Argonne NATIONAL LABORATORY

ANL/EVS/TM-15/1

RESRAD for Radiological Risk Assessment: Comparison with EPA CERCLA Tools — PRG and DCC Calculators

Environmental Science Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via DOE's SciTech Connect (http://www.osti.gov/scitech/).

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

ANL/EVS/TM-15/1

RESRAD for Radiological Risk Assessment: Comparison with EPA CERCLA Tools — PRG and DCC Calculators

prepared by
C. Yu, J.-J. Cheng, and S. Kamboj
Environmental Science Division, Argonne National Laboratory

July 2015

CONTENTS

CONTENTS (CONT.)

FIGURES

FIGURES (CONT.)

TABLES

TABLES (CONT.)

TABLES (CONT.)

This page intentionally left blank.

NOTATION

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document. Acronyms and abbreviations used only in tables and figures are defined in the respective tables and figures.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ACF	Area Correction Factor
ARAR	Applicable or Relevant and Appropriate Requirement(s)
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CF	Correction Factor
DAF	Dilution Attenuation Factor
DC	Dose Coefficient
DCC	Dose Compliance Concentration
DCF	Dose Conversion Factor
DCFPAK	Dose Coefficient File Package
DCGL	Derived Concentration Guideline Level
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FA	Area Factor
FGR	Federal Guidance Report
FS	Shape Factor
HEAST	Health Effects Assessment Summary Tables
HPS	Health Physics Society
HTO	tritiated water
ICRP	International Commission on Radiological Protection
ISCORS	International Steering Committee on Radiation Standards
K_d	Distribution Coefficient
LET	Linear Energy Transfer
MCL	Maximum Concentration Limit
MLF	Mass Loading Factor
NAS	National Academy of Sciences
NRC	U.S. Nuclear Regulatory Commission

ORNL	Oak Ridge National Laboratory
OSRTI	Office of Superfund Remediation and Technology Innovation
OSWER	Office of Solid Waste and Emergency Response
PEF	Particulate Emission Factor
PRG	Preliminary Remediation Goal
RBE	relative biological effectiveness
RESRAD	RESidual RADioactivity
SCG	Soil Concentration Guideline
SF	Slope Factor
SF_p	Source Factor
SSL	Soil Screening Limit
TEDE	Total Effective Dose Equivalent
TR	target risk
VF	Volatilization Factor

UNITS OF MEASURE

cm	centimeter(s)
cm^2	square centimeter(s)
cm^3	cubic centimeter(s)
d	day(s)
g	gram(s)
Gy	gray
h	hour(s)
kg	kilogram(s)
L	liter(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
mg	milligram
mrem	millirem(s)
mSv	milliSievert(s)
pCi	picocurie(s)
s	second(s)
Sv	Sievert(s)
yr	year(s)

1 INTRODUCTION

The RESRAD (RESidual RADioactivity) family of codes is a suite of software tools developed by the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC) to evaluate radiologically contaminated sites (Yu et al. 2001; Yu 1999, 2006, 2007). The codes can be used to derive cleanup criteria or Derived Concentration Guideline Levels (DCGLs) and estimate radiation dose or risk from residual radioactive material under various scenarios using appropriate parameters. They have been widely used throughout the world; more than 100 countries have downloaded and used the RESRAD family of codes. Over 140 RESRAD training courses have been conducted, and many of those were sponsored by the NRC, the U.S. Environmental Protection Agency (EPA), state agencies, the International Atomic Energy Agency (IAEA), and organizations within the private sector. Numerous benchmarking, verification, and validation studies have been conducted on the RESRAD family of codes, and many universities have used RESRAD as a teaching and research tool. More than 2,000 publications have been issued either using or citing RESRAD codes, including journal articles, Ph.D. dissertations, technical reports, and conference papers. RESRAD has been proven as an effective tool for evaluating radiologically contaminated sites. Appendix A, Section A.1, of this report provides a detailed overview of the RESRAD family of codes.

Recently, the EPA Office of Superfund Remediation and Technology Innovation (OSRTI) issued a Memorandum (Office of Solid Waste and Emergency Response [OSWER] 9285.6-20, June 13, 2014) providing updated guidance on “Radiation Risk Assessment at [Comprehensive Environmental Response, Compensation, and Liability Act] CERCLA Sites: Q & A” (Directive 9200.4-40, EPA 540-R-012-13, May 2014) (EPA 2014). In this Memorandum, OSRTI “changes the Superfund recommendation on what is considered a protective dose-based ARAR [Applicable or Relevant and Appropriate Requirement] from 15 to 12 millirem per year (mrem/yr). The new recommendation of 12 mrem/yr regarding what dose-based ARARs are protective is based on using an updated risk assessment to achieve the same 3×10^{-4} cancer risk as the previous recommendation using 15 mrem/yr.” It is also stated in the Radiation Risk Assessment at CERCLA Sites: Q & A document that the EPA Preliminary Remediation Goal (PRG) Calculators are “recommended by EPA for Superfund remedial radiation risk assessments.”

The RESRAD code calculates both radiological dose and risk, whereas the PRG Calculator calculates only risk. For dose calculations, the EPA uses another tool—the Dose Compliance Concentration (DCC) Calculator (Walker 2013). The EPA DCC Fact Sheet states that “The DCC Calculator is a tool that allows EPA to calculate cleanup levels in soil, water, and air that correspond to a specific dose of radiation at a Superfund site” (Walker undated). Thus, unlike RESRAD, which uses the same models and parameters for both dose and risk calculations, the EPA uses two different Calculators—DCC and PRG—which use different models and parameters to calculate dose and risk. An overview of the EPA tools, the PRG and DCC Calculators, is presented in Appendix A, Sections A.2.1 and A.2.2.

The purpose of this report is two-fold. First, the risk assessment methodology for both RESRAD and the EPA’s tools is reviewed. This includes a review of the EPA’s justification for using a dose-to-risk conversion factor to reduce the dose-based protective ARAR from 15 to 12 mrem/yr. Second, the models and parameters used in RESRAD and the EPA PRG and DCC Calculators are compared in detail, and the results are summarized and discussed. Although there are suites of software tools in the RESRAD family of codes and the EPA Calculators, the scope of this report is limited to the RESRAD (onsite) code for soil contamination and the EPA's PRG and DCC Calculators also for soil contamination.

The latest version of the RESRAD (onsite) code, Version 7.0, was used (www.evs.anl.gov/resrad) for this report. For simplicity in code name designation, unless specifically stated, RESRAD is used to mean RESRAD (onsite) Version 7.0 for this comparison study. With regard to the EPA Calculators, the online versions of both the DCC and PRG Calculators were used (http://epa-dccs.ornl.gov/cgi-bin/dose_search for the DCC Calculator and http://epa-prgs.ornl.gov/cgi-bin/radionuclides/rprg_search for the PRG Calculator). It should be noted that the online PRG Calculator is not always available and sometimes produces inconsistent results. The system can be found down for hours or days. Also, during the comparison exercise, inconsistent results were obtained from the PRG Calculator when run on different days in November 2014. The difference (by a factor of about 4 for some radionuclides) cannot be explained from the information posted on the PRG What's New page (http://epa-prgs.ornl.gov/radionuclides/whatsnew.html) for November 2014. Those results that could not be reproduced in later runs were discarded and not used in this report. However, it does indicate that there may be some quality control/quality assurance issues with the online PRG Calculator. Therefore, the date the Calculators were accessed is noted when necessary if different results were obtained on different days.

Section 2 describes different methods for radiological risk calculation and discusses the limitations and advantages/disadvantages of each method. Section 3 focuses on a comparison of the RESRAD (onsite) code and the PRG Calculator for both water-independent pathways (i.e., PRGs) and water-dependent pathways (i.e., Soil Screening Levels, or SSLs). Section 4 compares RESRAD (onsite) and the DCC Calculator. Section 5 presents a summary of findings and discussion on a path forward and recommendations. Section 6 is a list of the references used in preparation of this report. Appendix A contains detailed information on the RESRAD family of codes and the EPA PRG and DCC Calculators. Appendix B includes detailed radionuclide properties for some radionuclides selected for the comparison study as well as some comparison results.

2 DOSE AND RISK CALCULATION METHODS

For radiological dose and risk calculations, it is necessary to model how radionuclides are transported in the environment and reach receptors (humans). RESRAD uses a pathway analysis method to track radionuclide transport in the environment (air, water, and soil) and to model how radionuclides reach the receptor through the direct exposure, inhalation, and ingestion pathways. For radiation dose calculations, RESRAD users can select various sets of Dose Coefficients (DCs), including age- and gender-specific DCs, U.S.-population-weighted DCs, or International Commission on Radiological Protection (ICRP) Publications 26, 30, and 60 dosimetry methodology-based DCs (ICRP 1977, 1979–1982, 1991). RESRAD also has the capability to calculate radiation risk (cancer morbidity and mortality) using risk coefficients or Slope Factors (SFs). The sources of radionuclide SFs contained in the RESRAD database include Health Effects Assessment Summary Tables (HEAST), Federal Guidance Report (FGR) 13 (Eckerman et al. 1999), and the Dose Coefficient File Package (DCFPAK) 3.02. The DCFPAK 3.02 is the latest DC and SF database, with all the 1,252 radionuclides contained in ICRP Publication 107 radionuclide database (ICRP 2008). All 1,252 radionuclides are included in the RESRAD (onsite) code Version 7.0. For calculation of radiation risk, RESRAD considers parent radionuclide decay and progeny ingrowth during the exposure duration (e.g., 26 years for a resident and 40 years for a farmer) as well as during transport in the environment (e.g., groundwater and surface water pathways). Thus, RESRAD calculates time-integrated intake quantities and uses the appropriate SFs for parent and progenies to estimate the risk.

The EPA DCC and PRG Calculators also use DCs and SFs to calculate radiological dose and risk, respectively. It appears that the DCs used in the DCC Calculator are not taken from the latest DCFPAK 3.02. The SFs used in the PRG Calculator are taken from DCFPAK 3.02. However, there are issues as to how the SFs are applied to handle progenies. For instance, because the EPA PRG Calculator is a static model, it does not have the capability to model the variation of radionuclide concentration as a function of time; for example, such as long-lived progeny ingrowth during exposure duration, and water pathway delay during transport through unsaturated and saturated zones. This effect is further investigated and discussed in Section 3.

Using SFs to calculate radiological risk (both morbidity and mortality) is a standard method used in both RESRAD and the PRG Calculator. Another simplified approximation method is to use a dose-to-risk conversion factor to convert calculated radiological dose to estimate radiological risk. This method has limitations and assumes that the cancer mortality and morbidity risks are linearly proportional to radiological dose. This method is used in the EPA Radiation Risk Assessment at CERCLA Sites: Q & A document (EPA 2014) to draw the conclusion of reducing the protective ARAR from 15 to 12 mrem/yr. The cited dose-to-risk conversion factor is 8.46×10^{-4} per rem (see the following text box).

The value of 8.46×10^{-4} per rem is stated as being taken from FGR 13 (Eckerman et al. 1999), and it was increased from a previous value of 7.6×10^{-4} per rem used in the previous EPA Superfund Guidance document (EPA 1999) citing the EPA 1994 Blue Book (EPA 402-R-93-076 [EPA 1994]). A review of those references indicated that the EPA

Radiation Risk Assessment at CERCLA Sites: Q & A
(Directive 9200.4-40, EPA 540-R-012-13, May 2014)

Page-28, Q35: "Should the ARAR protectiveness criteria evaluation recommendation be changed from 15 mrem/yr to reflect the updates to radiation risk estimates in FGR 13?"

Answer: "Yes. … 15 mrem/yr should be changed to 12 mrem/yr… More recent scientific information reflected in EPA's Federal Guidance Report 13 risk estimates show that 12 mrem/yr is now considered to correspond approximately to 3×10^{-4} excess lifetime cancer risk. The updated approach is based on FGR 13's assumption of risk of cancer incidence of 8.46×10^{-4} per rem exposure (while still using the EPA CERCLA standard period of exposure of 30 years for residential land use, which was the basis of the 15 mrem/yr determination in OSWER Directive 9200.4-18). Therefore, the ARAR evaluation guidance first discussed in OSWER Directive 9200.4-18 is being updated to 12 mrem/yr so that ARARs that are greater than 12 mrem/yr effective dose equivalent (EDE) are generally not considered sufficiently protective for developing cleanup levels under CERCLA at remedial sites."

"… In 1997, 15 mrem/yr was estimated correspond to 3×10^{-4} under the then EPA practice of using the dose to risk estimate conversions assumption of a risk of cancer incidence of 7.6×10^{-4} per rem of exposure, found in ICRP 1991 and NAS 1990. This dose to risk estimate has been superseded by the assumption of a risk of cancer incidence of 8.46×10^{-4} per rem of exposure in FGR 13 (U.S. EPA 1999c)."

Superfund Guidance document misused the dose-to-risk conversion factors. First, the unit of dose-to-risk conversion factors presented in the original documents is risk per rad or per Gy (i.e., absorbed dose), not risk per rem or per Sv (i.e., effective dose or effective dose equivalent). Second, it is clearly stated in the original documents that the dose-to-risk values were derived based on low-linear energy transfer (LET), low gamma (γ) radiation dose with uniform irradiation of the body. Thus the dose-to-risk coefficients cannot be applied to high-LET or high energy radiation such as alpha (α) emitters and high energy beta (β,) and γ emitters. It should be noted that a more recent EPA document—the EPA 2011 Blue Book (EPA 2011), *EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population*—is not referenced in the 2014 Superfund Guidance document (EPA 2014). In the 2011 Blue Book, a dose-to risk conversion factor of 0.116/Gy is recommended. This value is also for a uniform whole-body exposure of low-dose gamma radiation to the entire population. In addition, the EPA 2011 Blue Book provided the 90% confidence interval of the cancer incidence risk coefficient of 0.056 to 0.21/Gy (EPA 2011).

To illustrate that the dose-to-risk conversion factor is not a constant for most radionuclides, a set of 21 radionuclides was selected with various half-lives and radiation decay, including alpha-, beta-, and high energy gamma-emitters. The cancer morbidity risk coefficients published in FGR 13 (Eckerman et al. 1999) and the age- and gender-averaged effective dose coefficients published in DOE-STD-1196-2011 (DOE 2011) were used. The results are shown in Figure 2.1. It can be seen that the ratio for each individual pathway varies by about 1 order of magnitude, and for most radionuclides, especially for alpha-emitters, the ratio is much lower than 8.46×10^{-4}/rem.

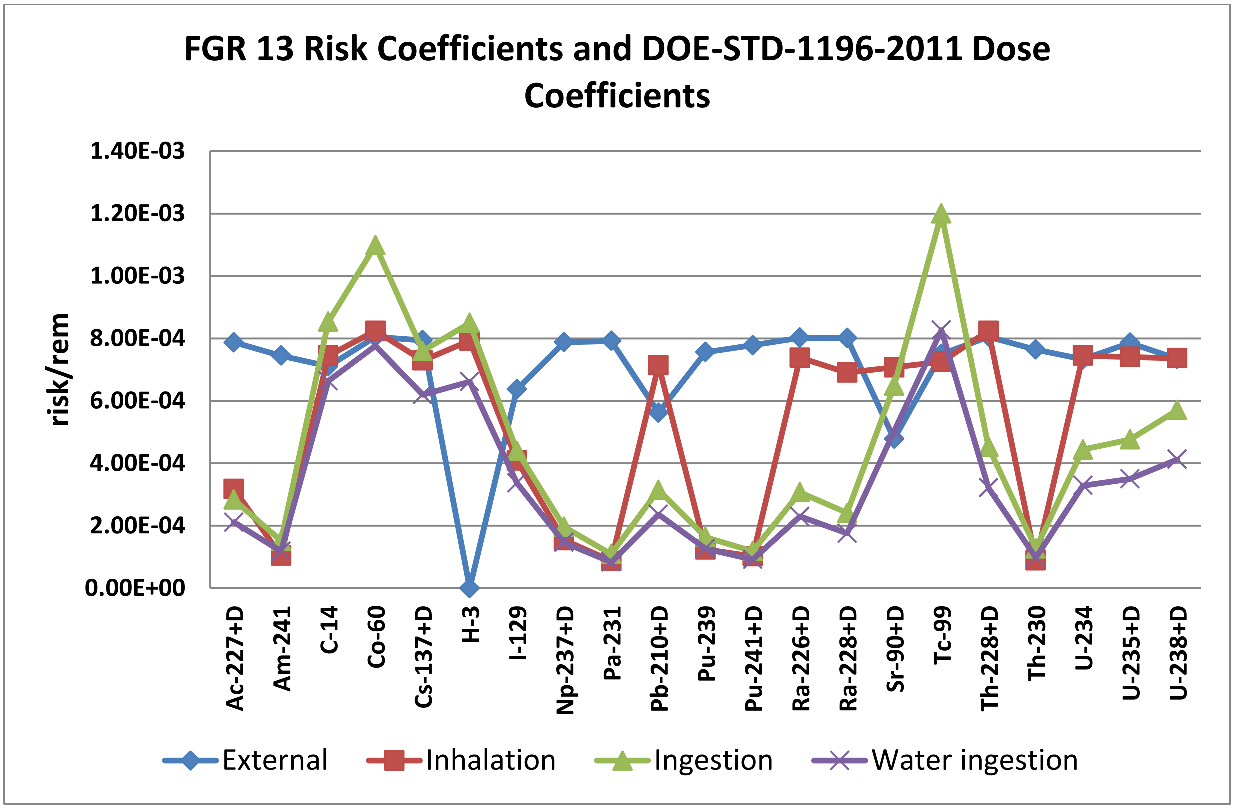

FIGURE 2.1 Risk/Dose Ratio by Pathways

In order to see the combined effect of all pathways for each radionuclide, the RESRAD code and PRG and DCC Calculators were used to generate results using a Farmer Scenario with all pathways active. First, a 12-mrem/yr dose criterion was used to derive the corresponding soil concentration for each radionuclide. Then the derived soil concentrations were used to calculate cancer morbidity risks. Figure 2.2 shows the RESRAD results. The results of using the DCC Calculator to derive soil concentrations and then using the PRG Calculator to calculate the corresponding cancer morbidity risks are shown in Figure 2.3. Also shown in Figures 2.2 and 2.3 are the results of using 15 mrem/yr to repeat the calculations. The red bar segments shown in Figures 2.2 and 2.3 are the increment of risk corresponding to an increment of a 3-mrem/yr dose. As can be seen when comparing the results shown in Figures 2.2 and 2.3, the RESRAD risk results have about 1 order of magnitude difference among the 21 radionuclides studied. The PRG risk results, however, vary by more than 5 orders of magnitude for the 21 radionuclides studied. The wide range in results when using the PRG and DCC Calculators indicated that the PRG and DCC are not consistent in the models and parameters used in these calculators. In contrast, RESRAD uses exactly the same models and parameters; thus RESRAD generated expected and reasonable results when compared with the risk/dose ratio results presented in Figure 2.1.

