01	1.64e-01
U-238	1.04e-01	1.14e-01	1.33e-01	1.56e-01	1.80e-01	2.01e-01	2.12e-01	1.57e-01
Xe-131m	0	0	0	0	0	0	0	0
Zn-65	3.06e-04	3.66e-04	5.30e-04	8.34e-04	1.28e-03	1.82e-03	2.28e-03	1.01e-03

Table E.6 Sludge Application Worker (mrem/yr per pCi/g in Sewage Sludge)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	1.71e-03	1.90e-03	2.35e-03	3.17e-03	4.40e-03	6.18e-03	7.62e-03	3.68e-03
Am-241	5.08e-05	6.04e-05	8.89e-05	1.43e-04	2.32e-04	3.48e-04	4.42e-04	1.80e-04
Be-7	3.79e-05	3.93e-05	3.99e-05	3.99e-05	3.99e-05	4.00e-05	4.00e-05	3.95e-05
C-14	3.66e-08	4.26e-08	5.66e-08	8.05e-08	1.13e-07	1.47e-07	1.71e-07	8.93e-08
Ce-141	2.59e-05	2.60e-05	2.60e-05	2.60e-05	2.60e-05	2.60e-05	2.60e-05	2.60e-05
Co-57	1.81e-04	1.94e-04	2.02e-04	2.04e-04	2.05e-04	2.05e-04	2.05e-04	2.00e-04
Co-60	8.55e-03	9.28e-03	9.74e-03	9.85e-03	9.87e-03	9.87e-03	9.87e-03	9.61e-03
Cr-51	1.16e-05	1.22e-05	1.26e-05	1.27e-05	1.27e-05	1.27e-05	1.27e-05	1.25e-05
Cs-134	5.04e-03	5.22e-03	5.32e-03	5.35e-03	5.35e-03	5.35e-03	5.35e-03	5.29e-03
Cs-137	2.12e-03	2.19e-03	2.23e-03	2.25e-03	2.25e-03	2.25e-03	2.25e-03	2.22e-03
Eu-154	4.13e-03	4.54e-03	4.70e-03	4.73e-03	4.73e-03	4.73e-03	4.73e-03	4.62e-03
Fe-59	8.19e-04	8.57e-04	8.76e-04	8.80e-04	8.81e-04	8.81e-04	8.81e-04	8.69e-04
H-3	6.46e-08	7.67e-08	1.03e-07	1.49e-07	2.13e-07	2.85e-07	3.36e-07	1.68e-07
I-125	1.11e-07	1.32e-07	1.69e-07	1.95e-07	2.02e-07	2.04e-07	2.05e-07	1.80e-07
I-131	4.47e-05	4.61e-05	4.78e-05	4.87e-05	4.89e-05	4.90e-05	4.90e-05	4.80e-05
In-111	2.73e-05	2.73e-05	2.73e-05	2.73e-05	2.73e-05	2.73e-05	2.73e-05	2.73e-05
K-40	5.27e-04	5.50e-04	5.83e-04	6.11e-04	6.32e-04	6.45e-04	6.51e-04	6.03e-04
La-138	8.98e-04	1.23e-03	2.64e-03	4.56e-03	5.01e-03	5.07e-03	5.08e-03	3.78e-03
Np-237	3.88e-04	5.49e-04	7.41e-04	8.18e-04	9.25e-04	1.06e-03	1.17e-03	8.20e-04