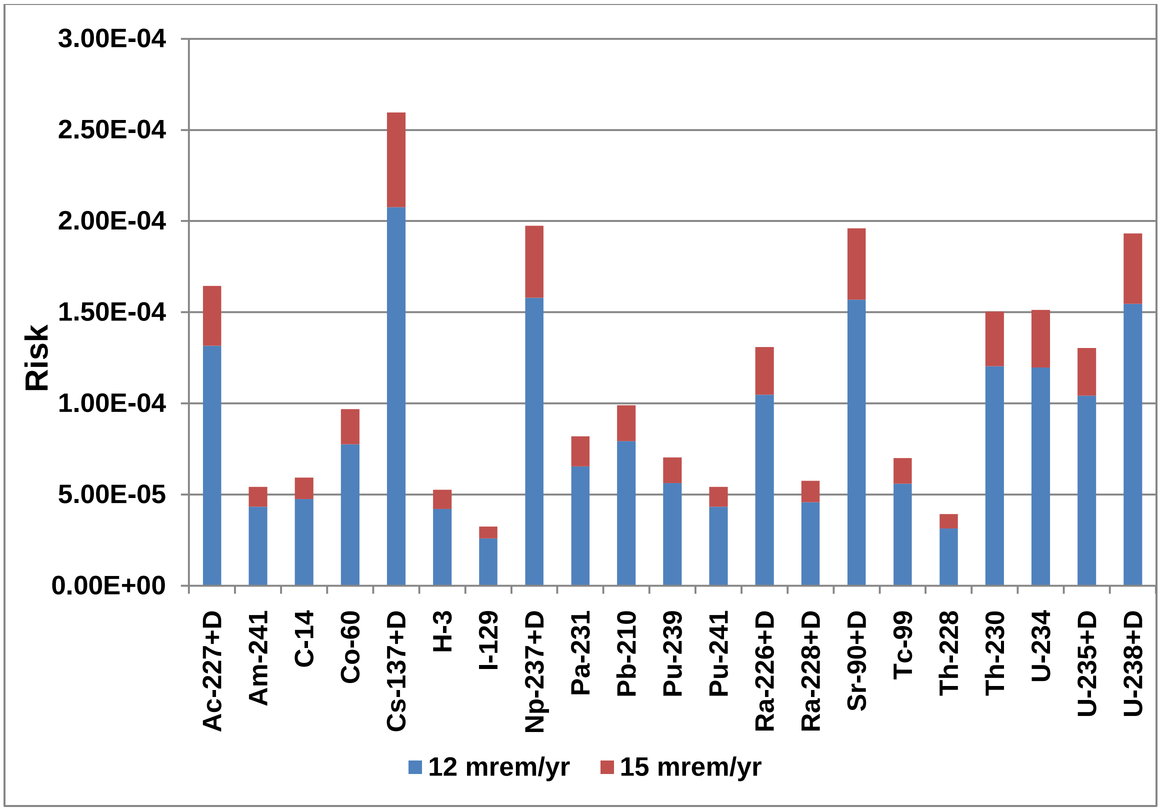

FIGURE 2.2 RESRAD Risk Corresponding to 12 mrem/yr and 15 mrem/yr Using RESRAD Defaults

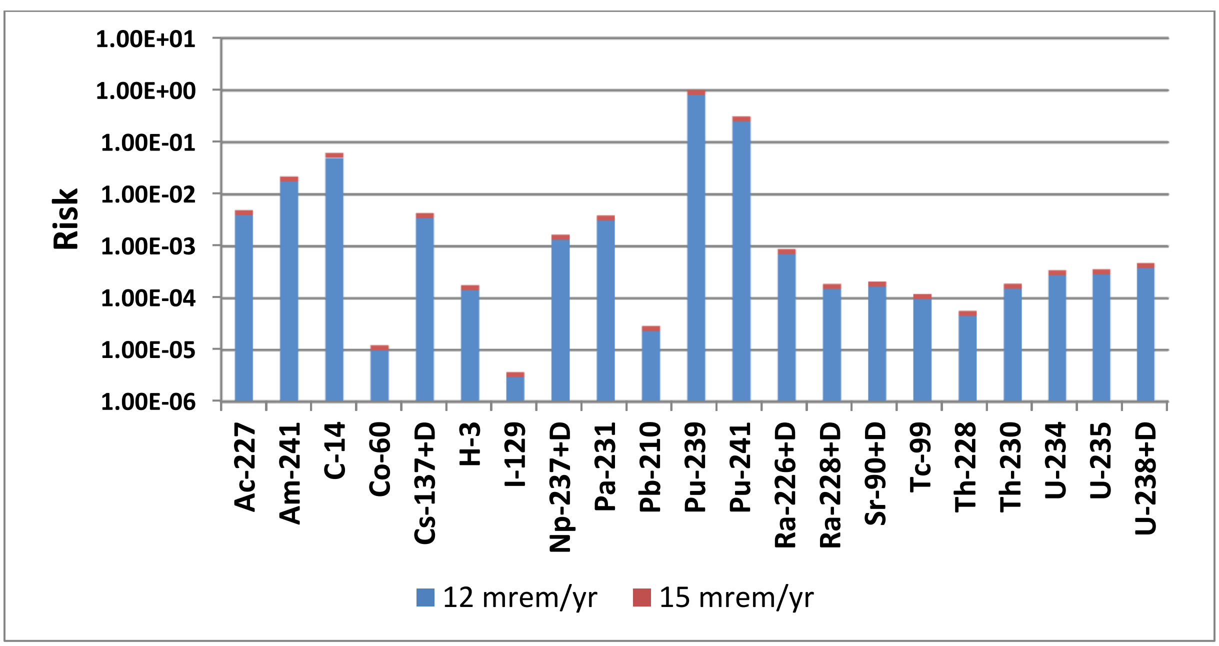

FIGURE 2.3 PRG Risk Corresponding to 12 mrem/yr and 15 mrem/yr Using the PRG and DCC Calculators

The differences in the DC and SF methodology are the net result of a variety of factors. These include the limitation of using effective dose as a measure of risk for non-uniformly distributed radionuclides. They also include differences between the high-LET radiation relative biological effectiveness (RBE) for some cancer types used in SF calculations and those used by the ICRP in DC calculations. Although the effective dose is a well-defined quantity, the tissue weighting factors used to calculate effective dose do not reflect the most up-to-date knowledge of the distribution of risk among the organs and tissues of the body (Eckerman et al. 1999).

Sources that contribute to the uncertainty in risk estimates for a chronic or low-dose exposure include the following:

- Statistical uncertainty,
- Uncertainty in the dose and dose-rate effectiveness factor (DDREF),
- Transfer of risk estimates based on a particular exposed population or to other radiation sources to the secondary population,
- Possible interaction of radiation to other cancer risk factors such as smoking,
- Uncertainty in RBE (the ICRP uses central values for radiological protection),
- Possible existence of a low-dose threshold for certain cancers, and
- Uncertainties in dose estimates for internal radionuclides (ICRP 2007).

The Interagency Steering Committee on Radiation Standards (ISCORS) published *A Method for Estimating Radiation Risk from Total Effective Dose Equivalent (TEDE)* (ISCORS 2002). In this report, ISCORS recommends a dose to risk conversion factor of 8×10^{-4} per rem and discusses many of the problems and qualification that go along with such estimates, including how TEDE can be estimated using the conversion factors for uniform low-LET external radiation provided the caveats mentioned above are acknowledged. In general, using these coefficients to convert TEDE to risk for a mixture of radionuclides will usually provide a high-sided estimate of risk. Furthermore, these factors are recommended for comparison and qualitative presentations only. Only one significant digit should be presented in a calculated risk to avoid implying more certainty than is warranted.

The Health Physics Society (HPS) published two Position Statements regarding radiation risk assessment. One is the "Uncertainty in Risk Assessment" (HPS 1993; revised 1995, 2013). It states that "The Health Physics Society supports risk assessments that are consistent, of high technical quality, unbiased, and based on sound, objective science. Risk assessments should employ the best available scientific and/or technical data and should include consideration of uncertainties." The RESRAD code has the capability of estimating the uncertainty of calculated radiological dose and risk. The EPA's PRG and DCC Calculators do not have uncertainty analysis capability. The other HPS Position Statement is "Radiation Risk in Perspective" (HPS 1996, revised 2010). In this Position Statement, the HPS states that "In accordance with current knowledge of radiation health risks, the Health Physics Society recommends against quantitative estimation of health risks below an individual dose of 50 millisievert (mSv) in 1 year or a lifetime dose of 100 mSv above that received from natural sources. Doses from natural background radiation in the United States average about 3 mSv per year. A dose of 50 mSv will be accumulated in the first 17 years of life and 0.25 Sv in a lifetime of 80 years. Estimation of health risk associated with radiation doses that are of similar magnitude as those received from natural sources should be strictly qualitative and encompass a range of hypothetical health outcomes, including the possibility of no adverse health effects at such low levels."

Radiation dose, either the absorbed dose or the effective dose, is a well-defined quantity. Dose criteria have been successfully used by regulatory agencies to set radiation exposure and release limits. Radiation risk, on the other hand, has not been used by regulatory agencies, except perhaps the EPA Superfund Office's 10^{-6} to 10^{-4} target risk (TR) range, to set official compliance criteria. The international and national radiation authority organizations, including the ICRP and the National Council on Radiation Protection (NCRP), federal and state agencies, and foreign countries, are all using radiation dose or dose rate in their recommendations or setting regulatory limits. From a scientific perspective, if the exposure scenarios and parameters are valid, the estimated radiation dose will occur. However, the existence of cancer risk at these low doses is speculative, and as stated in the HPS Position Statement, may not exist (HPS 1996, revised 2010). If radiation risk values are desired, they should be derived using a consistent methodology as that for dose calculations; that is, the same radionuclide transport models and parameters should be used for both dose and risk calculations. Also, the uncertainty of calculated risks should be quantified. RESRAD is equipped to do both dose and risk calculations with uncertainties.[1] The EPA's tools, the DCC and PRG Calculators, without modification, failed to produce credible results.

[1] The uncertainties computed are for the parameters and scenario assumptions. The uncertainty of dose and risk coefficients is not included in the uncertainty analysis.

3 COMPARISON OF RESRAD AND THE PRG CALCULATOR

For a comparison of RESRAD and the PRG Calculator, the RESRAD (onsite) code Version 7.0 (www.evs.anl.gov/resrad) and the EPA PRG Calculator available online (http://epa-prgs.ornl.gov/cgi-bin/radionuclides/rprg_search) were used. The comparison focused on the soil concentrations for radionuclides corresponding to a target cancer risk of 1×10^{-6}. These radionuclide soil concentrations are called various names in the literature such as soil guidelines, soil cleanup criteria, DCGLs, or Soil Concentration Guidelines (SCGs). The EPA PRG Calculator uses two terms for the soils concentration guidelines: (1) soil Preliminary Remediation Goals (PRGs) for water-independent pathways, and (2) Soil Screening Limits (SSLs) for water-dependent pathways. For this report, the soil PRGs and SSLs derived by the PRG Calculator were compared with the SCGs derived with RESRAD (onsite) code Version 7.0 for a resident scenario. For the RESRAD analysis, the maximum (peak) cancer risks within 1,000 years were used to derive the SCGs; the PRG Calculator, however, calculates current time risk by assuming that short-lived progenies are in equilibrium with the parent radionuclide. The comparison considered 20 radionuclides, including α, β, and γ emitters, which are commonly found in environmental risk assessment. The exposure scenarios and parameters used are described in detail in the following sections. Appendix B presents the decay scheme of selected radionuclides, along with some radionuclide properties.

3.1 COMMON SETTINGS FOR THE COMPARISON

To facilitate the comparison, the PRG Calculator and the RESRAD code were set to simulate the exposures of a resident under the same physical and environmental conditions. Because RESRAD performs fate and transport simulation to track the environmental distributions of radionuclides over time, whereas the PRG Calculator focuses on radiation exposures starting only at current time, RESRAD accepts more site-specific input parameters and provides more flexibility in matching specific exposure, physical, and environmental conditions than the PRG Calculator. Therefore, it was decided that the default settings of the PRG Calculator should be maintained as much as possible, while the input parameter values used in RESRAD should be adjusted. This included (1) changing the SFs used to convert radiation exposures to cancer risks, and (2) changing the root uptake transfer factors used to relate the concentrations of radionuclides in produce to those in soil.

Although the goal was to maintain the default settings of the PRG Calculator as much as possible, some changes were implemented to make the common settings more realistic and to maintain consistency across different exposure pathways. The changes included the slab size for the Area Correction Factor (ACF) and the water infiltration (rate); the slab size is used in the derivation of soil PRGs, and the water infiltration rate is used in the calculation of the Dilution Attenuation Factor (DAF) in groundwater. In addition to changing default values, some parameters used by the PRG Calculator do not have default values and were assigned the RESRAD default values, values derived with the other input parameters, or simply some assumed values. These parameters included (1) the aquifer hydraulic conductivity, (2) hydraulic gradient, (3) source length parallel to groundwater flow, (4) aquifer thickness, (5) water-filled soil porosity, and (6) depth of source. The first four parameters are used to calculate DAF, and the last two parameters are used to consider the migration of radionuclides from soil to groundwater; the water-filled porosity is used in the partition method, and the depth of source is used in the mass-limit method.

In summary, the comparison involved deriving soil PRGs, SSLs, and SCGs based on the potential cancer risk a resident would incur as a result of establishing residency in a contaminated area. The contaminated area was about 2,000 m^2, with soil contamination extending to 2 m below the ground surface. There were no clean, uncontaminated materials overlying the contaminated soil. A groundwater aquifer was assumed to flow across the area at 4 m below the bottom of the contaminated zone. The area had an annual precipitation of 0.5 m/yr and required water irrigation of 0.33 m/yr to maintain the growth of vegetables and fruit trees in the garden and the lawn surrounding the house. The resident and his family were assumed to use groundwater supplied by a well located at the downgradient edge of the contaminated zone. On average, the garden provided 25% of the plant foods needed by the family.

To derive SCGs with the RESRAD code, five exposure pathways were selected: (1) external radiation, (2) inhalation (of dust particles and tritium [H-3] and carbon-14 [C-14] vapors), (3) ingestion of plants, (4) ingestion of water, and (5) ingestion of soil. Because the PRG Calculator does not analyze the exposures associated with the inhalation of radon that is generated by the decay of radium-226 (Ra-226) or thorium-228 (Th-228) in soils and then diffuses out to the outdoor atmosphere or to a confined space inside a residence, the radon pathway available in the RESRAD code was not activated. The maximum cancer risks within 1,000 years from the water-independent pathways—external radiation, inhalation, ingestion of plants (water-independent component), and ingestion of soil—were obtained and used to derive SCGs for comparison with the soil PRGs derived by the PRG Calculator. For comparison with SSLs from the PRG Calculator, the maximum cancer risks within 1,000 years from the water-dependent pathways—ingestion of water and plants (from irrigation water-dependent component)—were obtained and used to derive SCGs. After the separate comparisons of water-dependent pathways and water-independent pathways, the final soil remediation goals, which were obtained by limiting the soil PRGs with SSLs, and the final SCGs, which were derived with the maximum total risks by combining the results of the water-dependent and water-independent pathways, were compared.

Table 3.1-1 lists all the input parameters, along with their values, used to derive soil PRGs, SSLs, and SCGs. The notes in the last column of the table provide explanations and/or comments on the use of the parameters in the PRG Calculator or RESRAD code and how the values of the parameters, if other than the default values, were determined. The parameters listed for the PRG Calculator are shown in three colors; parameters shown in red were used exclusively to derive water PRGs, those in green were used to derive SSLs, and the remaining parameters shown in black were used to derive soil PRGs. If the values are shown in bold, they are different from the default values used in the PRG Calculator. The above differentiations were not used among the RESRAD parameters, because the exposures associated with the water-independent pathways and water-dependent pathways were analyzed in the same run, and the default parameter values were changed to match those used by the PRG Calculator to the extent possible for the comparison. Parameter values highlighted with a yellow background, either under the

TABLE 3.1-1 Input Parameters Used for the Resident Scenario[a,b,c]

Parameter in the PRG Calculator	Parameter Value Used in the PRG Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Remarks
Area for Particulate Emission Factor (PEF) selection (acres)	0.5	Area of contaminated zone (m^2)	2,000	A contaminated area of 2,000 m^2 was assumed, which is close to 0.5 acre, the default value for “Area for PEF selection” in the PRG Calculator. Setting the “slab size for ACF” to 2,000 m^2 ensures consistency in the evaluation of external radiation exposure and inhalation exposure with the PRG Calculator.
Slab size for ACF (m^2)	**2,000**			
		Thickness of contaminated zone (m)	2	Assumption.
Soil thickness cover layer (cm) (for gamma shielding factor - outdoor)	0	Cover depth (m)	0	The PRG Calculator considers the influence of cover materials with a certain thickness on external exposure but not on inhalation exposure. To maintain consistency, no cover material was assumed.
Fraction of vegetative cover	0.5			Vegetative cover is considered by the PRG Calculator to reduce the resuspension of soil particles into the air. In RESRAD, the reduction is considered if a layer of cover material is present, as for external exposure. In the PRG Calculator, cover thickness is an input parameter for the external exposure pathway but not for the inhalation pathway.
		Cover erosion rate (m/yr)	0	
		Contaminated zone erosion rate (m/yr)	0	Erosion of the contaminated zone is not considered in the PRG Calculator.
		Humidity in air (g/m^3)	6	The PRG Calculator assumes that the humidity in air is 6 g/m^3 when considering the evaporation of H-3 in soil water to the air (PRG User's Guide, Section 4.26.1 [EPA 2015]).
Age-adjusted soil ingestion factor (mg)	1,120,000	Soil ingestion (g/yr)	59.34	In the PRG Calculator, the age-adjusted value is the total amount of contaminated soil ingested in 26 years. The RESRAD input is the annual amount of soil ingested. Its value is obtained by dividing the PRG value by 26 (yr), 1,000 (mg/g), and the total time fraction on site (0.726). In this way, the total amount of contaminated soil ingested as calculated by RESRAD would be the same as that considered by the PRG Calculator.

TABLE 3.1-1 (Cont.)

Parameter in the PRG Calculator	Parameter Value Used in the PRG Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Remarks
Age-adjusted soil inhalation factor (m^3)	161,000	Inhalation rate (m^3/yr)	8,531	In the PRG Calculator, the age-adjusted value is the total amount of contaminated air inhaled in 26 years. The RESRAD input is the annual amount of air inhaled. Its value is obtained by dividing the PRG value by 26 (yr) and the total time fraction on site (0.726).
Age-adjusted vegetable consumption factor (g)	970,970	Leafy vegetable consumption (kg/yr)	37.35	In the PRG Calculator, the age-adjusted value is the total amount of produce or water ingested in 26 years. The RESRAD input is the annual amount of produce or water ingested. Its value is obtained by dividing the PRG value by 26 (yr) and 1,000 (g/kg), if necessary.
Age-adjusted fruit consumption factor (g)	1,389,710	Fruit, vegetable, and grain consumption (kg/yr)	53.45	
Age-adjusted water intake factor (L)	19,138	Drinking water intake (L/yr)	736.08	
Age-adjusted immersion factor - resident (h)	6,140			Water immersion is not considered in RESRAD. The potential risk from this pathway is very small compared with the risk from other pathways.
Contaminated produce fraction	0.25	Contamination fraction for plant food	0.25	
		Contamination fraction of drinking water	1	In the PRG Calculator, drinking water and irrigation water are assumed to be 100% contaminated.
		Contamination fraction of irrigation water	1	
Outdoor exposure time fraction (h/d)	1.752	Outdoor time fraction	0.070	In the PRG Calculator, the indoor and outdoor exposure time fraction (h) is used only for the external radiation pathway. The sum can be less than 24 h. However, the exposure time used for the inhalation pathway is 24 h/d.
Indoor exposure time fraction (h/d)	16.416	Indoor time fraction	0.656	
Exposure time resident, resident adult, resident child (h/d)	24			

TABLE 3.1-1 (Cont.)

Parameter in the PRG Calculator	Parameter Value Used in the PRG Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Remarks
Exposure frequency for resident, resident child, resident adult (d/yr)	350			
Exposure duration - resident (yr)	26	Exposure duration (yr)	26	
Exposure duration - resident child (yr)	6			
Exposure duration - resident adult (yr)	20			
Produce plant mass loading factor	0.26			This parameter is used in the PRG Calculator to consider nuclide uptake by plants through the resuspension + foliage deposition mechanism. In RESRAD, the eventual uptake of radionuclides is modeled on the basis of the air concentration of radionuclides, their deposition rates, and several other input parameters.
Irrigation rate (L/m^2-d)	3.62	Irrigation (m/yr)	0.3303	The RESRAD input is calculated based on the PRG Calculator input values, 365 (d/yr) × 0.25 × 3.62 (L/m^2-d) × 0.001 (m^3/L).
Irrigation period	0.25			
		Precipitation (m/yr)	0.5	Because the irrigation rate is greater than the RESRAD default value (0.2 m/yr), the precipitation rate is set to a value smaller than the default value of 1 m/yr, because less precipitation would need more irrigation.
		Runoff coefficient	0.2	The RESRAD default value is used.
		Evapotranspiration coefficient	0.5	The RESRAD default value is used.
Soil leaching rate (L/d)	0.000027			In RESRAD, the soil leaching rate is nuclide-dependent and determined by the water infiltration rate, thickness of contamination, and K_d of the nuclide.
Interception fraction	0.42	Wet foliar interception fraction (all plant types)	0.42	The interception fraction is used in the PRG Calculator to consider uptake of nuclides through irrigation.

TABLE 3.1-1 (Cont.)

Parameter in the PRG Calculator	Parameter Value Used in the PRG Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Remarks
		Dry foliar interception fraction (all plant types)	0.25	In the PRG Calculator, the interception fraction is used to consider uptake of nuclides through wet deposition. Therefore, for RESRAD to consider dry deposition, the default value was used.
Translocation factor	1	Translocation factor for all types of plants	1	
Area density for root zone (kg/m^2)	240			
Long-term deposition and buildup (d)	10,950			RESRAD considers deposition and buildup during the growing season.
Aboveground exposure time for plants (d)	60	Length of growing season (yr) for all types of plants	0.16	
Weathering half-life for plants (d)	14	Weathering removal constant (1/yr)	18.07	The input weathering removal constant for RESRAD is calculated as ln (2)/weathering half-life (yr).
Plant yield-wet (kg/m^2)	2	Wet-weight crop yield (kg/m^2) (all plant types)	2	
		Storage time before use for plant foods and water (d)	0	
Gamma shielding factor (indoor)	0.4	External gamma shielding factor	0.4	
		Indoor dust filtration factor	1	In the PRG Calculator, the indoor and outdoor dust levels are the same. Therefore, the input for RESRAD was set to 1.
PEF (m^3/kg)	1.36E+9 (all nuclides other than H-3), 17 (as Volatilization Factor [VF]) for H-3	Mass loading for inhalation and foliar deposition (g/m^3)	0.0001	The PEF in the PRG Calculator is calculated; the inverse of which is physically equivalent to the multiplication product of the mass loading factor and the area factor for inhalation, which is calculated, in RESRAD.

TABLE 3.1-1 (Cont.)

Parameter in the PRG Calculator	Parameter Value Used in the PRG Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Remarks
Mean annual wind speed (m/s)	4.69	Wind speed (m/s)	4.69	
VF (L/m^3)	0.5			This parameter is used by the PRG Calculator to consider volatilization of radionuclides from water used in household activities. The PRG Calculator considers volatilization for H-3, C-14, radon-222 (Rn-222), and Rn-220.
DAF (Dilution Attenuation Factor)	2.401	Dilution factor for groundwater	1.358	In the PRG Calculator, the value of DAF can be specified or calculated with other parameters. For the comparison with RESRAD, the value of DAF was calculated. The calculated value (ranged from 2.305–2.401) does not change much as the thickness of the aquifer is changed from 12 m–20 m. Thus an aquifer thickness of 20 m was selected to obtain SSLs. In RESRAD, the dilution factor is calculated.
Infiltration rate (m/yr)	**0.365**			The infiltration rate in RESRAD is calculated based on the precipitation rate, irrigation rate, runoff coefficient, and evapotranspiration coefficient. The RESRAD-calculated value was used with the PRG Calculator to obtain SSLs for comparison.
Aquifer hydraulic conductivity (m/yr)	**100**	Saturated zone hydraulic conductivity (m/yr)	100	RESRAD default value was used.
Hydraulic gradient (m/m)	**0.02**	Saturated zone hydraulic gradient	0.02	RESRAD default value was used.
Source length parallel to groundwater flow (m)	**44.72**	Length parallel to aquifer flow (m)	44.72	The parameter value is assumed to be the square root of the contaminated area.
Mixing zone depth (m)	11.434	Well pump intake depth below water table (m)	10	The mixing zone depth is calculated in the PRG Calculator with an empirical equation involving the aquifer thickness.
		Well pumping rate (m^3/yr)	992	The RESRAD input value is estimated based on the water ingestion rate, irrigation rate, contaminated area, and household water use of 225 L/d. It is assumed that there are four people living in the residence.

TABLE 3.1-1 (Cont.)

Parameter in the PRG Calculator	Parameter Value Used in the PRG Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Remarks
Aquifer thickness (m)	**20**			Assumed; the value should be greater than the well pump intake depth below the water table (10 m) as used in RESRAD.
		Water table drop rate (m/yr)	0	
Method 1 for migration to groundwater - partitioning				
Dry soil bulk density (kg/L)	1.5	Density of saturated zone (g/cm^3)	1.5	
Water-filled soil porosity	**0.3136**	Contaminated zone total porosity	0.4	The water-filled soil porosity is the product of total porosity in the contaminated zone and the saturation ratio, which is determined to be 0.784 based on several parameters according to Eq. (E-7) in the RESRAD User's Manual (Yu et al. 2001). The parameters that determine the saturation ratio are the water infiltration rate of 0.365 m/yr and the saturated hydraulic conductivity of 10 m/yr, and the soil-specific exponential b parameter of 5.3 for the contaminated zone. The latter two are input parameters for RESRAD and their default values are used.
		Contaminated zone hydraulic conductivity (m/yr)	10	
Time (yr)	**26**			To account for decay in soil during exposure; therefore, the exposure duration is used as the value.
Method 2 for migration to groundwater - mass limit				
Depth of source (m)	**2**			Same as thickness of the contaminated zone.
Exposure duration (yr) - dissolution period	70			Default value used in the PRG Calculator.
Dry soil bulk density (kg/L)	1.5	Density of saturated zone (g/cm^3)	1.5	

TABLE 3.1-1 (Cont.)

[a] Parameters for the PRG Calculator are shown in three colors: red = used exclusively to derive water PRGs; green = used to derive SSLs; and black = used to derive soil PRGs. Values shown in bold type indicate that the values are different from the default values used in the PRG Calculator.

[b] Parameter values with a yellow background indicate that the value is calculated with other input parameters within RESRAD or the PRG Calculator.

[c] The ingestion of animal products is not considered in the PRG Calculator for the Resident Scenario; thus the ingestion of meat, milk, and aquatic food pathways are disabled in the RESRAD modeling.

PRG Calculator or the RESRAD column, are calculated values. There are other RESRAD parameters that do not have counterparts in the PRG Calculator and are not listed in Table 3.1-1; for this comparison, their default values were used to derive SCGs.

3.2 COMPARISON OF WATER-INDEPENDENT PATHWAYS

Table 3.2-1 lists the total soil PRGs obtained with the PRG Calculator and the SCGs derived with the RESRAD results of the maximum cancer risks from all water-independent pathways within 1,000 years, corresponding to a target cancer risk of 1×10^{-6}. Two sets of SCGs were derived, one based on RESRAD's default Distribution Coefficients (K_ds) and the other based on the PRG Calculator's default K_ds. To differentiate them, the SCGs derived based on the PRG Calculator's default K_ds are termed SCG′s in the table. In addition to the values of soil PRGs and SCGs, the most critical pathway (the one that contributes the most cancer risk), the time of maximum cancer risk (for SCGs and SCG′s only), and the ratios of SCGs to soil PRGs and SCG′s to soil PRGs are also listed. Figure 3.2-1 is a graphic illustration of the ratios.

Except for cobalt-60 (Co-60) (for both ratios) and Th-230 (for the ratio of SCG to soil PRG), the ratios of SCG or SCG′ to soil PRG are all greater than 1, which indicates that the potential cancer risks calculated by RESRAD are less than those calculated by the PRG Calculator (when the same initial soil concentration for each radionuclide is used). For some radionuclides, the SCG/SCG′ is 2 to 3 orders of magnitude greater than the soil PRG. The most critical pathways identified by the PRG Calculator and RESRAD are also different. Based on the results of the PRG Calculator, the most critical pathway is the ingestion of produce pathway for all the radionuclides studied, except for Co-60, cesium-137 (Cs-137), or H-3. The most critical pathways identified by RESRAD are more diverse; depending on the radionuclide of concern—it can be the external exposure, ingestion of produce, or ingestion of soil pathway. For protactinium-231 (Pa-231), plutonium (Pu-241), and Th-230, the maximum cancer risk would occur at a later time rather than at the current time ($t = 0$), according to the RESRAD result. The PRG Calculator does not model the ingrowth of long-lived progenies; therefore, the soil PRGs are always derived with the cancer risks estimated at time 0.

Investigation of the data and equations used in the PRG Calculator revealed five main reasons for the observed differences between soil PRGs and SCGs/SCG′s:

1. For some radionuclides, the contributions of short-lived progenies to cancer risk are not accounted for or are not accurately accounted for;

2. The loss of radionuclides from the soil source through leaching is not taken into account;

3. There is no consideration of long-lived progenies which can outweigh the parent nuclide in terms of risk contribution, even for the 26-year exposure period that starts at the current time;

TABLE 3.2-1 Comparison of Soil PRGs and SCGs Corresponding to a Target Cancer Risk Level of 1 ×10^{-6} – Based on Exposures Associated with Water-Independent Pathways for the Resident Scenario[a]

	PRG Calculator		RESRAD (with RESRAD K_ds)				RESRAD (with PRG K_ds)			
Parent Nuclide	Total Soil PRG (pCi/g)	Most Critical Pathway	SCG (pCi/g)	Most Critical Pathway	Calculated Ratio (SCG/Soil PRG)	Time of Peak Risk (yr)	SCG′ (pCi/g)	Most Critical Pathway	Calculated Ratio (SCG′/Soil PRG′)	Time of Peak Risk (yr)
Ac-227	3.85E-02	Ingestion of produce	1.07E-01	External exposure	2.79	0	1.01E-01	External	2.62	0
Am-241	4.88E-02	Ingestion of produce	2.33E+00	External exposure	47.83	0	3.09E+00	External	63.27	0
C-14	1.47E-01	Ingestion of produce	2.87E+01	Ingestion of produce	195.24	0	2.69E+01	Ingestion of produce	182.99	0
Co-60	3.73E-02	External exposure	3.64E-02	External exposure	0.98	0	3.64E-02	External	0.98	0
Cs-137	5.36E-02	External exposure	6.54E-02	External exposure	1.22	0	7.49E-02	External	1.40	0
H-3	2.32E-01	Inhalation	1.82E+02	Ingestion of produce	784.48	0	1.82E+02	Ingestion of produce	784.48	0
I-129	3.27E-02	Ingestion of produce	2.39E+01	Ingestion of soil	730.89	0	3.54E+01	Ingestion of soil	1,082.57	0
Np-237	4.90E-02	Ingestion of produce	1.40E-01	External exposure	2.87	0	1.09E+00	External exposure	22.24	0
Pa-231	2.69E-02	Ingestion of produce	8.04E-02	External exposure	2.99	60	5.85E-02	External exposure	2.18	170
			(1.42E-01)				(1.35E-01)			
Pb-210	7.72E-03	Ingestion of produce	5.89E-02	Ingestion of produce	7.63	0	5.87E-02	Ingestion of produce	7.60	0
Pu-239	3.70E-02	Ingestion of produce	3.22E+00	Ingestion of soil	87.16	0	4.30E+00	Ingestion of soil	116.20	0
Pu-241	4.97E+00	Ingestion of produce	8.72E+01	Ingestion of soil	17.54	29.5	1.58E+02	Ingestion of soil	31.75	4.9
			(1.17E+02)				(1.63E+02)			
Ra-226	6.92E-03	Ingestion of produce	1.23E-02	External exposure	1.77	33.4	3.49E-02	External exposure	5.04	0
			(1.31E-02)							
Ra-228	1.24E-02	Ingestion of produce	3.20E-02	External exposure	2.58	0	5.54E-02	External exposure	4.47	0
Sr-90	6.63E-02	Ingestion of produce	2.48E-01	Ingestion of produce	3.74	0	5.94E-01	Ingestion of produce	8.96	0

TABLE 3.2-1 (Cont.)

	PRG Calculator		RESRAD (with RESRAD K_ds)				RESRAD (with PRG K_ds)			
Parent Nuclide	Total Soil PRG (pCi/g)	Most Critical Pathway	SCG (pCi/g)	Most Critical Pathway	Calculated Ratio (SCG/Soil PRG)	Time of Peak Risk (yr)	SCG′ (pCi/g)	Most Critical Pathway	Calculated Ratio (SCG′/Soil PRG′)	Time of Peak Risk (yr)
Tc-99	3.04E-01	Ingestion of produce	5.65E+00	Ingestion of produce	18.59	0	5.66E+00	Ingestion of produce	18.62	0
Th-230	5.37E-02	Ingestion of produce	5.86E-02	External exposure	1.09	1,000	1.70E+00	Ingestion of soil	31.65	16.7
			(1.29E+00)				(1.89E+00)			
U-234	6.61E-02	Ingestion of produce	2.07E+00	Ingestion of produce	31.35	0	1.05E+01	Ingestion of produce	158.85	0
U-235	5.22E-02	Ingestion of produce	2.02E-01	External exposure	3.86	0	1.02E+00	External exposure	19.54	0
U-238	5.00E-02	Ingestion of produce	6.61E-01	External exposure	13.23	0	3.35E+00	External exposure	67.00	0

[a] The value of SCG or SCG’ was derived with the peak risk-to-source ratio calculated by RESRAD, which occurred at time 0 except for those highlighted with a yellow background. When the peak ratio time is other than time 0, for comparison, the SCG or SCG’ derived with the ratio at time 0 is also listed in parentheses.

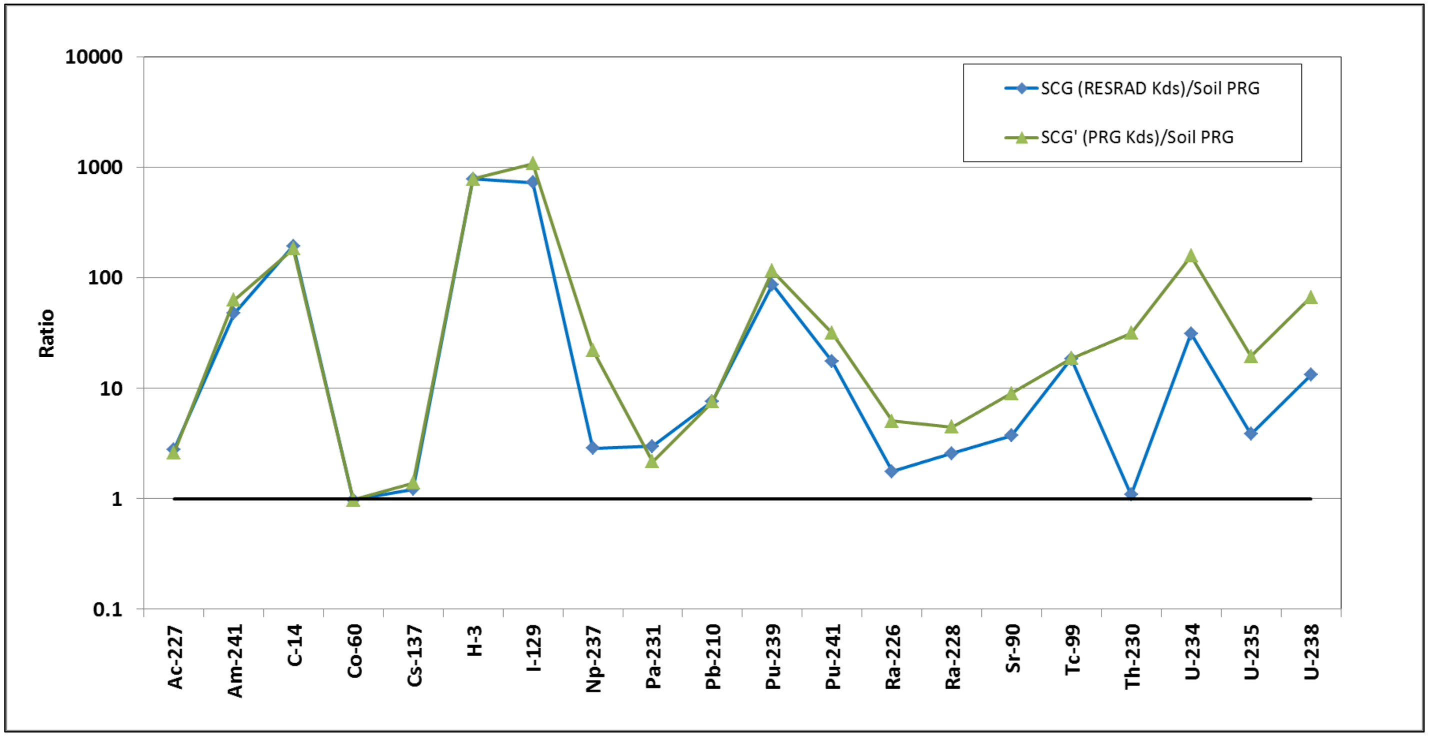

FIGURE 3.2-1 Ratios of SCG/SCG′ to Soil PRG for the Resident Scenario

4. The evaporation modeling of H-3 from soil does not consider dilution in the air; and

5. The produce uptake of radionuclides through the resuspension mechanism maybe overly exaggerated.

The following sections provide more detailed discussions on each of the findings.