Pa-231	3.27e-04	4.86e-04	1.02e-03	2.06e-03	3.40e-03	5.06e-03	6.41e-03	2.50e-03
Pb-210	4.46e-06	4.97e-06	6.38e-06	8.95e-06	1.31e-05	1.89e-05	2.34e-05	1.08e-05
Po-210	3.40e-07	4.46e-07	7.30e-07	1.24e-06	2.08e-06	3.22e-06	4.16e-06	1.62e-06
Pu-238	2.98e-05	3.91e-05	6.48e-05	1.11e-04	1.88e-04	2.91e-04	3.75e-04	1.46e-04
Pu-239	3.27e-05	4.24e-05	7.10e-05	1.25e-04	2.09e-04	3.24e-04	4.16e-04	1.59e-04
Ra-226	7.37e-03	7.38e-03	7.38e-03	7.39e-03	7.40e-03	7.41e-03	7.41e-03	7.39e-03
Ra-228	6.15e-03	6.37e-03	6.47e-03	6.53e-03	6.60e-03	6.68e-03	6.74e-03	6.49e-03
Sm-153	1.78e-06	1.78e-06	1.78e-06	1.78e-06	1.78e-06	1.78e-06	1.78e-06	1.78e-06
Sr-89	9.58e-07	1.04e-06	1.12e-06	1.14e-06	1.15e-06	1.15e-06	1.15e-06	1.11e-06
Sr-90	1.02e-05	1.25e-05	1.50e-05	1.58e-05	1.61e-05	1.64e-05	1.67e-05	1.51e-05
Th-228	5.68e-03	5.77e-03	5.84e-03	5.91e-03	6.01e-03	6.13e-03	6.23e-03	5.90e-03
Th-229	1.20e-03	1.25e-03	1.39e-03	1.66e-03	2.06e-03	2.68e-03	3.15e-03	1.84e-03
Th-230	1.00e-04	1.82e-04	5.47e-04	1.58e-03	2.31e-03	2.56e-03	2.63e-03	1.46e-03
Th-232	4.79e-03	7.32e-03	1.01e-02	1.10e-02	1.15e-02	1.20e-02	1.25e-02	1.03e-02
Tl-201	3.27e-06	3.28e-06	3.28e-06	3.28e-06	3.28e-06	3.28e-06	3.28e-06	3.28e-06
Tl-202	7.30e-05	7.71e-05	7.98e-05	8.03e-05	8.03e-05	8.03e-05	8.03e-05	7.92e-05
U-233	1.07e-05	1.51e-05	2.65e-05	5.22e-05	9.92e-05	1.58e-04	1.99e-04	7.34e-05
U-234	9.31e-06	1.23e-05	2.06e-05	3.64e-05	6.00e-05	9.50e-05	1.23e-04	4.70e-05
U-235	2.94e-04	4.19e-04	4.99e-04	5.17e-04	5.43e-04	5.79e-04	6.08e-04	5.05e-04
U-238	7.18e-05	8.93e-05	9.95e-05	1.14e-04	1.36e-04	1.67e-04	1.94e-04	1.21e-04
Xe-131m	3.37e-07	3.48e-07	3.70e-07	3.93e-07	4.12e-07	4.28e-07	4.35e-07	3.90e-07
Zn-65	9.59e-04	1.33e-03	1.50e-03	1.52e-03	1.52e-03	1.52e-03	1.52e-03	1.45e-03