3.2.1 Consideration of Short-lived Progenies

One common assumption or approximation used by modelers when the model cannot track radionuclide decay progeny transport in the environment is to assume that the short-lived progenies travel with the parent so that they are in secular equilibrium (same concentration) with their parent nuclide. This assumption is a good approximation only when the short-lived progenies have similar properties (e.g., K_d) and a short half-life compared with the parent. To account for cancer risk contributions from short-lived progenies, the SFs of short-lived progenies are added to that of the parent nuclide, and the sum is used with the estimated exposures of the parent nuclide to characterize the associated cancer risk.

According to the PRG Calculator User's Guide (EPA 2015), a radionuclide name followed by a "+D" suffix indicates that the SFs used in the risk calculation would include the contributions from short-lived progenies that have a half-life up to 100 years. The intention of using such a long time (100 years) as the cut-off criterion for short-lived radionuclides is to ensure conservatism with the cancer risk estimates. However, examination of the SFs for some "+D" radionuclides found that this cut-off criterion is not strictly followed by the PRG Calculator for many radionuclides. For example, the SF used for Th-232+D does not include the contribution from Ra-228, which is a progeny of Th-232 with a half-life of 5.75 years. Another example is Ra-226; the SF used for Ra-226+D does not include the contribution from Pb-210, which is a progeny of Ra-226 and has a half-life of 22.3 years.

Table 3.2-2 lists the SFs used for the 20 radionuclides studied in the comparison. Although SFs of individual radionuclides in the RESRAD code were set to those of the PRG Calculator, the SFs for "+D" radionuclides were calculated by RESRAD on the basis of the decay and ingrowth structures provided in ICRP Publication 107 (ICRP 2008) (which is also referenced by the PRG Calculator) and the user's selection of a cut-off criterion. A cut-off time of 6 months was selected for this comparison.

According to the listing in Table 3-2.2, in which significant differences between RESRAD and the PRG Calculator are highlighted with a yellow background, the PRG Calculator fails to include contributions of short-lived progenies for actinium-227 (Ac-227) and lead-210 (Pb-210), because the nuclide names Ac-227+D and Pb-210+D are not available for selection. This could lead to underestimating the potential cancer risks by a factor of 8,190 for Ac-227 for the external exposure pathway, and by a factor of about 2 to 3 for Pb-210 for all exposure pathways. For Pu-241, the PRG Calculator neglects a small decay branch that accounts for just 0.00245% of the nuclide disintegrations. However, the negligence could lead to underestimating

TABLE 3.2-2 Comparison of Slope Factors Used by the PRG Calculator and RESRAD for Cancer Risk Characterization[a]

Parent Nuclide	Nuclide Designation		Inhalation Slope Factor (risk/pCi)			Food Ingestion Slope Factor (risk/pCi)			Water Ingestion Slope Factor (risk/pCi)			Soil Ingestion Slope Factor (risk/pCi)			External Exposure Slope Factor (risk/yr per pCi/g)		
	PRG Calculator	RESRAD	PRG Calculator	RESRAD	Ratio (RESRAD/ PRG Calculator)	PRG Calculator	RESRAD	Ratio (RESRAD/ PRG Calculator)	PRG Calculator	RESRAD	Ratio (RESRAD/ PRG Calculator)	PRG Calculator	RESRAD	Ratio (RESRAD/ PRG Calculator)	PRG Calculator	RESRAD	Ratio (RESRAD/ PRG Calculator)
Ac-227[b]	Ac-227	Ac-227+D Ac-227+D2	1.49E-07	2.14E-07 1.79E-07	1.43E+00	2.45E-10	6.55E-10 5.94E-10	2.66E+00	2.01E-10	4.88E-10 4.47E-10	2.42E+00	2.90E-10	1.02E-09 9.07E-10	3.50E+00	1.98E-10	1.63E-06 1.32E-06	8.19E+03
Am-241	Am-241	Am-241	3.77E-08	3.77E-08	1.00E+00	1.34E-10	1.34E-10	1.00E+00	1.04E-10	1.04E-10	1.00E+00	1.84E-10	1.84E-10	1.00E+00	2.77E-08	2.77E-08	1.00E+00
C-14	C-14	C-14	1.69E-11	1.69E-11 (p)	1.00E+00	2.00E-12	2.00E-12	1.00E+00	1.55E-12	1.55E-12	1.00E+00	2.77E-12	2.77E-12	1.00E+00	7.86E-12	7.86E-12	1.00E+00
Co-60	Co-60	Co-60	1.01E-10	1.01E-10	1.00E+00	2.23E-11	2.23E-11	1.00E+00	1.58E-11	1.58E-11	1.00E+00	3.81E-11	3.81E-11	1.00E+00	1.24E-05	1.24E-05	1.00E+00
Cs-137	Cs-137+D	Cs-137+D	1.12E-10	1.12E-10	1.00E+00	3.74E-11	3.74E-11	1.00E+00	3.05E-11	3.05E-11	1.00E+00	4.26E-11	4.26E-11	1.00E+00	2.53E-06	2.55E-06	1.00E+00
H-3	H-3	H-3	8.47E-13	8.47E-13	1.00E+00	6.51E-14	6.51E-14	1.00E+00	Does not calculate water PRGs	5.07E-14	–	8.99E-14	8.99E-14	1.00E+00	0.00E+00	0.00E+00	1.00E+00
I-129	I-129	I-129	1.64E-10	1.64E-10	1.00E+00	1.97E-10	1.97E-10	1.00E+00	1.51E-10	1.51E-10	1.00E+00	2.78E-10	2.78E-10	1.00E+00	6.18E-09	6.18E-09	1.00E+00
Np-237	Np-237+D	Np-237+D	2.87E-08	2.87E-08	1.00E+00	9.18E-11	9.18E-11	1.00E+00	6.83E-11	6.83E-11	1.00E+00	1.42E-10	1.42E-10	1.00E+00	8.55E-07	8.55E-07	1.00E+00
Pa-231	Pa-231	Pa-231	7.62E-08	7.62E-08	1.00E+00	2.26E-10	2.26E-10	1.00E+00	1.72E-10	1.72E-10	1.00E+00	2.98E-10	2.98E-10	1.00E+00	1.27E-07	1.27E-07	1.00E+00
Pb-210	Pb-210	Pb-210+D	1.59E-08	3.08E-08	1.94E+00	1.18E-09	3.44E-09	2.92E+00	8.84E-10	2.67E-09	3.02E+00	1.72E-09	5.01E-09	2.91E+00	1.48E-09	4.30E-09	2.91E+00
Pu-239	Pu-239+D	Pu-239+D	5.55E-08	5.55E-08	1.00E+00	1.74E-10	1.74E-10	1.00E+00	1.35E-10	1.35E-10	1.00E+00	2.28E-10	2.28E-10	1.00E+00	2.09E-10	2.09E-10	1.00E+00
Pu-241[c]	Pu-241	Pu-241 Pu-241+D	8.66E-10	8.66E-10 8.73E-10	1.00E+00	2.28E-12	2.28E-12 9.57E-12	1.01E+00	1.76E-12	1.77E-12 6.76E-12	1.02E+00	2.72E-12	2.72E-12 1.61E-11	1.01E+00	4.06E-12	4.06E-12 3.72E-07	3.24E+00
Ra-226	Ra-226+D	Ra-226+D	2.82E-08	2.83E-08	1.00E+00	5.14E-10	5.15E-10	1.00E+00	3.85E-10	3.85E-10	1.00E+00	6.77E-10	6.78E-10	1.00E+00	8.37E-06	8.36E-06	1.00E+00
Ra-228	Ra-228+D	Ra-228+D	4.37E-08	4.37E-08	1.00E+00	1.43E-09	1.43E-09	1.00E+00	1.04E-09	1.04E-09	1.00E+00	1.98E-09	1.98E-09	1.00E+00	4.04E-06	4.04E-06	1.00E+00
Sr-90	Sr-90+D	Sr-90+D	4.33E-10	4.34E-10	1.00E+00	9.51E-11	9.53E-11	1.00E+00	7.40E-11	7.39E-11	1.00E+00	1.35E-10	1.35E-10	1.00E+00	1.95E-08	1.95E-08	1.00E+00
Tc-99	Tc-99	Tc-99	3.81E-11	3.81E-11	1.00E+00	4.00E-12	4.00E-12	1.00E+00	2.75E-12	2.75E-12	1.00E+00	7.25E-12	7.25E-12	1.00E+00	8.28E-11	8.28E-11	1.00E+00
Th-230	Th-230	Th-230	3.41E-08	3.41E-08	1.00E+00	1.19E-10	1.19E-10	1.00E+00	9.14E-11	9.14E-11	1.00E+00	1.66E-10	1.66E-10	1.00E+00	8.45E-10	8.45E-10	1.00E+00
U-234	U-234	U-234	2.78E-08	2.78E-08	1.00E+00	9.55E-11	9.55E-11	1.00E+00	7.07E-11	7.07E-11	1.00E+00	1.48E-10	1.48E-10	1.00E+00	2.53E-10	2.53E-10	1.00E+00
U-235	U-235+D	U-235+D	2.50E-08	2.50E-08	1.00E+00	9.77E-11	9.76E-11	1.00E+00	7.18E-11	7.17E-11	1.00E+00	1.54E-10	1.54E-10	1.00E+00	5.76E-07	5.76E-07	1.00E+00
U-238[d]	U-238+D	U-238+D U-238+D1	2.37E-08	2.37E-08 2.37E-08	1.00E+00	1.21E-10	1.24E-10 1.20E-10	9.91E-01	8.70E-11	8.92E-11 8.71E-11	1.00E+00	1.97E-10	2.02E-10 1.96E-10	9.95E-01	1.19E-07	6.73E-06 1.08E-07	9.96E-01

TABLE 3.2-2 (Cont.)

[a] A yellow background indicates a significant difference between RESRAD and the PRG Calculator.

[b] For Ac-227, RESRAD considers multiple decay branches. The values listed are those used for the two most dominating branches—one has a branching ratio of 98.35% and the other has a branching ratio of 1.38%. The ratio of RESRAD/PRG Calculator is calculated by taking into account the branching ratios considered in RESRAD modeling.

[c] For Pu-241, RESRAD considers two decay branches—one has a branching ratio of 0.00245%, involves a short-lived nuclide (U-237), and decays to Np-237; the other has a branching ratio of 99.9976% and decays to Am-241. The ratio of RESRAD/PRG Calculator is calculated by taking into account the branching ratios considered in RESRAD modeling.

[d] For U-238, RESRAD considers multiple decay branches. The values listed are those used for the two most dominating branches—one has a branching ratio of 0.1599% and the other has a branching ratio of 99.8%. The ratio of RESRAD/PRG Calculator is calculated by taking into account the branching ratios considered in RESRAD modeling.

the potential cancer risk for Pu-241 by a factor of about 3 (calculated value 3.24) for the external exposure pathway, according to the ratio of SFs shown in Table 3.2-2.

3.2.2 Consideration of Leaching Loss

Concentrations of radionuclides initially existing in soil would decrease with time due to radiological decay and leaching. However, when deriving soil PRGs, the PRG Calculator only considers the decrease due to radiological decay, essentially assuming radionuclides would strongly adsorb to soil particles and would not dissolve in the infiltration water and leach out from the contaminated zone. On the other hand, to derive SSLs that consider the migration of radionuclides from soil to groundwater, radionuclides are assumed to dissolve in water and leach out from the contaminated zone. To facilitate leaching, the PRG Calculator chooses much smaller values than those reported in literature data as the default K_ds for quite a few radionuclides (see Table 3.2-3) (Note: $K_d$is defined as the ratio of radionuclide concentration in the solid phase to that in the liquid phase in soils, and a small $K_d$indicates that radionuclides tend to dissolve in the liquid phase.) The negligence of leaching in the derivation of soil PRGs would result in overestimating the potential cancer risks associated with water-independent pathways, thereby driving down the values of soil PRGs.

The influence on the derived soil PRGs associated with neglecting leaching loss from the contaminated zone was studied with the average soil concentration over the exposure duration (26 years) starting at time 0, which is used with exposure factors and slope factors to estimate cancer risks associated with the water-independent pathways in the PRG Calculator. The average soil concentration is calculated by multiplying the initial soil concentration with a correction factor ($CF_{res-soil}$) that accounts for the loss of radionuclides through radiological decay over the exposure duration of residents. In RESRAD, a similar factor called the source factor ($SF_p,\ p$ indicates parent nuclide) is used to multiply the initial soil concentration to obtain the soil concentration at any other time. The value of SF_p is time dependent and accounts for the loss in radioactivity through both radiological decay (for parent nuclide) and leaching. The average of SF_p, $SF_{p-res-avg}$, over the exposure duration of residents starting at time 0 is the counterpart of $CF_{res-soil}$ and can be multiplied by the initial soil concentration to obtain the average soil concentration considering loss through both radiological decay and leaching. Table 3.2-4 compares $CF_{res-soil}$ used in the PRG Calculator with $SF_{p-res-avg}$ calculated with the SF_p values from RESRAD.

According to the ratios shown in Table 3.2-4 (those significantly greater than 1 are in red), the average soil concentrations were greatly overestimated by the PRG Calculator for some radionuclides, including C-14, H-3, iodine-129 (I-129), neptunium-237 (Np-237), technetium-99 (Tc-99), uranium-234 (U-234), U-235, and U-238. As a result, the soil PRGs derived for these radionuclides could be overly conservative.

TABLE 3.2-3 Comparison of Default K_ds Used in the PRG Calculator and RESRAD

Element	K_d (g/cm^3)						
	PRG Calculator	RESRAD	GM[a] for Sand Soil Type[b]	GM for Loam Soil Type[b]	GM for Clay Soil Type[b]	GM for Organic Soil Type[b]	GM for Generic Soil Type[b]
Ac	1,700	20	450	1,500	2,400	5,400	1,700
Am	4	20	1,000	4,200	8,100	2,500	2,600
C	1	0	NA[c]	NA	NA	NA	
Co	480	1,000	260	810	3,800	87	480
Cs	10	4,600	530[d]	3,500[d]	5,500[d]	270[d]	1,200[d]
H	0	0	0.1	NA	NA	NA	?
I	0	0	4	7	7	36	7
Np	0.2	257	14	23	NA	810	36
Pa	2,000	50	540	1,800	2,700	6,600	2,000
Pb	150	100	220[e]	10,000[e]	NA	2,500[e]	2,100[e]
Po	210	210	100[e]	230[c]	732[e]	NA	180[e]
Pu	5	2,000	400	950	1,800	760	740
Ra	1	70	3,100[e]	710–1,100[e]	13,000–38,000[e]	200[e]	2,500[e]
Sr	1	30	22[d]	57[d]	95[d]	110[d]	52[d]
Tc	0	0	0.04	0.07	0.09	3	0.2
Th	20	60,000	700[e]	18,000[e]	4,500[e]	730[e]	1,900[e]
U	0.4	50	110[e]	310[e]	28[e]	1,200[e]	200[e]

[a] GM = geometric mean.

[b] Source: Gil-Garcia et al. (2009a), except as noted.

[c] NA = not available.

[d] Source: Gil-Garcia et al. (2009b).

[e] Source: Vandenhove et al. (2009).

3.2.3 Consideration of Long-lived Progenies

The PRG Calculator lacks the capability to track the formation of long-lived progenies over time and derives soil PRGs based only on the estimated cancer risks at current time. The negligence of long-lived progenies could compromise the intention of the PRG Calculator to derive conservative soil PRGs, because long-lived progenies may accumulate in soils, concentrate in plants, and/or have a high risk potential (i.e., with large slope factors), thereby contributing significant risks which, in some cases, may outweigh the risks posed by the parent nuclide.

TABLE 3.2-4 Comparison of Correction Factors for Initial Soil Concentrations[a]

Parent Nuclide	$SF_{p-res-avg}$ with RESRAD (based on RESRAD's K_ds)	$SF'_{p-res-avg}$ with RESRAD (based on PRG Calculator's K_ds)[a]	$CF_{res-soil}$ with PRG Calculator	Ratio of $CF_{res-soil}/SF_{p-res-avg}$	Ratio of $CF_{res-soil}/SF'_{p-res-avg}$
Ac-227	0.637	0.679	0.680	1.07	1.00
Am-241	0.907	0.690	0.979	1.08	1.42
C-14[b]	0.066	0.305	0.998	15.12[c]	3.28
Co-60	0.284	0.283	0.284	1.00	1.00
Cs-137	0.752	0.657	0.753	1.00	1.15
H-3[b]	0.060	0.060	0.525	8.72	8.72
I-129	0.098	0.066	1.000	10.24	15.14
Np-237	0.998	0.129	1.000	1.00	7.74
Pa-231	0.969	0.999	1.000	1.03	1.00
Pb-210	0.676	0.679	0.685	1.01	1.01
Pu-239	0.999	0.749	1.000	1.00	1.33
Pu-241	0.569	0.453	0.569	1.00	1.26
Ra-226	0.972	0.353	0.994	1.02	2.82
Ra-228	0.300	0.173	0.304	1.01	1.76
Sr-90	0.709	0.296	0.743	1.05	2.51
Tc-99	0.066	0.066	1.000	15.14	15.14
Th-230	1.000	0.926	1.000	1.00	1.08
U-234	0.969	0.191	1.000	1.03	5.22
U-235	0.969	0.191	1.000	1.03	5.22
U-238	0.969	0.191	1.000	1.03	5.22

[a] SF' = Source Factor in RESRAD, obtained by setting radionuclide K_ds to the PRG Calculator's default values.

[b] C-14 and H-3 in soil could also evaporate/volatilize from the contaminated soil. The Source Factor and Correction Factor values listed in the table do not take into account the loss through this mechanism.

[c] Ratios significantly greater than 1 are shown in red.