Table E.7a POTW Worker: Biosolids Loading (mrem/yr per pCi/g in Sewage Sludge)

Radio-nuclide	5%	10%	25%	50%	75%	90%	95%	mean
Ac-227	8.50E-02	8.70E-02	9.45E-02	1.17E-01	1.77E-01	3.07E-01	4.05E-01	1.74E-01
Am-241	1.58E-03	1.72E-03	2.30E-03	3.85E-03	7.85E-03	1.74E-02	2.35E-02	7.75E-03
Be-7	1.23E-02	1.23E-02	1.23E-02	1.23E-02	1.23E-02	1.23E-02	1.23E-02	1.23E-02
C-14	4.39E-07	4.40E-07	4.42E-07	4.50E-07	4.72E-07	5.10E-07	5.60E-07	4.68E-07
Ce-141	1.25E-02	1.25E-02	1.25E-02	1.25E-02	1.25E-02	1.25E-02	1.25E-02	1.25E-02
Co-57	1.92E-02	1.92E-02	1.92E-02	1.92E-02	1.92E-02	1.92E-02	1.92E-02	1.92E-02
Co-60	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01	7.00E-01
Cr-51	7.40E-03	7.40E-03	7.40E-03	7.40E-03	7.40E-03	7.40E-03	7.40E-03	7.40E-03
Cs-134	4.07E-01	4.07E-01	4.07E-01	4.07E-01	4.07E-01	4.07E-01	4.07E-01	4.07E-01
Cs-137	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01	1.46E-01
Eu-154	3.32E-01	3.32E-01	3.32E-01	3.32E-01	3.32E-01	3.32E-01	3.32E-01	3.32E-01
Fe-59	3.31E-01	3.31E-01	3.31E-01	3.31E-01	3.31E-01	3.31E-01	3.31E-01	3.31E-01
H-3	7.05E-05	1.01E-04	1.64E-04	3.06E-04	5.85E-04	9.25E-04	1.33E-03	4.62E-04
I-125	6.00E-04	6.00E-04	6.00E-04	6.00E-04	6.00E-04	6.00E-04	6.00E-04	6.00E-04
I-131	9.20E-02	9.20E-02	9.20E-02	9.20E-02	9.20E-02	9.20E-02	9.20E-02	9.20E-02
In-111	8.05E-02	8.05E-02	8.05E-02	8.05E-02	8.05E-02	8.05E-02	8.05E-02	8.05E-02
K-40	4.53E-02	4.53E-02	4.53E-02	4.53E-02	4.53E-02	4.53E-02	4.53E-02	4.53E-02
La-138	3.45E-01	3.45E-01	3.45E-01	3.45E-01	3.45E-01	3.45E-01	3.46E-01	3.45E-01
Np-237	1.36E-04	2.98E-04	1.00E-03	2.83E-03	7.50E-03	1.77E-02	2.89E-02	7.50E-03
Pa-231	8.40E-03	8.75E-03	1.02E-02	1.51E-02	2.74E-02	4.90E-02	8.05E-02	2.57E-02
Pb-210	2.09E-04	2.16E-04	2.41E-04	3.23E-04	5.25E-04	9.50E-04	1.33E-03	5.00E-04
Po-210	4.39E-06	6.40E-06	1.62E-05	4.76E-05	1.23E-04	2.70E-04	4.35E-04	1.11E-04
Pu-238	9.60E-05	2.07E-04	6.55E-04	2.17E-03	5.75E-03	1.19E-02	1.80E-02	5.15E-03
Pu-239	9.45E-05	2.17E-04	7.55E-04	2.25E-03	6.20E-03	1.56E-02	2.38E-02	5.95E-03
Ra-228	2.59E-01	2.59E-01	2.59E-01	2.59E-01	2.59E-01	2.59E-01	2.59E-01	2.59E-01
Sm-153	5.80E-03	5.80E-03	5.80E-03	5.80E-03	5.80E-03	5.80E-03	5.80E-03	5.80E-03
Sr-89	3.93E-04	3.93E-04	3.93E-04	3.94E-04	3.94E-04	3.94E-04	3.95E-04	3.94E-04
Sr-90	9.85E-04	9.85E-04	9.90E-04	9.95E-04	1.01E-03	1.03E-03	1.05E-03	1.01E-03
Th-229	6.60E-02	6.70E-02	6.95E-02	7.75E-02	9.75E-02	1.39E-01	1.74E-01	9.50E-02
Th-230	1.18E-04	2.06E-04	5.85E-04	1.84E-03	4.97E-03	1.11E-02	1.68E-02	4.49E-03
Th-232	3.81E-04	8.75E-04	2.95E-03	8.80E-03	2.56E-02	5.60E-02	8.35E-02	2.21E-02
Tl-201	1.01E-02	1.01E-02	1.01E-02	1.01E-02	1.01E-02	1.01E-02	1.01E-02	1.01E-02
Tl-202	1.05E-01	1.05E-01	1.05E-01	1.05E-01	1.05E-01	1.05E-01	1.05E-01	1.05E-01
U-233	8.55E-05	1.24E-04	2.94E-04	7.60E-04	2.00E-03	4.97E-03	7.55E-03	1.93E-03
U-234	4.70E-05	8.50E-05	2.39E-04	7.75E-04	2.01E-03	4.17E-03	6.15E-03	1.80E-03
U-235	3.02E-02	3.02E-02	3.04E-02	3.08E-02	3.19E-02	3.42E-02	3.68E-02	3.19E-02
U-238	5.75E-03	5.75E-03	5.90E-03	6.35E-03	7.55E-03	9.55E-03	1.13E-02	7.25E-03
Xe-131m	8.75E-04	8.75E-04	8.75E-04	8.75E-04	8.75E-04	8.75E-04	8.75E-04	8.75E-04
Zn-65	1.60E-01	1.60E-01	1.60E-01	1.60E-01	1.60E-01	1.60E-01	1.60E-01	1.60E-01

Table E.7b POTW Worker: Biosolids Loading for Ra-226 and Combinations of Air Exchange Rate and Building Height

air exchange rate (h^{-1})	room height (m)	5%	10%	25%	50%	75%	90%	95%	mean
1.5	2	1.5	1.7	2.2	2.6	2.7	2.7	2.7	2.4
	4	1.2	1.3	1.5	1.6	1.6	1.6	1.6	1.5
	6	1.0	1.1	1.2	1.2	1.2	1.2	1.2	1.2
3	2	0.92	0.98	1.1	1.2	1.2	1.2	1.2	1.1
	4	0.76	0.78	0.82	0.85	0.85	0.85	0.85	0.83
	6	0.68	0.69	0.72	0.73	0.73	0.73	0.73	0.72
5	2	0.70	0.72	0.76	0.79	0.79	0.79	0.79	0.77
	4	0.61	0.62	0.63	0.64	0.64	0.64	0.64	0.63
	6	0.57	0.58	0.58	0.59	0.59	0.59	0.59	0.59

Table E.7c POTW Worker: Biosolids Loading for Th-228 and Combinations of Air Exchange Rate and Building Height

air exchange rate (h^{-1})	room height (m)	5%	10%	25%	50%	75%	90%	95%	mean
1.5	2	6.4	7.8	12	17	18	18	18	15
	4	4.9	5.6	7.6	9.1	9.4	9.4	9.4	8.3
	6	4.0	4.5	5.5	6.3	6.4	6.4	6.4	5.9
3	2	4.8	5.6	7.5	8.9	9.2	9.3	9.3	8.2
	4	3.4	3.7	4.3	4.8	4.8	4.9	4.9	4.5
	6	2.6	2.8	3.1	3.3	3.4	3.4	3.4	3.2
5	2	3.7	4.0	4.9	5.5	5.6	5.6	5.6	5.2
	4	2.4	2.6	2.8	3.0	3.0	3.0	3.0	2.9
	6	1.9	1.9	2.1	2.1	2.2	2.2	2.2	2.1

Appendix F

Responses to Peer Review Comments on ISCORS Dose Modeling Document

F.1 Overview of Peer/General Review Process

In this appendix, ISCORS responds to comments solicited from a group of expert peer reviewers and from members of the public with regard to the modeling methodology employed and to the technical aspects of the methodology and assumptions underlying the dose assessment.[1]

Solicitation for Comments from Peer Reviewers and Others

The draft final version of this report was reviewed in depth by a committee of peer reviewers selected by ISCORS, and it also was reviewed by interested organizations and members of the general public. The individuals who were asked to serve as members of the new peer group are all professional experts in sludge management and/or environment pathway modeling, and are representatives of the Pacific Northwest National Laboratory, Weston Solutions, Black & Veatch Engineering Company, the Madison and Cincinnati METROs, and the States of Colorado, and Pennsylvania. The reviewers met in a conference call, and although they were encouraged to communicate with one another and with ISCORS, they submitted independent reports. Six of the eight submitted written comments. The members of the invited committee of peer reviewers include the following:

1. Pacific NW National Lab – Gene Whelan, Dennis Strenge, and James Droppo (PNNL)
2. State of Colorado, Department of Public Health and the Environment – Phil Egidi (CO)
3. State of Pennsylvania, Department of Environmental Protection – Jeff Whitehead (PA)
4. State of Washington, Department of Health – Debra McBaugh and Mike Brennan (WA)
5. Weston Solutions – Mark Miller and Marc Garcia (Weston)
6. Madison METRO – David Taylor (Madison)
7. Black & Veatch Engrs – Dick Kuchenrither (*no written comments*)
8. Cincinnati METRO – Pat Karney, Mike Heitz, and Beverly Mead (*no written comments*)

The peer reviewers were asked to provide general technical review and to respond to three categories of specific questions:

1. Are the dose modeling scenarios reasonable? Does the document adequately explain them? Are the scenarios sufficiently representative of the major exposure situations?
2. Is the dose modeling approach scientifically reasonable and appropriately documented and characterized? Are the selection of model parameters and distributions and the approach for characterizing uncertainty reasonable?

1 An earlier version of this report was reviewed during 2000–2001 by EPA's Science Advisory Board (SAB). Their response was generally favorable, but they offered numerous suggestions and recommendations, virtually all of which were incorporated into this report. The work has evolved considerably since that time, and it was felt that a new review by an independent peer group would be both appropriate and beneficial to the project.