The importance of considering long-lived progenies in deriving soil remediation goals can be demonstrated with the RESRAD results in Table 3.2-1. If considering only the cancer risks that would be incurred at the current time (i.e., starting at time 0 for 26 years), the SCGs based on a TR level of 1×10^{-6} would be 0.142, 117, and 1.29 pCi/g for Pa-231, Pu-241, and Th-230, respectively. However, because of the ingrowth of long-lived progenies over time, the potential cancer risks would increase with time for a certain period. If the SCGs are derived based on the maximum cancer risks within 1,000 years, then the SCGs should be 0.08, 87.2, and 0.0586 pCi/g for Pa-231, Pu-241, and Th-230, respectively, which are 57%, 75%, and 4.5%, respectively, of the previous SCGs.

The significance of cancer risk contributions from long-lived progenies can be seen starting at the current time (t = 0) with some radionuclides. Table 3.2-5 shows the cancer risks (for 1 pCi/g initial soil concentration) associated with water-independent pathways at time 0, calculated by RESRAD with its default K_d values. (Note: Although cancer risk estimates are generally reported with one significant digit, in this report, they are shown with multiple digits to preserve the calculation results from the RESRAD code or the PRG Calculator.) For each pathway, the total cancer risk contributed by both parent nuclide and long-lived progenies and the cancer risk contributed by the parent nuclide only are listed side by side, followed by the ratio between them. The ratios greater than 1.3 are highlighted with a yellow background. According to the calculated ratios, the potential cancer risk from all pathways at time 0 would be underestimated by a factor of about 3 (calculated value 2.64) for Pa-231, 4 (calculated value 3.77) for Pa-241, 2 (calculated value 2.25) for Ra-228, and also 2 (calculated value 2.20) for Th-230, if long-lived progenies were not considered. The underestimation in cancer risk could be more pronounced if each pathway was examined separately. As shown in Table 3.2-5, the underestimation is up to a factor of about 54 (calculated value 54.27) for the external exposure pathway (Th-230), 4 (calculated value 4.23) for the inhalation of dust pathway (Ra-228), 4 (calculated value 2.93) for the ingestion of produce pathway (Pu-241), and 3 (calculated value 2.58) for the ingestion of soil pathway (Pu-241).

3.2.4 Consideration of Air Dilution for H-3

Radionuclides attached to soil particles could become airborne due to disturbance by wind or human activities. For the Resident Scenario, the PRG Calculator considers wind disturbance as the primary driving force. The radionuclide concentration in the air is determined by the concentration in soil, the emission flux of soil particles per unit area, and the dispersion of the emitted soil particles. The dispersion of the emitted soil particles is expressed as the ratio between the concentration of soil particles in air at the center of the contaminated area to the emission flux of soil particles; that is, C_{wind}/Q, in which C_{wind} (kg/m^3) is the soil particle concentration in air due to wind disturbance and Q is the soil particle emission flux (g/m^2-s). The dispersion takes into account the dilution of the emitted soil particles in the air, and its value increases as the area of contamination increases. The air dispersion and dilution are also considered by RESRAD to calculate air concentrations of radionuclides attached to soil particles.

In the environment, H-3 often exists as tritiated water (HTO), which can evaporate from soil and get into the air. To calculate the air concentration of H-3, the PRG Calculator adopts the assumption that the ratio of H-3 in the air moisture (default is 6 g/m^3) is the same as the ratio of H-3 in soil water (100 g/kg as the default). Therefore, for a soil concentration of 1 pCi/g for H-3, its air concentration would be 60 pCi/m^3, corresponding to a Volatilization Factor (VF) of 17 m^3/kg, as stated in the User's Guide for the PRG Calculator (EPA 2015). The adopted assumption implies that all the air moisture above the center of the contaminated area results from the evaporation of soil water in the contaminated zone, which is reasonable only when the contaminated area is infinitely large. In reality, HTO would be dispersed and diluted by moisture from outside the contaminated area, just like the soil particles emitted from the contaminated area. A more realistic estimate gives an air moisture concentration of 0.123 g/m^3 when considering the evaporation of soil water from the contaminated zone. This air moisture

TABLE 3.2-5 Comparison of Cancer Risks Associated with Water-independent Pathways at Time 0 – Total versus Parent Contributions[a]

	Water-independent Pathways														
	External Exposure			Inhalation			Ingestion of Produce			Ingestion of Soil			All Pathways		
Parent Nuclide	Total	Parent	Ratio (Total/ Parent)	Total	Parent	Ratio (Total/ Parent)	Total	Parent	Ratio (Total/ Parent)	Total	Parent	Ratio (Total/ Parent)	Total	Parent	Ratio (Total/ Parent)
Ac-227	8.21E-06	8.21E-06	1.00	1.28E-07	1.28E-07	1.00	2.46E-07	2.46E-07	1.00	7.25E-07	7.25E-07	1.00	9.31E-06	9.31E-06	1.00
Am-241	2.08E-07	2.08E-07	1.00	3.23E-08	3.23E-08	1.00	1.45E-09	1.45E-09	1.00	1.87E-07	1.87E-07	1.00	4.28E-07	4.28E-07	1.00
C-14	7.79E-13	7.79E-13	1.00	2.96E-11	2.96E-11	1.00	3.47E-08	3.47E-08	1.00	3.79E-11	3.79E-11	1.00	3.48E-08	3.48E-08	1.00
Co-60	2.74E-05	2.74E-05	1.00	2.69E-11	2.69E-11	1.00	2.76E-08	2.76E-08	1.00	1.21E-08	1.21E-08	1.00	2.75E-05	2.75E-05	1.00
Cs-137	1.48E-05	1.48E-05	1.00	8.00E-11	8.00E-11	1.00	4.18E-07	4.18E-07	1.00	3.59E-08	3.59E-08	1.00	1.53E-05	1.53E-05	1.00
H-3	0.00E+00	0.00E+00	NA[b]	8.54E-10	8.54E-10	1.00	4.65E-09	4.65E-09	1.00	3.19E-12	3.19E-12	1.00	5.50E-09	5.50E-09	1.00
I-129	4.99E-09	4.99E-09	1.00	1.51E-11	1.51E-11	1.00	6.35E-09	6.35E-09	1.00	3.04E-08	3.04E-08	1.00	4.18E-08	4.18E-08	1.00
Np-237	6.80E-06	6.80E-06	1.00	2.70E-08	2.70E-08	1.00	1.36E-07	1.36E-07	1.00	1.58E-07	1.58E-07	1.00	7.12E-06	7.12E-06	1.00
Pa-231	4.84E-06	9.79E-07	4.94	1.30E-07	6.97E-08	1.86	1.41E-06	1.29E-06	1.09	6.64E-07	3.23E-07	2.05	7.04E-06	2.66E-06	2.64
Pb-210	2.36E-08	2.36E-08	1.00	1.97E-08	1.97E-08	1.00	1.31E-05	1.31E-05	1.00	3.79E-06	3.79E-06	1.00	1.70E-05	1.70E-05	1.00
Pu-239	1.69E-09	1.69E-09	1.00	5.24E-08	5.24E-08	1.00	9.74E-10	9.74E-10	1.00	2.55E-07	2.55E-07	1.00	3.10E-07	3.10E-07	1.00
Pu-241	3.11E-09	6.02E-11	51.63	9.40E-10	4.65E-10	2.02	2.86E-11	7.27E-12	3.93	4.48E-09	1.73E-09	2.58	8.55E-09	2.27E-09	3.77
Ra-226	6.38E-05	6.38E-05	1.00	3.49E-08	2.60E-08	1.34	1.03E-05	4.37E-06	2.36	2.46E-06	7.39E-07	3.33	7.66E-05	6.89E-05	1.11
Ra-228	2.64E-05	9.46E-06	2.79	5.27E-08	1.24E-08	4.23	3.89E-06	3.76E-06	1.04	9.13E-07	6.70E-07	1.36	3.12E-05	1.39E-05	2.25
Sr-90	1.08E-07	1.08E-07	1.00	2.91E-10	2.91E-10	1.00	3.82E-06	3.82E-06	1.00	1.08E-07	1.08E-07	1.00	4.03E-06	4.03E-06	1.00
Tc-99	4.39E-11	4.39E-11	1.00	2.38E-12	2.38E-12	1.00	1.76E-07	1.76E-07	1.00	5.37E-10	5.37E-10	1.00	1.77E-07	1.77E-07	1.00
Th-230	3.69E-07	6.81E-09	54.27	3.24E-08	3.22E-08	1.01	1.78E-07	1.29E-07	1.38	1.97E-07	1.86E-07	1.06	7.76E-07	3.54E-07	2.20
U-234	2.14E-09	2.11E-09	1.01	2.55E-08	2.55E-08	1.00	2.94E-07	2.94E-07	1.00	1.61E-07	1.61E-07	1.00	4.83E-07	4.83E-07	1.00
U-235	4.47E-06	4.47E-06	1.00	2.29E-08	2.29E-08	1.00	3.01E-07	3.01E-07	1.00	1.67E-07	1.67E-07	1.00	4.96E-06	4.96E-06	1.00
U-238	9.06E-07	9.06E-07	1.00	2.17E-08	2.17E-08	1.00	3.72E-07	3.72E-07	1.00	2.13E-07	2.13E-07	1.00	1.51E-06	1.51E-06	1.00

[a] Ratios greater than 1.3 are highlighted with a yellow background.

[b] NA – not applicable.

concentration accounts for just 0.2% of the total moisture concentration of 6 g/m^3. Therefore, the PRG Calculator overestimates the potential cancer risk associated with the inhalation of H-3 by a factor of about 50 (calculated value 48.6 = 6/0.123) in this comparison due to the adoption of an overly conservative assumption.

The 0.123-g/m^3 air moisture concentration was obtained with the following procedure. Based on the assumed precipitation rate (0.5 m/yr), irrigation rate (0.3303 m/yr), runoff coefficient (0.2), and evapotranspiration coefficient (0.5), a water evaporation rate of 0.365 m/yr was calculated (with Eq. E-4 of the RESRAD User's Manual [Yu et al. 2001]). Assuming a water density of 1 g/cm^3, the emission flux (Q) of water vapor from a contaminated area of 2,000 m^2 assumed for this comparison would be 0.01158 g/m^2-s [(0.365 m/yr × 1,000,000 cm^3/m^3 × 1 g/cm^3/(8,760 h/yr × 3,600 s/h)]. Assuming the emitted water vapor was dispersed in the air like the emitted soil particles, then the dispersion factor, C_{wind}/Q [0.010664 (kg/m^3)/(g/m^2-s) = 10.664 (g/m^3)/(g/m^2-s)], calculated by the PRG Calculator could be applied to obtain the air moisture concentration resulting from the evaporation of soil water in the contaminated zone, which is 0.123 g/m^3 [0.1158 g/m^2-s × 10.664 (g/m^2)/(g/m^2-s)].

3.2.5 Consideration of the Resuspension Mechanism for Produce Contamination

With soils being contaminated by radionuclides, vegetation growing in the soils could uptake radionuclides and become contaminated. The uptake of radionuclides is contributed by two mechanisms, root absorption and resuspension. Both mechanisms are modeled by the PRG Calculator and RESRAD.

In general, the root absorption mechanism is considered a significant mechanism for radionuclide uptake by vegetation, especially for radionuclides that could dissolve in water. However, this is not what was observed with the PRG Calculator. The PRG Calculator uses a root uptake multiplier (equivalent to root uptake transfer factor, Bv_{wet}) and a soil resuspension multiplier (equivalent to produce plant Mass Loading Factor [MLF]) to relate the concentration of radionuclide in vegetation as contributed by the two mechanisms to the concentration of radionuclide in soils. Note that the MLF used in the PRG Calculator is dimensionless, and it is different from the mass loading (ML_{prod}) used in RESRAD that has a unit of g/m^3. Table 3.2-6 compares the default Bv_{wet}'s and MLF used by the PRG Calculator. As the ratios of MLF/Bv_{wet} indicate, the resuspension mechanism is far more important than the root uptake mechanism (by a factor ranging from 2.72 to 31,400, excluding C-14, H-3, and Tc-99).

A default value of 0.26 for the MLF is used by the PRG Calculator, which indicates that the mass of soil particles deposited and retained on plant leaves is 26% of the total mass of the plants, regardless of the type of plant (i.e., a leafy vegetable or grain). Although such a high level of soil deposition might be seen for some types of vegetation during their growth, not all radionuclides in the deposited soil would be absorbed and translocated to edible plant tissues during the growth period. Furthermore, with such a high level of soil deposition, washing the vegetation before eating or cooking would be inevitable. The PRG Calculator does not adjust the MLF with an absorption fraction, a translocation factor, or a removal factor for washing; therefore, it could overestimate radionuclide concentrations in produce by orders of magnitude.

TABLE 3.2-6 Comparison of the Default Root Uptake Transfer Factors and Produce Plant Mass Loading Factors in the PRG Calculator

Radionuclide	Root Uptake Transfer Factor ($B_{v,wet}$)	Produce Plant *MLF*	Ratio ($MLF/B_{v,wet}$)
Ac-227	1.00E-03	0.26	2.60E+02
Am-241	1.91E-05	0.26	1.36E+04
C-14	5.50E+00	0.26	3.73E-02
Co-60	7.40E-03	0.26	3.51E+01
Cs-137	2.52E-02	0.26	1.03E+01
H-3	4.80E+00	0.26	5.42E-02
I-129	5.48E-04	0.26	4.74E+02
Np-237	2.52E-03	0.26	1.03E+02
Pa-231	1.00E-02	0.26	2.60E+01
Pb-210	9.57E-03	0.26	2.72E+01
Pu-239, Pu-241	8.27E-06	0.26	3.14E+04
Ra-226, Ra-228	1.48E-02	0.26	1.76E+01
Sr-90	9.57E-02	0.26	2.72E+00
Tc-99	1.13E+00	0.26	2.30E-01
Th-230	1.83E-03	0.26	1.42E+02
U-234, U-235, U-238	5.39E-03	0.26	4.82E+01

No wonder that for 17 out of the 20 radionuclides (except for Co-60, Cs-137, and H-3) selected for this comparison, the most critical exposure pathway for determining the soil PRG is the ingestion of produce pathway, according to Table 3.2-1.

3.2.6 Comparison of Cancer Risk Modeling for Each Exposure Pathway

RESRAD performs time-dependent modeling and evaluates potential radiation exposures and cancer risks at current time (time 0) as well as at many future times determined by input specifications of the users. The PRG Calculator, on the other hand, evaluates only the exposures and cancer risks at current time. To investigate the modeling differences between RESRAD and the PRG Calculator in each exposure pathway, the RESRAD results at time 0 were used for comparison with the PRG Calculator's results. However, the potential issues associated with limiting radiation exposure and cancer risk modeling to the current time should be recognized (see the discussion in Section 3.2.3).

In the following sections, Sf is used to represent a slope factor, while SF is used to represent a source correction factor in the RESRAD modeling.

3.2.6.1 External Exposure Pathway

The equations used by the PRG Calculator to calculate cancer risk associated with each initially present radionuclide in soil from the external exposure pathway are given below. The PRG equations available at the PRG Calculator's website are for the derivation of soil PRGs based on a TR level. To facilitate comparison with RESRAD, the corresponding cancer risk equations were obtained by taking the ratio between the TR and the soil PRG (to obtain the risk-to-source ratio) and then multiplying the ratio with the initial soil concentration, that is, $C_s(0)$.

$$Risk_{res-soil-ext} = C_{res-soil-avg} \times \left(\frac{ET_{r-o}}{24} \times GSF_o + \frac{ET_{r-i}}{24} \times GSF_i\right) \times \frac{EF_r}{365} \times \times ED_r \times ACF_{ext-sv} \times Sf_{ext-sv}$$

$$C_{res-soil-avg} = C_{soil}(0) \times CF_{res-soil} = C_{soil}(0) \times \frac{(1 - e^{-\lambda \times ED_r})}{\lambda \times ED_r}$$

where

$Risk_{res-soil-ext}$ = cancer risk to resident from the external exposure pathway;

$C_{res-soil-avg}$ = average soil concentration (of the parent nuclide) over the exposure duration of the resident (pCi/g);

ET_{r-o} = exposure time outdoors for residents (h/d);

ET_{r-i} = exposure time indoors for residents (h/d);

24 = conversion factor (h/d);

GSF_o = groundshine shielding factor outdoors;

GSF_i = groundshine shielding factor indoors;

ED_r = exposure duration for residents (yr);

EF_r = exposure frequency for residents (d/yr);

365 = conversion factor (d/yr);

Sf_{ext-sv} = external exposure slope factor, volume source [(1/yr)/(pCi/g)];

$ACF_{ext-res}$ = area and cover factor for external exposure;

$CF_{res-soil}$ = correction factor for soil concentration for resident exposure;

λ = radiological decay constant (1/yr); and

$C_{soil}(0)$ = initial soil concentration (pCi/g).

The default value of GSF_o is 1. For nuclides with the suffix "+D", the Sf_{ext-sv} is the sum of its Sf and the Sfs of its short-lived progenies. The average soil concentration is obtained by adjusting the initial concentration, $C_{soil}(0)$, with a correction factor, $CF_{res-soil}$, for radiological decay.

As mentioned previously, RESRAD tracks the formation and environmental distributions of each long-lived progeny and adds their risk contributions to that of the parent nuclide. The following equations describe the calculations performed by RESRAD:

$$Risk_{res-soil-ext} = [f_{otd} + (f_{ind} \times F_{sh})] \times FS_{ext} \times \sum_j [\int_0^{ED_r} C_{j-soil}(t) \times FCD_{j-ext}(t)\, dt] \times FA_{j-ext} \times Sf_{j-ext-sv}$$

$$C_{j-soil}(t) = C_{soil}(0) \times SF_j(t)$$

where

f_{otd} = annual outdoor time fraction;

f_{ind} = annual indoor time fraction;

F_{sh} = groundshine shielding factor indoors;

FS_{ext} = external exposure shape factor;

j = index for radionuclides, including the parent and short-lived and long-lived progenies;

$C_{j-soil}(t)$ = soil concentration of nuclide *j* at time *t* (pCi/g);

$FCD_{j-ext}(t)$ = external exposure cover and depth factor for nuclide *j* at time *t*;

FA_{j-ext} = external exposure area factor for nuclide *j*;

$Sf_{j-ext-sv}$ = external exposure slope factor for nuclide *j*, volume source [(1/yr)/(pCi/g)]; and

$SF_j(t)$ = source factor for nuclide *j* at time *t*.