3. Are the overall conclusions consistent with the results of the dose modeling and appropriately characterized?

In addition, the November 26, 2003, issue of the *Federal Register* (Vol. 68, No. 228: 66503-66504) announced the availability of the *Final Survey Report*, the *Draft Final Dose Modeling Report*, and the *Draft Final POTW Recommendations Document*, and ISCORS requested comment on the two draft final documents. In addition, ISCORS directly informed the relevant Federal agencies and the directors of all State radiation control programs, the Conference of Radiation Control Program Directors (CRCPD), and the Organization of Agreement States (OAS). A total of nine sets of comments were received, apart from those of the peer reviewers, from the following:

1. Association of Metropolitan Sewerage Agencies (AMSA)
2. American Water Works Association (AWWA)
3. Council on Radionuclides and Radiopharmaceuticals, Inc. (CORAR)
4. State of Illinois Dept. of Environmental Protection
5. State of New Jersey Dept. of Environmental Protection
6. UniTech Corp.
7. U.S. DOE Richland Operations Office (Hanford, Washington)
8. U.S. NRC Division of Waste Management and Environmental Protection
9. Water Remediation Technology, LLC (WRT)

The comments from AMSA, AWWA, and CORAR dealt almost entirely with the draft final recommendations document. The few comments that addressed modeling are discussed herein. Upon request by EPA, UniTech clarified in a letter dated April 15, 2004, several of its earlier comments. WRT submitted comments and a report they commissioned: *Total Effective Dose Equivalent (TEDE) Calculations for Radium-Bearing Sewage Sludge Under Various Exposure Scenarios*. Upon request by EPA, WRT submitted an e-mail on April 20, 2004, intended to highlight the major, relevant points in their report.

The comments from the peer reviewers were positive and supportive, as were those from all but one of the other commenters. They all offered a number of specific constructive suggestions for changes, and, after considering them carefully, ISCORS separated them into categories to facilitate response. ISCORS agreed with a number of the comments and made appropriate revisions. ISCORS disagreed with other comments and the explanations are presented below. ISCORS considered some of the recommendations to be useful but not essential to the analysis and, in some cases, beyond the scope of the ISCORS effort: implementing these recommendations would require additional resources, and these recommendations are included as possible future activities.

F.2 Positive Comments

The following general positive comments were provided by the peer reviewers that required no response:

- The document uses generally accepted models and risk assessment tools.
- The document is comprehensive/thorough.
- The answer to all three questions posed to the peer reviewers is “Yes.”
- The process was sound, scientifically reasonable, and complete.
- The report covers virtually every reasonably anticipated scenario and operational assumptions for screening.
- The procedures were implemented in a systematic, scientific manner.
- The modeling approach is scientifically reasonable.
- The parameters/distributions and approach for characterizing uncertainty appear reasonable and conservative.
- ISCORS adequately bounds the issue—the level of conservatism was generally appropriate.
- The scenarios are reasonable for screening.
- The report represents most major exposure situations.
- The commenters agree that NORM and TENORM are likely to be the major potential sources for elevated sources of radiation in sewage sludge—this was a surprising and irrefutable finding of the study.
- ISCORS should publicize the results of the dose modeling effort via HPS and ANS meetings, Health Physics Journal, the Internet, and other venues.

F.3 Comments Requiring Response

The comments from peer reviewers that required a response are discussed below.

F.3.1 Documentation/Presentation

- **Comment:** The document needs a more detailed explanation of models (e.g., how modeling was done).

  Response: ISCORS provided an appendix on RESRAD and included a reference (i.e., a URL) to the online RESRAD Users Manual.

- **Comment:** The document should provide a more complete description of the parameters and distributions (rather than just referencing other reports). There is too much reliance on references to other reports; ISCORS should supply the information.

  Response: ISCORS made no change to the document because NRC NUREG/CR-6697, the EPA *Exposure Factors Handbook* (EPA/600-P-95-002Fa), and other sources listed as references provide comprehensive documentation and are readily available.

- **Comment:** The document should include a list of appropriate Federal and State agency contacts, and access to an updated list should be available via the ISCORS Web site.

  Response: ISCORS provides such a list in the final recommendations document.

- **Comment:** ISCORS should develop an executive summary for the dose modeling document.

  Response: ISCORS included an executive summary in the final document.

- **Comment:** ISCORS should upgrade the presentation of results by crafting and presenting output in visual/graphical format (PNNL).

  Response: ISCORS modified some tables to improve their appearance and readability. Due to resource constraints, no significant visual/graphical format enhancements were undertaken.

F.3.2 Scenarios/Parameters

F.3.2.1 Conservativeness of Parameters

- **Comment:** Some assumptions are overly conservative (or must be justified) (e.g., 100% of milk and meat, building height, air exchange rate—2 times per hour, sewage sludge density) for most POTWs.

  Response: ISCORS reexamined all potentially sensitive parameters and altered some significantly, including exposure duration, room height, and air exchange rates for the POTW loader scenario. For the building height and air exchange rates, ISCORS developed three values (for each parameter) that represent more typical conditions at POTWs, which significantly reduced the DSRs and thus doses from Ra-226 and Th-228 for the worker loading scenario. The report was revised accordingly.

  Response: While it was noted that the sewage sludge density can vary considerably by the type of sludge processing, the current approach was considered to be reasonably conservative but realistic. The dose calculations were found to be relatively insensitive to milk and meat consumption rates, so no changes were made. In some cases, no changes were made in the scenarios and results, but the text was revised accordingly.

- **Comment:** Why was Columbus, Ohio, used to represent the United States?

  Response: ISCORS had no reason to consider changing the default location in CAP-88 (used by RESRAD-OFFSITE), which has a strong predominant wind direction, and is a typical mid-continent location providing reasonably conservative site conditions. In any case, the three scenarios where RESRAD-OFFSITE was used, all have low DSR values.

- **Comment:** Use of the upper 95th percentile DSRs is very conservative.

  Response: ISCORS considers that the primary use of the calculated DSR values is for screening purposes only for which 95th percentile is reasonable and is discussed further in the final Recommendations document. Other DSR percentile values (i.e., 5, 10, 25, 50, 75, 90, 95, and mean) are provided in Appendix E.

- **Comment:** The compounding effect of assumptions can be significant.

  Response: ISCORS agrees with this comment and tried to reduce conservatism for individual parameters which had resulted in a compounding effect.

F.3.2.2 Radionuclides

- **Comment:** Explain why, regardless of the activity, K-40 is not of concern.

  Response: ISCORS added an explanation to the text that K-40 is a naturally occurring radioactive material in fertilizers and food products that may concentrate in sewage sludge or ash, and as such is of concern for this analysis. However, exposure to K-40 is only of potential concern for external exposures. Internal exposures are not of concern, because of the equilibrium of K-40 with nonradioactive potassium in the body. Therefore, the DSRs calculated account for external exposures only.

- **Comment:** The dominance of Ra-226 via radon in almost all scenarios was enlightening. How do levels in sewage sludge compare with levels in native soils? Is there the possibility that sometimes the sewage sludge dilutes Ra-226 levels in native soils?

  Response: The recommendations report, in Table 5, and the *Final Survey Report*, in Table 4.3, provide a comparison of concentrations in sewage sludge and ash to concentrations in soil, fertilizer, and building materials. ISCORS does not believe this needs to be addressed in this report.

  ISCORS agrees that when sewage sludge contains little or no Ra-226, it could dilute radionuclide levels in native soils; for conservatism, ISCORS does not believe this needs to be addressed in this report.

F.3.2.3 Scenarios/Parameters—General

- **Comment:** ISCORS should base the assessment on a number of real-world sites, not on generic or hypothetical locations, geology, hydrology, situations, and scenarios.
- **Comment:** The "closest" scenario may be significantly different from site-specific conditions.

  Response: While the use of real-world sites is a valid approach, ISCORS believes that the current approach is sufficient to meet the charge to the Subcommittee. The current approach also provides an opportunity to represent a wider population of potential sites.

- **Comment:** The document has no ecological analysis.

  Response: The dose modeling was performed to evaluate, in part, whether the presence of radioactive materials in sewage sludge and ash could pose a threat to the health and safety of POTW workers or the general public. Thus, no ecological analysis was performed.

F.3.2.4 Onsite Resident Scenario

- **Comment:** All meat and dairy products consumed are produced onsite (50% of the fruit, vegetables, and fish): this is higher than for the recently completed Part 503 exposure/risk assessment. ISCORS should justify this as it seems unreasonable.

  Response: ISCORS agrees that the assumed consumption values were highly conservative. However, the food pathway had negligible impact on the calculated doses, and no changes were made to this report.

- **Comment:** ISCORS should consider expanding scenarios to address future farm workers. Why is the onsite resident scenario representative also of farm workers? Land application workers are assumed to be exposed chronically, but farm workers are on the field much less.

- **Comment:** For non-sludge-application agricultural workers, there is comparable exposure time, more direct gamma dose (no shielding), and inadvertent ingestion of soil.