RESRAD considers that a contaminated area may assume a different shape other than a circle and uses a shape factor, FS_{ext}, to adjust the external exposure calculated from a circular area of the same size to obtain an estimate of external exposure for the contaminated area. The PRG Calculator does not consider the shape of the contaminated area; it assumes that it has a circular shape to maximize the external exposure. In this comparison, FS_{ext} was set to 1 to comply with the assumption of the PRG Calculator. In addition to the shape and area, the bulk density and thickness of the contaminated zone and the cover layer can also affect the intensity of external radiation. While RESRAD allows the specifications of bulk densities, the PRG Calculator does not, fixing both densities at 1.5 g/cm^3. In RESRAD, any cover thickness of less than 100 m and any contamination thickness of less than 1,000 m can be specified. In the PRG Calculator, the cover thickness has to be one of the nine pre-determined values ranging from 0 to 1 m. As to the thickness of the contaminated zone, it is beyond the user's control; that is, it is not an input parameter. The PRG Calculator assumes that the intensity of external radiation from the contaminated zone is the same as that from an infinitely thick volume source. A separate calculation for the external exposure pathway can be performed with the PRG Calculator by choosing "2-D External Exposure" rather than "soil" as the medium of concern for the Resident Scenario, and the results for a soil source with a thickness of 0 cm, 1 cm, 5 cm, or 15 cm will be calculated. However, users have to manually combine the results for the external exposure pathway with the results for the other pathways (obtained by choosing "soil" as the medium of concern) to derive the total soil PRGs. To simplify the comparison, no cover layer was considered above the contaminated zone and the thickness of contamination was set to 2 m; such a radiation source would emit external radiation with intensity about the same as that from an infinitely thick source. These settings gave FCD_{j-ext} a value of 1 for all the radionuclides studied.

Because different radionuclides decay with different types of radiation (α, β, and γ) and energies, the values of the Area Factor, FA_{ext}, for different radionuclides could be different. (The values of FCD_{ext} could be different, also, but not in this comparison.) To obtain more precise estimates of cancer risk, in RESRAD, the cancer risk contribution from each nuclide in a decay chain (including the parent nuclides and short- and long-lived progenies) is evaluated separately, with its own soil concentration (C_{soil}), FA_{ext}, and slope factor (Sf_{ext-sv}). The secular equilibrium principle is applied to obtain soil concentrations for short-lived progenies (with a radiological decay half-life of less than 6 months, i.e., 180 days, in this comparison). The soil concentration of a parent nuclide or a long-lived progeny in the decay chain at any time t is obtained by adjusting the initial concentration of the parent nuclide, $C_{soil}(0)$, with a source factor, SF, that accounts for radiological decay/ingrowth as well as leaching. The total cancer risk from the external exposure pathway for the initially present nuclide can be written as the sum of cancer risk from itself and its immediate short-lived progenies, and the cancer risk from long-lived nuclides in the decay chain and their immediate short-lived progenies. The cancer risk equation for RESRAD can be rewritten as follows:

$$
\begin{aligned}
Risk_{res-soil-ext} &= Risk_{p-res-soil-ext} + Risk_{l-res-soil-ext} \\
&= C_{p-res-soil-avg} \times [f_{otd} + (f_{ind} \times F_{sh})] \times ED_r \\
&\times \sum_{k} (FA_{k-ext} \times Sf_{k-ext-sv}) \\
&+ \sum_{l} C_{l-res-soil-avg} \times [f_{otd} + (f_{ind} \times F_{sh})] \times ED_r \\
&\times \sum_{m} (FA_{m-ext} \times Sf_{m-ext-sv})
\end{aligned}
$$

$$
C_{p\ or\ l-res-soil-avg} = C_{soil}(0) \times SF_{p\ or\ l-res-avg} = C_{soil}(0) \times \int_0^{ED_r} SF_{p\ or\ l}(t)dt \ / \ ED_r
$$

where

p = parent nuclide;

l = index for long-lived progenies in the decay chain;

k = index for the immediate short-lived progenies of the parent nuclide;

m = index for the immediate short-lived progenies of a long-lived nuclide l in the decay chain;

$Risk_{p-res-soil-ext}$ = cancer risk to residents from the external exposure pathway, contributed by the parent and its immediate short-lived progenies;

$Risk_{l-res-soil-ext}$ = cancer risk to residents from the external exposure pathway, contributed by long-lived nuclides and their immediate short-lived progenies;

$C_{p\ or\ l-res-soil-avg}$ = average soil concentration of the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of residents (pCi/g); and

$SF_{p\ or\ l-res-avg}$ = average source factor for the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of residents.

For this comparison, the value of F_{sh} was set to the value of GSF_i used for soil PRG derivations. The values of f_{otd} and f_{ind} were selected so that the annual exposure hours indoors and outdoors considered by RESRAD matched those considered by the PRG Calculator with the use of ET_{r-o}, ET_{r-i}, and EF_r (see Table 3.1-1 for their values.) With such selections, the ratio of the cancer risk from the parent nuclide and its immediate short-lived progenies, ($Risk_{p-res-soil-ext}$), calculated by RESRAD, to the cancer risk calculated by the PRG Calculator, would equal the ratio of $[SF_{p-res-avg} \times (\sum_k FA_{k-ext} \times Sf_{k-ext-sv})]$ with the RESRAD code, to $(CF_{res-soil} \times ACF \times Sf_{ext-sv})$ with the PRG Calculator. Table 3.2-7 compares the final cancer risk results (based on an initial soil concentration of 1 pCi/g) obtained

TABLE 3.2-7 Comparison of the External Exposure Cancer Risks at the Current Time for the Resident Scenario[a]

Parent Nuclide	Cancer Risk RESRAD Result (total)	Cancer Risk RESRAD Result (parent and its short-lived progenies)	Cancer Risk PRG Result	Calculated Ratio (RESRAD total /PRG)	Calculated Ratio (RESRAD parent and short-lived progenies/PRG)
Ac-227	8.21E-06	8.21E-06	1.14E-09	7.20E+03	7.20E+03
Am-241	2.08E-07	2.08E-07	2.04E-07	1.02E+00	1.02E+00
C-14	7.79E-13	7.79E-13	6.10E-11	1.28E-02	1.28E-02
Co-60	2.74E-05	2.74E-05	2.58E-05	1.06E+00	1.06E+00
Cs-137	1.48E-05	1.48E-05	1.39E-05	1.07E+00	1.07E+00
H-3	0.00E+00	0.00E+00	0.00E+00	–[b]	–
I-129	4.99E-09	4.99E-09	4.58E-08	1.09E-01	1.09E-01
Np-237	6.80E-06	6.80E-06	6.04E-06	1.13E+00	1.13E+00
Pa-231	4.84E-06	9.79E-07	9.30E-07	5.20E+00	1.05E+00
Pb-210	2.36E-08	2.36E-08	7.94E-09	2.97E+00	2.97E+00
Pu-239	1.69E-09	1.69E-09	1.81E-09	9.31E-01	9.31E-01
Pu-241	3.11E-09	6.02E-11	1.49E-11	2.08E+02	4.04E+00
Ra-226	6.38E-05	6.38E-05	6.08E-05	1.05E+00	1.05E+00
Ra-228	2.64E-05	9.46E-06	9.20E-06	2.87E+00	1.03E+00
Sr-90	1.08E-07	1.08E-07	1.25E-07	8.65E-01	8.65E-01
Tc-99	4.39E-11	4.39E-11	5.60E-10	7.84E-02	7.84E-02
Th-230	3.69E-07	6.81E-09	7.03E-09	5.25E+01	9.68E-01
U-234	2.14E-09	2.11E-09	2.19E-09	9.79E-01	9.65E-01
U-235	4.47E-06	4.47E-06	3.68E-06	1.21E+00	1.21E+00
U-238	9.06E-07	9.06E-07	8.81E-07	1.03E+00	1.03E+00

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios in the last column are shown in red if they are very different from 1.

[b] A dash indicates not applicable.

from RESRAD and the PRG Calculator. Table 3.2-8 lists the intermediate variables calculated and the ratios of the variables.

Comparing the ratios of cancer risk listed in the last two columns of Table 3.2-7 for each radionuclide, the ratios are very different for Pa-231, Pu-241, Ra-228, and Th-230, which indicates that long-lived progenies made significant cancer risk contributions. The PRG Calculator does not account for long-lived progenies. Therefore, the cancer risks it calculated for these four radionuclides are much lower than the total cancer risks calculated by RESRAD by a factor ranging from 3 to 210 (calculated range 2.87 to 208). Excluding long-lived nuclides and their immediate short-lived progenies and comparing the cancer risks just from the parent

TABLE 3.2-8 Intermediate Variables Calculated for the External Exposure Pathway and Their Ratios[a]

Parent Nuclide	RESRAD FA_{p-ext}	PRG ACF_{ext-sv}	Ratio FA_{p-ext}/ACF_{ext-sv}	Ratio $SF_{p-res-avg}$ / $CF_{res-soil}$	Ratio $(\sum_k FA_{k-ext} \times Sf_{k-ext-sv})$ / $(ACF \times Sf_{ext-sv})$	Ratio $[SF_{p-res-avg} \times (\sum_k FA_{k-ext} \times Sf_{k-ext-sv})]$ / $(CF_{res-soil} \times ACF \times Sf_{ext-sv})$	Ratio of Cancer Risks (RESRAD parent and short-lived progenies/PRG)
Ac-227	0.944	0.98	0.96	9.36E-01	7.70E+03	7.20E+03	7.20E+03
Am-241	0.956	0.872	1.10	9.26E-01	1.10E+00	1.02E+00	1.02E+00
C-14	0.939	0.9	1.04	9.86E-03[b]	1.04E+00	1.03E-02	1.28E-02
Co-60	0.906	0.852	1.06	9.99E-01	1.06E+00	1.06E+00	1.06E+00
Cs-137	0.92	0.843	1.09	1.00E+00	1.07E+00	1.07E+00	1.07E+00
H-3	1	0.9	1.11	6.00E-02[c]	–[d]	–	–
I-129	0.957	0.858	1.12	9.77E-02	1.12E+00	1.09E-01	1.09E-01
Np-237	0.957	0.818	1.17	9.98E-01	1.13E+00	1.12E+00	1.13E+00
Pa-231	0.92	0.846	1.09	9.69E-01	1.09E+00	1.05E+00	1.05E+00
Pb-210	0.999	0.905	1.10	9.86E-01	3.02E+00	2.98E+00	2.97E+00
Pu-239	0.935	1	0.94	9.99E-01	9.35E-01	9.34E-01	9.31E-01
Pu-241	0.929	0.746	1.25	9.99E-01	4.04E+00	4.04E+00	4.04E+00
Ra-226	0.923	0.846	1.09	9.78E-01	1.07E+00	1.05E+00	1.05E+00
Ra-228	1	0.864	1.16	9.88E-01	1.04E+00	1.03E+00	1.03E+00
Sr-90	0.923	1	0.92	9.55E-01	9.04E-01	8.63E-01	8.65E-01
Tc-99	0.928	0.782	1.19	6.61E-02	1.19E+00	7.84E-02	7.84E-02
Th-230	0.932	0.962	0.97	1.00E+00	9.69E-01	9.69E-01	9.68E-01
U-234	0.998	1	1.00	9.69E-01	9.98E-01	9.67E-01	9.65E-01
U-235	0.923	0.74	1.25	9.69E-01	1.25E+00	1.21E+00	1.21E+00
U-238	0.951	0.856	1.11	9.69E-01	1.06E+00	1.03E+00	1.03E+00

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios of the intermediate variables (listed in the 5th and 6th columns) are shown in red if their values are very different from 1.

[b] In addition to radiological decay and leaching, RESRAD considers the loss of C-14 in soil through volatilization, which is accounted for with the listed $SF_{p-res-avg}$.

[c] RESRAD incorporates a special model to consider evaporation of HTO from the contaminated zone. In RESRAD, the value of $SF_p(t)$ accounts for the loss through evaporation, in addition to loss through decay/ingrowth and leaching. Although the PRG Calculator also considers evaporation of HTO, according to the available equations, the adjustment of initial soil concentration (with $CF_{res-soil}$) only considers loss through radiological decay.

[d] A dash indicates ratios were not calculated because the external exposure cancer risks calculated by RESRAD and the PRG Calculator were zero.

nuclide and its immediate short-lived progenies, the results from RESRAD and the PRG Calculator are still very different for Ac-227, C-14, I-129, Pb-210, Pu-241, and Tc-99, because the ratios listed in the last column are very different from 1, the supposed ratio if the results were the same. The intermediate variables and their ratios listed in Table 3.2-8 provide explanations for the differences.

In Table 3.2-8, the ratios of $[SF_{p-res-avg} \times (\sum_k FA_{k-ext} \times Sf_{k-ext-sv})]$ (with RESRAD) to $(CF_{res-soil} \times ACF \times Sf_{ext-sv})$ (with the PRG Calculator) as listed in the second from last column are almost the same as the ratios of cancer risk (RESRAD parent and short-lived progenies/PRG) listed in the last column, except for C-14. This consistency confirms that the differences in cancer risks, RESRAD parent and short-lived progenies versus PRG, can be explained with the ratios of the intermediate variables used in the calculations.

For Ac-227, Pb-210, and Pu-241, the differences in cancer risks are due to the differences between $(\sum_k FA_{k-ext} \times Sf_{k-ext-sv})$ (with RESRAD) and $(ACF \times Sf_{ext-sv})$ (with the PRG Calculator). Because FAs and ACFs for individual nuclides agree fairly well (within 25%), it is the values of *Sf* that cause the significant differences in cancer risks. As pointed out in Section 3.2.1, the PRG Calculator fails to include the *Sf*s of the immediate short-lived progenies with the *Sf*s of these three radionuclides.

For I-129 and Tc-99, the differences in cancer risks are due to the differences between $SF_{p-res-avg}$ (with RESRAD) and $CF_{res-soil}$ (with the PRG Calculator). The PRG Calculator does not consider the loss of radionuclides in soil through leaching. Therefore, the potential cancer risk associated with external exposure to I-129 and Tc-99 are greatly overestimated.

For C-14, the difference in cancer risk could not be explained completely with the ratio of $SF_{p-res-avg}$ (with RESRAD) to $CF_{res-soil}$ (with the PRG Calculator) shown in Table 3.2-8. Whether the PRG Calculator considers volatilization of C-14, like RESRAD, and adjusts the equations presented in this section or the external exposure slope factor shown in Table 3.2-2 to calculate the associated cancer risk, is not clear. Therefore, further investigation cannot be conducted.

3.2.6.2 Inhalation Pathway (Excluding Radon)

The PRG Calculator does not model the emission of radon (Rn-220 and Rn-222) from soils contaminated with radon precursors, that is, Ra-226, Th-228, and other radionuclides that can generate them. Therefore, the comparison of modeling for the inhalation pathway focuses on the emission of contaminated soil (dust) particles and the cancer risks associated with inhalation of airborne particles.

The PRG Calculator uses the following equations to calculate cancer risk associated with each initially present radionuclide in soil from the inhalation pathway:

$$Risk_{res-soil-inh} = C_{res-soil-avg} \times \frac{1}{PEF_w} \times 1{,}000 \times IFA_{r-adj} \times Sf_i$$

$$IFA_{r-adj} = IRA_c \times \frac{ET_{r-c}}{24} \times EF_{r-c} \times ED_{r-c} + IRA_a \times \frac{ET_{r-a}}{24} \times EF_{r-a} \times ED_{r-a}$$

$$\frac{1}{PEF_w} = \frac{C_{wind}}{Q} \times \frac{0.036 \times (1 - \mathrm{V}) \times (U_m/U_t)^3 \times F(x)}{3{,}600}$$

$$C_{res-soil-avg} = C_{soil}(0) \times CF_{res-soil} = C_{soil}(0) \times \frac{(1 - e^{-\lambda \times ED_r})}{\lambda \times ED_r}$$

where

$Risk_{res-soil-inh}$ = cancer risk to the resident from the inhalation pathway;

$C_{res-soil-avg}$ = average soil concentration (of the parent nuclide) over the exposure duration of residents (pCi/g);

PEF_w = particulate emission factor, due to wind erosion (m^3/kg);

1,000 = conversion factor (g/kg);

IFA_{r-adj} = age-adjusted inhalation factor of air for residents (m^3);

Sf_i = slope factor for inhalation (1/pCi);

IRA_c = daily inhalation rate of air, child (m^3/d);

IRA_a = daily inhalation rate of air, adult (m^3/d);

ET_{r-c} = exposure time of residents, child (h/d);

ET_{r-a} = exposure time of residents, adult (h/d);

EF_{r-c} = exposure frequency of residents, child (d/yr);

EF_{r-a} = exposure frequency of residents, adult (d/yr);

ED_{r-c} = exposure duration of residents, child (yr);

ED_{r-a} = exposure duration of residents, adult (yr);

24 = conversion factor (h/d);

C_{wind} = mean air concentration of contaminated soil particles at the center of the contaminated area, wind erosion (kg/m^3);

Q = flux of soil particles emitted from the contaminated area (g/m^{2-s});

V = fraction of vegetative cover;

U_m = mean annual wind speed (m/s);

U_t = equivalent threshold value of wind speed at 7 m (m/s);

F(x) = derived function of x (= 0.886 × U_t/U_m);

3,600 = conversion factor (s/h);

$CF_{res-soil}$ = correction factor for soil concentration for resident exposure;

λ = radiological decay constant (1/yr); and

$C_{soil}(0)$ = initial soil concentration (pCi/g).

The reciprocal of the particulate emission factor ($1/PEF_w$) gives the air concentration of soil particles that are emitted from the contaminated area. Its value is dependent on the emission flux (the second term on the right of the equation) and the extent of dispersion (C_{wind}/Q) in the air. The emission flux is dependent on wind speed (U_m) and the fraction of vegetative cover (V). The extent of dispersion is a function of U_m and the size of the contaminated area. The PRG Calculator assumes that the air concentration of contaminated soil particles is the same indoors and outdoors. It does not check to ensure that the amounts of time spent indoors and outdoors specified for the inhalation pathway are consistent with those specified for the external exposure pathway. Also, a cover layer (with its thickness as input) that can be considered to reduce external radiation is not considered for reducing the inhalation exposure. This inconsistency may be resolved by carefully selecting the fraction of vegetative cover to simulate the effect of a cover layer; however, users need to determine the effect of a cover layer on their own.

The calculations performed by RESRAD for the inhalation pathway can be described with the following equations:

$$Risk_{res-soil-inh} = [f_{otd} + (f_{ind} \times F_{dust})] \times FI_{inh} \times ML_{inh} \times FA_{inh} \times \sum_j [\int_0^{ED_r} C_{j-soil}(t) \times FCD_{inh}(t)\, dt] \times Sf_{j-i}$$

$$C_{j-soil}(t) = C_{soil}(0) \times SF_j(t)$$

where

f_{otd} = annual outdoor time fraction;

f_{ind} = annual indoor time fraction;

F_{dust} = dust filtration factor (i.e., ratio of airborne dust level indoors to outdoors);

FI_{inh} = annual inhalation rate of air (m^3/yr);

ML_{inh} = mass loading of dust particles for inhalation (g/m^3);

FA_{inh} = area correction factor for inhalation;

j = index for radionuclides, including the parent and long-lived progenies;

$C_{j-soil}(t)$ = soil concentration of nuclide *j* at time *t* (pCi/g);

$FCD_{inh}(t)$ = cover and depth factor for inhalation at time *t*;

Sf_{j-i} = inhalation slope factor for nuclide *j*, including contributions from short-lived progenies (1/pCi); and

$SF_j(t)$ = source factor for nuclide *j* at time *t*.

In RESRAD, the exposure times spent indoors and outdoors considered for the inhalation pathway are the same as those considered for the external exposure pathway. The indoor airborne dust level could be less than the outdoor level when the dust filtration factor, F_{dust}, is given a value of less than 1. For the comparison, a value of 1 was used to be consistent with the assumption in the PRG Calculator. The cover layer above the contaminated zone that is considered for reducing external radiation is also considered for reducing the inhalation exposure in RESRAD. Due to the cover, the soil particles in the surface layer that are susceptible to wind erosion may not be contaminated or are less contaminated, that is, of a lower concentration than soil particles in the contaminated zone. The level of reduction in the inhalation exposure, compared with that without the cover, is dependent on the thicknesses of the cover and the contaminated zone relative to the thickness of mixing, which can be specified an input value. For this comparison, the default thickness of mixing was used which, when combined with the assumptions of no cover and 2 m of soil contamination, gave the cover and depth factor, $FCD_{inh}(t)$, a value of 1 at all times.

The approach used by RESRAD to estimate the air concentration of contaminated dust particles is different from that used by the PRG Calculator. Rather than calculating the emission rate of soil particles from the contaminated area and the subsequent dispersion, it accepts the input of an empirical mass loading factor for dust particles, ML_{inh}, that is, air concentration of dust particles, and multiplies ML_{inh} with an area factor, FA_{inh}, which is the fraction of ML_{inh} coming from the contaminated area. The value of FA_{inh} calculated by RESRAD is dependent on the area of contamination and average wind speed.

The total cancer risk associated with the inhalation pathway that RESRAD calculates at time 0 includes contributions from the parent nuclide (including its short-lived progenies) and from long-lived nuclides in the decay chain (including their short-lived progenies). Therefore, the cancer risk equation shown above can be written as follows:

$$Risk_{res-soil-inh} = Risk_{p-res-soil-inh} + Risk_{l-res-soil-inh}$$
$$= C_{p-res-soil-avg} \times (f_{otd} + f_{ind}) \times ED_r \times FI_{inh} \times ML_{inh} \times FA_{inh} \times Sf_{p-i}$$
$$+ \sum_l C_{l-res-soil-avg} \times (f_{otd} + f_{ind}) \times ED_r \times FI_{inh} \times ML_{inh} \times FA_{inh} \times Sf_{l-i}$$

$$C_{p\ or\ l-res-soil-avg} = C_{soil}(0) \times SF_{p\ or\ l-res-avg} = C_{soil}(0) \times \int_0^{ED_r} SF_{p\ or\ l}(t)dt\ /\ ED_r$$

where

p = parent nuclide;

l = index for long-lived progenies in the decay chain;

$Risk_{p-res-soil-inh}$ = cancer risk to residents from the inhalation pathway, contributed by the parent and its immediate short-lived progenies;

$Risk_{l-res-soil-inh}$ = cancer risk to residents from the inhalation pathway, contributed by long-lived nuclides and their immediate short-lived progenies;

$C_{p\ or\ l-res-soil-avg}$ = average soil concentration of the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of residents (pCi/g); and

$SF_{p\ or\ l-res-avg}$ = average source factor for the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of residents.

For this comparison, the annual inhalation rate of air, FI_{inh}, was selected so that with f_{otd}, f_{ind}, and ED_r, the total volume of air inhaled used by RESRAD for the exposure calculation matched the value of IF_{r-adj} used by the PRG Calculator (see Table 3.1-1 for their values.) With such a selection, the ratio of the cancer risk from the parent nuclide and its immediate short-lived progenies, ($Risk_{p-res-soil-inh}$), calculated by RESRAD, to the cancer risk calculated by the PRG Calculator, would equal the ratio of ($SF_{p-res-avg} \times ML_{inh} \times FA_{inh} \times Sf_{p-i}$) with the RESRAD code, to ($CF_{res-soil} \times 1{,}000/PEF_w \times Sf_i$) with the PRG Calculator. Table 3.2-9 compares the final cancer risk results (based on an initial soil concentration of 1 pCi/g) obtained from RESRAD and the PRG Calculator. Table 3.2-10 lists the intermediate variables calculated and the ratios of the variables.

TABLE 3.2-9 Comparison of Inhalation Cancer Risks at the Current Time for the Resident Scenario[a]

Parent Nuclide	Cancer Risk RESRAD Result (total)	Cancer Risk RESRAD Result (parent and its short-lived progenies)	Cancer Risk PRG Result	Calculated Ratio (RESRAD total/PRG)	Calculated Ratio (RESRAD parent and short-lived progenies/PRG)
Ac-227	1.28E-07	1.28E-07	1.20E-08	1.07E+01	1.07E+01
Am-241	3.23E-08	3.23E-08	4.38E-09	7.38E+00	7.38E+00
C-14	2.96E-11	2.96E-11	2.00E-12	1.48E+01	1.48E+01
Co-60	2.69E-11	2.69E-11	3.37E-12	7.97E+00	7.97E+00
Cs-137	8.00E-11	8.00E-11	1.00E-11	8.00E+00	8.00E+00
H-3	8.54E-10	8.54E-10	4.22E-06	2.02E-04	2.02E-04
I-129	1.51E-11	1.51E-11	1.94E-11	7.77E-01	7.77E-01
Np-237	2.70E-08	2.70E-08	3.40E-09	7.95E+00	7.95E+00
Pa-231	1.30E-07	6.97E-08	9.02E-09	1.44E+01	7.73E+00
Pb-210	1.97E-08	1.97E-08	1.29E-09	1.52E+01	1.52E+01
Pu-239	5.24E-08	5.24E-08	6.57E-09	7.97E+00	7.97E+00
Pu-241	9.40E-10	4.65E-10	5.84E-11	1.61E+01	7.97E+00
Ra-226	3.49E-08	2.60E-08	3.32E-09	1.05E+01	7.82E+00
Ra-228	5.27E-08	1.24E-08	1.58E-09	3.33E+01	7.87E+00
Sr-90	2.91E-10	2.91E-10	3.81E-11	7.63E+00	7.63E+00
Tc-99	2.38E-12	2.38E-12	4.51E-12	5.27E-01	5.27E-01
Th-230	3.24E-08	3.22E-08	4.04E-09	8.01E+00	7.96E+00
U-234	2.55E-08	2.55E-08	3.30E-09	7.72E+00	7.72E+00
U-235	2.29E-08	2.29E-08	2.96E-09	7.74E+00	7.73E+00
U-238	2.17E-08	2.17E-08	2.80E-09	7.74E+00	7.74E+00

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios in the last column are shown in red if they are very different from 1.

A comparison of the ratios of cancer risk listed in the last two columns of Table 3.2-9 for each radionuclide shows that the ratios are very different for Pa-231, Pu-241, Ra-226, and Ra-228, which indicates that the long-lived progenies made significant cancer risk contributions. The PRG Calculator does not account for long-lived progenies; therefore, it may underestimate the actual cancer risk associated with inhalation exposure to these four radionuclides. Excluding long-lived progenies (and their immediate short-lived progenies) and comparing the cancer risks just from the parent nuclide and its immediate short-lived progenies (with the ratios listed in the last column), the results from RESRAD and the PRG Calculator are still very different for all radionuclides, except for I-129. The cancer risk calculated by RESRAD is about 8 times that calculated by the PRG Calculator for most radionuclides except for Ac-227, C-14, H-3, Pb-210, and Tc-99. The intermediate variables and their ratios listed in Table 3.2-10 provide explanations for the differences.

TABLE 3.2-10 Comparison of Intermediate Variables Used for the Inhalation Exposure Calculations[a]

Parent Nuclide	PRG PEF_w	RESRAD $ML_{inh} \times FA_{inh}$	Ratio $(ML_{inh} \times FA_{inh})$ / $(1{,}000/PEF_w)$	Ratio $SF_{p-res-avg}$ / $CF_{res-soil}$	Ratio RESRAD Sf_{p-i} / PRG Sf_i	Ratio $(SF_{p-res-avg} \times ML_{inh} \times FA_{inh} \times Sf_{p-i})$ / $(CF_{res-soil} \times 1{,}000/PEF_w \times Sf_i)$	Ratio of Cancer Risk (RESRAD parent and short-lived progenies/PRG)
Ac-227	1.36E+09	5.87E-06	7.98E+00	9.36E-01	1.43E+00	1.07E+01	1.07E+01
Am-241	1.36E+09	5.87E-06	7.98E+00	9.26E-01	1.00E+00	7.39E+00	7.38E+00
C-14	1.36E+09	–[b]	–	9.86E-03	1.00E+00	–	1.48E+01
Co-60	1.36E+09	5.87E-06	7.98E+00	9.99E-01	1.00E+00	7.97E+00	7.97E+00
Cs-137	1.36E+09	5.87E-06	7.98E+00	1.00E+00	1.00E+00	7.97E+00	8.00E+00
H-3	1.70E+01[c]	–	–	6.00E-02	1.00E+00	–	2.02E-04
I-129	1.36E+09	5.87E-06	7.98E+00	9.77E-02	1.00E+00	7.79E-01	7.77E-01
Np-237	1.36E+09	5.87E-06	7.98E+00	9.98E-01	1.00E+00	7.96E+00	7.95E+00
Pa-231	1.36E+09	5.87E-06	7.98E+00	9.69E-01	1.00E+00	7.73E+00	7.73E+00
Pb-210	1.36E+09	5.87E-06	7.98E+00	9.86E-01	1.94E+00	1.52E+01	1.52E+01
Pu-239	1.36E+09	5.87E-06	7.98E+00	9.99E-01	1.00E+00	7.97E+00	7.97E+00
Pu-241	1.36E+09	5.87E-06	7.98E+00	9.99E-01	1.00E+00	7.99E+00	7.97E+00
Ra-226	1.36E+09	5.87E-06	7.98E+00	9.78E-01	1.00E+00	7.80E+00	7.82E+00
Ra-228	1.36E+09	5.87E-06	7.98E+00	9.88E-01	1.00E+00	7.88E+00	7.87E+00
Sr-90	1.36E+09	5.87E-06	7.98E+00	9.55E-01	1.00E+00	7.61E+00	7.63E+00
Tc-99	1.36E+09	5.87E-06	7.98E+00	6.61E-02	1.00E+00	5.27E-01	5.27E-01
Th-230	1.36E+09	5.87E-06	7.98E+00	1.00E+00	1.00E+00	7.98E+00	7.96E+00
U-234	1.36E+09	5.87E-06	7.98E+00	9.69E-01	1.00E+00	7.73E+00	7.72E+00
U-235	1.36E+09	5.87E-06	7.98E+00	9.69E-01	1.00E+00	7.73E+00	7.73E+00
U-238	1.36E+09	5.87E-06	7.98E+00	9.69E-01	1.00E+00	7.73E+00	7.74E+00

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios of the intermediate variables (listed in the 4th, 5th, and 6th columns) are shown in red if their values are very different from 1.

[b] A dash indicates that RESRAD uses special models to consider evaporation/volatilization of C-14 and H-3, which do not involve the use of ML_{inh} and FA_{inh}. Therefore, the values of $(ML_{inh} \times FA_{inh})$ are not listed, nor are the ratios of the intermediate variables involving the products.

[c] The PRG Calculator considers evaporation of H-3 with a VF rather than a PEF. The listed value is the value of VF.

In Table 3.2-10, the ratios of ($SF_{p-res-avg} \times ML_{inh} \times FA_{inh} \times Sf_{p-i}$) (with RESRAD) to ($CF_{res-soil} \times 1000/PEF_w \times Sf_i$) (with the PRG Calculator) as listed in the second from last column are almost the same as the ratios of cancer risk (RESRAD parent and short-lived progenies) to PRG, listed in the last column, except for C-14 and H-3. This consistency confirms that the differences in cancer risks, RESRAD parent and short-lived progenies versus PRG, can be explained with the ratios of intermediate variables used in the calculations.

For all radionuclides with a listed value, the ratio of $(ML_{inh} \times FA_{inh})$ (with RESRAD) to $(1{,}000/PEF_w)$ (with the PRG Calculator) is 7.98, indicating that the contaminated dust particles concentration in the air considered by RESRAD is greater than that considered by the PRG Calculator. The default value of ML_{inh}, 1×10^{-4} (g/m^3) used by RESRAD is conservative, and if a lower value were used, the cancer risk results would be closer to those obtained with the PRG Calculator.

For I-129 and Tc-99, in addition to the ratio of $(ML_{inh} \times FA_{inh})$ (with RESRAD) to $(1{,}000/PEF_w)$ (with the PRG Calculator), the ratio of $SF_{p-res-avg}$ (with RESRAD) to $CF_{res-soil}$ (with the PRG Calculator) is also very different from 1 (well below 1). This is because the leaching loss of radionuclide in soil was significant, but it was not considered by the PRG Calculator.

For Ac-227 and Pb-210, the difference in cancer risk results is also due to the difference in the inhalation slope factor used. The PRG Calculator fails to include the *Sf*s of the immediate short-lived progenies to the *Sf*s of these two radionuclides.

With regard to C-14 and H-3, RESRAD implements special models to consider evaporation and volatilization and calculates the associated cancer risks, which are different from the use of ML_{inh} and FA_{inh} for solid radionuclides. The source factors, $SF(t)$, of C-14 and H-3 account for the loss through this mechanism. According to the equations available, the PRG Calculator also considers evaporation of H-3 from soil and uses the VF (listed in Table 3.2-10) in place of PEF to calculate the associated cancer risk. As pointed out in Section 3.2.4, the value of VF used fails to account for air dispersion, which could result in overestimating the cancer risk greatly. In addition, the negligence to account for the loss of H-3 in soils through leaching and evaporation could further contribute to the overestimation of the cancer risk by the PRG Calculator. As to C-14, the cancer risk calculated by the PRG Calculator is much lower than that calculated by RESRAD, which seems to indicate that the inhalation cancer risk calculated by the PRG Calculator does not consider volatilization of C-14.

3.2.6.3 Ingestion of Soil Pathway

The PRG Calculator uses the following equations to calculate cancer risk associated with each initially present radionuclide in soil from the ingestion of soil pathway:

$$Risk_{res-soil-ing} = C_{res-soil-avg} \times \frac{1}{1{,}000} \times IFS_{r-adj} \times Sf_s$$

$$IFS_{r-adj} = IRS_c \times EF_{r-c} \times ED_{r-c} + IRS_a \times EF_{r-a} \times ED_{r-a}$$

$$C_{res-soil-avg} = C_{soil}(0) \times CF_{res-soil} = C_{soil}(0) \times \frac{(1 - e^{-\lambda \times ED_r})}{\lambda \times ED_r}$$

where

$Risk_{res-soil-ing}$ = cancer risk to resident from the ingestion of soil pathway;

$C_{res-soil-avg}$ = average soil concentration (of parent nuclide) over the exposure duration of resident (pCi/g);

$1/1{,}000$ = conversion factor (g/mg);

IFS_{r-adj} = age-adjusted soil ingestion factor for residents (mg);

Sf_s = slope factor for soil ingestion (1/pCi);

IRS_c = daily ingestion rate of soil, child (mg/d);

IRS_a = daily ingestion rate of soil, adult (mg/d);

EF_{r-c} = exposure frequency of residents, child (d/yr);

EF_{r-a} = exposure frequency of residents, adult (d/yr);

ED_{r-c} = exposure duration of residents, child (yr);

ED_{r-a} = exposure duration of residents, adult (yr);

$CF_{res-soil}$ = correction factor for soil concentration for resident exposure;

λ = radiological decay constant (1/yr); and

$C_{soil}(0)$ = initial soil concentration (pCi/g).

The fraction of vegetative cover, *V*, which is considered by the PRG Calculator to reduce the emission of soil particles to the air for the inhalation pathway, is expected to reduce the incidental ingestion of soil. However, it is not used in the above equation. Nor is the cover thickness, which is considered by the PRG Calculator to reduce the intensity of external radiation and would reduce the radiation exposure associated with incidental soil ingestion. Therefore, the potential cancer risk associated with the soil ingestion pathway could be greatly overestimated by the PRG Calculator.

The calculations performed by RESRAD for the ingestion of soil pathway can be described with the following equations:

$$Risk_{res-soil-ing} = (f_{otd} + f_{ind}) \times FI_{ing} \times FA_{ing} \times \sum_j [\int_0^{ED_r} C_{j-soil}(t) \times FCD_{ing}(t)\, dt] \times Sf_{j-s}$$

$$C_{j-soil}(t) = C_{soil}(0) \times SF_j(t)$$

where

f_{otd} = annual outdoor time fraction;

f_{ind} = annual indoor time fraction;

FI_{ing} = annual ingestion rate of soil (g/yr);

FA_{ing} = area correction factor for soil ingestion;

j = index for radionuclides, including the parent and long-lived progenies;

$C_{j-soil}(t)$ = soil concentration of nuclide *j* at time *t* (pCi/g);

$FCD_{ing}(t)$ = over and depth factor for soil ingestion at time *t* $=FCD_{inh}(t)$;

Sf_{j-s} = ingestion of soil slope factor for nuclide *j*, including contributions from short-lived progenies (1/pCi); and

$SF_j(t)$ = source factor for nuclide *j* at time *t*.

An area factor, FA_{ing}, is used in the equation to account for the fact that a fraction of the soil particles ingested by the residents while staying on site may originate from outside the contaminated area due to transport by wind. In addition to FA_{ing}, a cover and depth factor, FCD_{ing}, is used to consider the effect of a cover layer so as to maintain consistency with the external exposure and inhalation pathways. With a contaminated area of 2,000 m^2 and a cover thickness of 0 m used for this comparison, both FA_{ing} and FCD_{ing} had a value of 1.

The total cancer risk associated with the ingestion of soil pathway that RESRAD calculates at time 0 includes contributions from the parent nuclide (including its short-lived progenies) and from long-lived nuclides in the decay chain (including their short-lived progenies). Therefore, the cancer risk equation shown above can be written as follows:

$$Risk_{res-soil-ing} = Risk_{p-res-soil-ing} + Risk_{l-res-soil-ing}$$
$$= C_{p-res-soil-avg} \times (f_{otd} + f_{ind}) \times ED_r \times FI_{ing} \times Sf_{p-i}$$
$$+ \sum_l C_{l-res-soil-avg} \times (f_{otd} + f_{ind}) \times ED_r \times FI_{ing} \times Sf_{l-s}$$
$$C_{p\ or\ l-res-soil-avg} = C_{soil}(0) \times SF_{p\ or\ l-res-avg} = C_{soil}(0) \times \int_0^{ED_r} SF_{p\ or\ l}(t)dt\ /\ ED_r$$

where

p	=	parent nuclide;
l	=	index for long-lived progenies in the decay chain;
$Risk_{p-res-soil-ing}$	=	cancer risk to residents from the soil ingestion pathway, contributed by the parent and its immediate short-lived progenies;
$Risk_{l-res-soil-ing}$	=	cancer risk to residents from the soil ingestion pathway, contributed by long-lived nuclides and their immediate short-lived progenies;
$C_{p\ or\ l-res-soil-avg}$	=	average soil concentration of the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of resident (pCi/g); and
$SF_{p\ or\ l-res-avg}$	=	average source factor for the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of residents.