  Response: There could be numerous potential exposure scenarios that may be plausible. ISCORS selected those that were felt to be most typical and realistic. The recommendations report discusses the need for considering other types of exposures, such as farm workers. Thus, no changes were made to this report.

F.3.2.5 Landfill Neighbor Scenario

- **Comment:** Liner fails sometime in the future; calculations are carried out for 1,000 years (CO/CRCPD); fence prevents access for 1,000 years; reliance on State laws and deed restrictions is *non*-conservative.

  Response: ISCORS believes that reliance on State laws and deed restrictions is a reasonable assumption for modeling the most likely future scenarios. The recommendations report mentions the possibility that site restrictions might not be followed. No changes to this report were made.

F.3.2.6 Sludge Application Worker Scenario

- **Comment:** The sludge application worker scenario may be improved if also made to represent future farm field workers in fields.

  Response: ISCORS believes the onsite resident provides a more conservative scenario than that of farm field workers. There could be numerous potential exposure scenarios that may be plausible. ISCORS selected those that were felt to be most typical and realistic. The recommendations report discusses the need for considering other types of exposures, such as farm workers. Thus, no changes were made to this report.

F.4 Modeling

- **Comment:** In Equations 7.2 and 7.3 for DSR for Ra-226 and Th-228, it would be relatively straightforward to develop a similar approach for all exposure scenarios and radionuclides, by identifying the three or four most sensitive parameters for each scenario and providing equations to allow a user to vary parameters to fit local conditions.

Response: ISCORS agrees that additional fitting formulas could be useful to some POTW operators to address site-specific conditions, if the consultation level is exceeded using the screening process described in the Recommendations document. However, the dose modeling was intended to provide screening calculations, and ISCORS does not find it necessary to develop similar fitting formulas for all scenarios, because of the general insensitivity of dose calculations to parameters other than source variability, as suggested by Table 7.3. For common variable parameters, ISCORS has added a table to the recommendations report that provides radon concentration screening levels for combinations of room heights and ventilation rates. Another parameter that can be easily adjusted is time of exposure. If site specific conditions exist where exposures are either less than or greater than 1,000 hours for a POTW worker, for example, the DSR could be easily changed by multiplying by the ratio of the site specific hours to 1,000 hours. (Example: If a worker only spent 500 hours per year loading sludge, the DSR should be multiplied by 0.5.)

- **Comment:** Reproducibility is not addressed. Can the entire analysis be duplicated? Are the results of the report reproducible, ready-made for emulation, given site-specific inputs?

  Response: ISCORS attempted to describe the calculations in a manner that readers could reproduce the results.

- **Comment:** Attempts made to force-fit the source-term analyses into a source term model that did not contain critical attributes (e.g., time-varying analysis)—although an adequate alternative solution was implemented which involved more work and a confusing presentation—should have considered additional models that addressed deficiencies in the chosen set of models.

  Response: ISCORS considered many codes for the dose calculations and determined that RESRAD was the best overall choice. ISCORS believes that the source term calculations used for multiple years of application provide adequate detail for these screening calculations.

- **Comment:** The report should track the mass throughout the system to determine the fraction that accounts for the dose and any subsequent risk.

  Response: ISCORS believes that the suggestion is beyond the scope of the project and believes that the methods used are adequate.

F.5 Sensitivity/Uncertainty

- **Comment:** Choices of values used in the sensitivity/ uncertainty analysis (e.g., differences between the 95^{th} and 5^{th} percentiles) appear to be unexpectedly small.

  Response: ISCORS believes that the sensitivity/uncertainty analysis performed was sufficient for the screening nature of the calculations.

F.6 Validation

ISCORS agrees that model validation, as addressed in the following peer review comments, is an important next step in assessments such as this, but such studies are beyond the scope of the ISCORS study effort:

- **Comment:** The results of the TLD influent monitoring program (from Feb'96–Dec'00) for Albuquerque, NM, might serve as a potential field validation site**.**
- **Comment:** The document should address empirical testing of at least all of the POTW worker scenarios, including use of spiked samples and measured exposures.
- **Comment:** Some of the exposure scenarios, including all of the POTW worker scenarios, can and should be tested.

NRC FORM 335 (9-2004) NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

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 sewage 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 sewage 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 sewage 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 sewage sludge. Then, the RESRAD multi-pathway environmental transport model generated sewage 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, dose modeling, sewage sludge, dose assessment, sludge management, scenarios, municipal sewage, publicly owned treatment facilities, POTW.

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