For this comparison, the annual ingestion rate of soil, FI_{ing}, was selected so that with f_{otd}, f_{ind}, and ED_r, the total amount of soil ingested and used by RESRAD for the exposure calculation matched the value of $(IFS_{r-adj}/1{,}000)$ used by the PRG Calculator (see Table 3.1-1 for their values.) With such a selection, the ratio of the cancer risk from the parent nuclide and its immediate short-lived progenies, $(Risk_{p-res-soil-ing})$, calculated by RESRAD, to the cancer risk calculated by the PRG Calculator, would equal the ratio of $(SF_{p-res-avg} \times Sf_{p-s})$ with the RESRAD code to $(CF_{res-soil} \times Sf_s)$ with the PRG Calculator. Table 3.2-11 shows the comparison of the final cancer risk results (based on an initial soil concentration of 1 pCi/g) obtained from RESRAD and the PRG Calculator. Table 3.2-12 lists the ratios of the intermediate variables.

Comparing the ratios of cancer risk listed in the last two columns of Table 3.2-11 for each radionuclide, the ratios are very different for Pa-231, Pu-241, Ra-226, and Ra-228, which indicates that long-lived progenies made significant cancer risk contributions. The PRG Calculator does not account for long-lived progenies; therefore, it may underestimate the actual cancer risk associated with ingestion of soil exposure for these four radionuclides. Excluding

TABLE 3.2-11 Comparison of Soil Ingestion Cancer Risks at the Current Time for the Resident Scenario[a]

Parent Nuclide	Cancer Risk RESRAD Result (total)	Cancer Risk RESRAD Result (parent and its short-lived progenies)	Cancer Risk PRG Result	Calculated Ratio (RESRAD total /PRG)	Calculated Ratio (RESRAD parent and short-lived progenies/PRG)
Ac-227	7.25E-07	7.25E-07	2.21E-07	3.28E+00	3.28E+00
Am-241	1.87E-07	1.87E-07	2.02E-07	9.26E-01	9.26E-01
C-14	3.79E-11	3.79E-11	3.09E-09	1.23E-02	1.23E-02
Co-60	1.21E-08	1.21E-08	1.21E-08	9.98E-01	9.98E-01
Cs-137	3.59E-08	3.59E-08	3.59E-08	1.00E+00	1.00E+00
H-3	3.19E-12	3.19E-12	5.29E-11	6.02E-02	6.02E-02
I-129	3.04E-08	3.04E-08	3.11E-07	9.78E-02	9.78E-02
Np-237	1.58E-07	1.58E-07	1.58E-07	1.00E+00	1.00E+00
Pa-231	6.64E-07	3.23E-07	3.34E-07	1.99E+00	9.68E-01
Pb-210	3.79E-06	3.79E-06	1.32E-06	2.87E+00	2.87E+00
Pu-239	2.55E-07	2.55E-07	2.55E-07	1.00E+00	1.00E+00
Pu-241	4.48E-09	1.73E-09	1.73E-09	2.59E+00	1.00E+00
Ra-226	2.46E-06	7.39E-07	7.54E-07	3.26E+00	9.80E-01
Ra-228	9.13E-07	6.70E-07	6.78E-07	1.35E+00	9.88E-01
Sr-90	1.08E-07	1.08E-07	1.13E-07	9.52E-01	9.52E-01
Tc-99	5.37E-10	5.37E-10	8.12E-09	6.61E-02	6.61E-02
Th-230	1.97E-07	1.86E-07	1.86E-07	1.06E+00	9.99E-01
U-234	1.61E-07	1.61E-07	1.66E-07	9.68E-01	9.68E-01
U-235	1.67E-07	1.67E-07	1.72E-07	9.73E-01	9.72E-01
U-238	2.13E-07	2.13E-07	2.20E-07	9.70E-01	9.70E-01

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios in the last column are shown in red if they are very different from 1.

long-lived nuclides and their immediate short-lived progenies and comparing the cancer risks just from the parent nuclide and its immediate short-lived progenies (with the ratios listed in the last column), the results from RESRAD and the PRG Calculator are still very different for Ac-227, C-14, H-3, I-129, Pb-210, and Tc-99. The ratios of intermediate variables listed in Table 3.2-12 provide explanations for the differences.

In Table 3.2-12, the ratios of ($SF_{p-res-avg} \times Sf_{p-s}$) (with RESRAD) to ($CF_{res-soil} \times Sf_s$) (with the PRG Calculator) as listed in the second from last column are almost the same as the ratios of cancer risk (RESRAD parent and short-lived progenies) to PRG listed in the last column, except for C-14. This consistency confirms that the differences in cancer risks (RESRAD parent and short-lived progenies vs. PRG) can be explained with the ratios of intermediate variables used in the calculations.

TABLE 3.2-12 Comparison of Intermediate Variables Used for the Soil Ingestion Exposure Calculations[a]

Parent Nuclide	Ratio $SF_{p-res-avg}$ / $CF_{res-soil}$	RatioRESRAD Sf_{p-s} / / PRG Sf_s	Ratio($SF_{p-res-avg}$ × × Sf_{p-s}) / ($CF_{res-soil}$ × Sf_s)	Ratio of Cancer Risk (RESRAD parent and short-lived progenies/PRG)
Ac-227	9.36E-01	3.50E+00	3.28E+00	3.28E+00
Am-241	9.26E-01	1.00E+00	9.26E-01	9.26E-01
C-14	9.92E-03	1.00E+00	9.92E-03	1.23E-02
Co-60	9.99E-01	1.00E+00	9.99E-01	9.98E-01
Cs-137	1.00E+00	1.00E+00	1.00E+00	1.00E+00
H-3	6.00E-02	1.00E+00	6.00E-02	6.02E-02
I-129	9.77E-02	1.00E+00	9.77E-02	9.78E-02
Np-237	9.98E-01	1.00E+00	9.98E-01	1.00E+00
Pa-231	9.69E-01	1.00E+00	9.69E-01	9.68E-01
Pb-210	9.86E-01	2.91E+00	2.87E+00	2.87E+00
Pu-239	9.99E-01	1.00E+00	9.99E-01	1.00E+00
Pu-241	9.99E-01	1.01E+00	1.01E+00	1.00E+00
Ra-226	9.78E-01	1.00E+00	9.78E-01	9.80E-01
Ra-228	9.88E-01	1.00E+00	9.88E-01	9.88E-01
Sr-90	9.55E-01	1.00E+00	9.55E-01	9.52E-01
Tc-99	6.61E-02	1.00E+00	6.61E-02	6.61E-02
Th-230	1.00E+00	1.00E+00	1.00E+00	9.99E-01
U-234	9.69E-01	1.00E+00	9.69E-01	9.68E-01
U-235	9.69E-01	1.00E+00	9.69E-01	9.72E-01
U-238	9.69E-01	9.95E-01	9.64E-01	9.70E-01

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios of the intermediate variables (listed in the 2nd and 3rd columns) are shown in red if their values are very different from 1.

For Ac-227 and Pb-210, the differences in cancer risks are due to the differences in slope factors used. As pointed out in Section 3.2.1, the PRG Calculator fails to include the *Sf*s of the immediate short-lived progenies to the *Sf*s of these two radionuclides.

For H-3, I-129, and Tc-99, the differences in cancer risks are due to the differences between $SF_{p-res-avg}$ (with RESRAD) and $CF_{res-soil}$ (with the PRG Calculator). The PRG Calculator does not consider the loss of radionuclides in soil through leaching and evaporation for H-3; therefore, the potential cancer risks associated with the soil ingestion pathway for H-3, I-129, and Tc-99 are greatly overestimated.

For C-14, the difference in cancer risks from RESRAD and the PRG Calculator cannot be explained completely by the difference between $SF_{p-res-avg}$ (with RESRAD) and $CF_{res-soil}$ (with the PRG Calculator). However, no further investigation can be conducted at this point.

3.2.6.4 Ingestion of Produce Pathway

The PRG Calculator uses the following equations to calculate cancer risk associated with each initially present radionuclide in soil from the ingestion of produce pathway:

$$Risk_{res-soil-prod-ing} = C_{res-soil-avg} \times (R_{upv} + R_{es}) \times (IFF_{r-adj} + IFV_{r-adj}) \times CPF_r \times Sf_f$$

$$IFF_{r-adj} = IRF_c \times EF_{r-c} \times ED_{r-c} + IRF_a \times EF_{r-a} \times ED_{r-a}$$

$$IFV_{r-adj} = IRV_c \times EF_{r-c} \times ED_{r-c} + IRV_a \times EF_{r-a} \times ED_{r-a}$$

$$C_{res-soil-avg} = C_{soil}(0) \times CF_{res-soil} = C_{soil}(0) \times \frac{(1 - e^{-\lambda \times ED_r})}{\lambda \times ED_r}$$

where

$Risk_{res-soil-prod-ing}$ = cancer risk to resident from the ingestion of produce pathway;

$C_{res-soil-avg}$ = average soil concentration (of parent nuclide) over the exposure duration of residents (pCi/g);

R_{upv} = wet root uptake multiplier = Bv_{wet};

R_{es} = soil resuspension multiplier = MLF;

IFF_{r-adj} = age-adjusted fruit ingestion factor for residents (g);

IFV_{r-adj} = age-adjusted vegetable ingestion factor for residents (g);

CPF_r = contamination fraction of produce for residents (g);

Sf_f = slope factor for food ingestion (1/pCi);

IRF_c = daily ingestion rate of fruit, child (g/d);

IRF_a = daily ingestion rate of fruit, adult (g/d);

IRV_c = daily ingestion rate of vegetable, child (g/d);

IRV_a = daily ingestion rate of vegetable, adult (g/d);

EF_{r-c} = exposure frequency of residents, child (d/yr);

EF_{r-a} = exposure frequency of residents, adult (d/yr);

ED_{r-c} = exposure duration of residents, child (yr);

ED_{r-a} = exposure duration of residents, adult (yr);

$CF_{res-soil}$ = correction factor for soil concentration for resident exposure;

λ = radiological decay constant (1/yr); and

$C_{soil}(0)$ = initial soil concentration (pCi/g).

For the ingestion of produce pathway, the PRG Calculator considers radiation exposures associated with eating contaminated fruits and vegetables. The age-adjusted ingestion factors, IFF_{r-adj} and IFV_{r-adj}, are multiplied by a contamination fraction, CPF_r, to obtain the amounts of contaminated fruits and vegetables ingested. The contamination in fruits and vegetables results from two mechanisms—root absorption and resuspension. A root uptake multiplier, R_{upv}, which is equivalent to the root uptake transfer factor, Bv_{wet}, and a soil resuspension multiplier, R_{es}, which is equivalent to the produce mass loading factor, MLF, are used to relate the concentrations in fruits and vegetables to the concentration in soil for these two mechanisms, respectively. The modeling of the produce ingestion pathway does not consider the influence of a cover layer, which is considered in the modeling of the external exposure pathway.

The calculations performed by RESRAD for the produce ingestion pathway can be described with the following equations:

$$Risk_{res-soil-prod-ing} = FA_{prod-ing} \times \sum_j \left[\int_0^{ED_r} C_{j-soil}(t) \times \sum_k FSR_{j,k-prod}(t) \times FI_{k-prod}\, dt \right] \times Sf_{j-f}$$

$$FSR_{j,k-prod}(t) = Bv_{j-wet} \times FCD_{prod-root}\,(t) + ML_{prod-res} \times FCD_{prod-res}\,(t) \times FAR_k$$

$$C_{j-soil}(t) = C_{soil}(0) \times SF_j\,(t)$$

where

$FA_{prod-ing}$ = area factor for produce ingestion, that is, contamination fraction;

j = index for radionuclides, including the parent and long-lived progenies;

k = index for produce categories, including fruit, vegetables, and grain as one category, and leafy vegetables as another;

$C_{j-soil}(t)$ = soil concentration of nuclide *j* at time *t* (pCi/g);

$FSR_{j,k-prod}\ (t)$ = food-to-soil concentration ratio for radionuclide *j* and category *k* of produce at time *t*;

FI_{k-prod} = annual ingestion rate of category *k* of produce (kg/yr);

Sf_{j-f} = food ingestion slope factor for nuclide *j*, including contributions from short-lived progenies (1/pCi);

Bv_{j-wet} = root uptake transfer factor for radionuclide *j*;

$FCD_{prod-root}\ (t)$ = cover and depth factor for root uptake at time *t*;

$ML_{prod-res}$ = mass loading of airborne soil particles from the contaminated area, for the resuspension-foliar deposition mechanism;

$FCD_{prod-res}\ (t)$ = cover and depth factor for resuspension uptake at time *t* = FCD_{inh};

FAR_k = food-to-air concentration ratio; and

$SF_j(t)$ = source factor for nuclide *j* at time *t*.

Two categories of produce are considered by RESRAD: (1) fruits, non-leafy vegetables, and grains and (2) leafy vegetables. In this comparison, the first category was used to simulate the fruits category considered in the PRG Calculator, and the second category was used to simulate the vegetables category considered in the PRG Calculator.

Like the PRG Calculator, RESRAD also considers two mechanisms resulting in produce contamination—root uptake and resuspension (followed by foliar deposition). However, the resuspension mechanism considered by the PRG Calculator includes contributions from rain splash, wind erosion, and other driving forces that would result in radionuclides being transferred from surface soil to plant leaves. A soil resuspension multiplier, R_{es}, is used to integrate all the driving forces and relate plant concentration to soil concentration directly. In RESRAD, the resuspension mechanism focuses on soil disturbances (including wind erosion) that suspend radionuclides in soil into the air followed by deposition of airborne nuclides onto plant leaves. Therefore, the ratio of radionuclide concentration in plants to radionuclide concentration in soil is the product of the airborne mass loading, $ML_{prod-res}$, and the food-to-air concentration ratio, FAR. The FAR is calculated with the airborne particle deposition velocity, fraction of deposited radionuclides retained on leaves, foliage-to-food translocation factor, weathering removal constant, growing period of the produce, and the wet-weight yield of the produce. In this comparison, these input parameters were assigned the same values for the two produce categories so that they have the same value of FAR.

To maintain consistency with the external exposure, inhalation, and soil ingestion pathways, the effect of a cover layer to reduce radionuclide uptake by plants is considered by RESRAD with the use of two cover and depth factors—$FCD_{prod-root}$ for the root absorption mechanism and $FCD_{prod-res}$ for the resuspension mechanism. $FCD_{prod-root}$ is determined by the fraction of plant roots exposed to contaminated soil. $FCD_{prod-res}$ assumes the same value as FCD_{inh}. In addition to the cover and depth factor, an area factor, $FA_{prod-ing}$, is used by RESRAD to consider the contamination fraction of produce ingested. By default, the value of $FA_{prod-ing}$ is determined by the area of contamination; however, its value can also be specified directly. In this comparison, the values of $FCD_{prod-root}$ and $FCD_{prod-res}$ were both 1 at any time.

The total cancer risk associated with the ingestion of produce pathway that RESRAD calculates at time 0 includes contributions from the parent nuclide (including its short-lived progenies) and from long-lived nuclides in the decay chain (including their short-lived progenies). Therefore, the cancer risk equation shown above can be written as follows:

$$
\begin{aligned}
Risk_{res-soil-prod-ing} &= Risk_{p-res-soil-prod-ing} + Risk_{l-res-soil-prod-ing} \\
&= C_{p-res-soil-avg} \times (Bv_{p-wet} + ML_{prod-res} \times FAR) \times \sum_k FI_{k-prod} \times ED_r \\
&\times FA_{prod-ing} \times Sf_{p-f} \\
&+ \sum_l C_{l-res-soil-avg} \times (Bv_{j-wet} + ML_{prod-res} \times FAR) \times \sum_k FI_{k-prod} \times ED_r \\
&\times FA_{prod-ing} \times Sf_{l-f}
\end{aligned}
$$

$$
C_{p\ or\ l-res-soil-avg} = C_{soil}(0) \times SF_{p\ or\ l-res-avg} = C_{soil}(0) \times \int_0^{ED_r} SF_{p\ or\ l}(t)dt / \ ED_r
$$

where

p	=	parent nuclide;
l	=	index for long-lived progenies in the decay chain;
$Risk_{p-res-soil-prod-ing}$	=	cancer risk to residents from the produce ingestion pathway, contributed by the parent and its immediate short-lived progenies;
$Risk_{l-res-soil-prod-ing}$	=	cancer risk to residents from the produce ingestion pathway, contributed by long-lived nuclides and their immediate short-lived progenies;

$C_{p\ or\ l-res-soil-avg}$ = average soil concentration of the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of residents (pCi/g); and

$SF_{p\ or\ l-res-avg}$ = average source factor for the parent nuclide or a long-lived nuclide in the decay chain over the exposure duration of residents.

For this comparison, the values of FI_{k-prod} for both produce categories were selected so that the total ingestion rates match the values of IFF_{r-adj} and IFV_{r-adj} used by the PRG Calculator (see Table 3.1-1). The value of $FA_{prod-ing}$ was also set to that of CPF_r used by the PRG Calculator. With such selections, the ratio of the cancer risk from the parent nuclide and its immediate short-lived progenies, ($Risk_{p-res-soil-prod-ing}$), calculated by RESRAD, to the cancer risk calculated by the PRG Calculator would equal the ratio of $[SF_{p-res-avg} \times (Bv_{j-wet} + ML_{prod-res} \times FAR) \times Sf_{p-f}]$ with the RESRAD code to $[CF_{res-soil} \times (Bv_{j-wet} + MLF) \times Sf_f]$ with the PRG Calculator. Table 3.2-13 compares the final cancer risk results (based on an initial soil concentration of 1 pCi/g) obtained from RESRAD and the PRG Calculator. Table 3.2-14 lists the ratios of the intermediate variables.

Comparing the ratios of cancer risk listed in the last two columns of Table 3.2-13 for each radionuclide, the ratios are very different for Pu-241, Ra-226, and Th-230, which indicates that the long-lived progenies made significant cancer risk contributions. The PRG Calculator does not account for long-lived progenies; therefore, it may underestimate the actual cancer risk associated with ingestion of produce exposed to these four radionuclides. Excluding long-lived nuclides and their immediate short-lived progenies and comparing the cancer risks just from the parent nuclide and its immediate short-lived progenies (with the ratios listed in the last column), the results from RESRAD and the PRG Calculator are very different for all radionuclides. The ratios of intermediate variables listed in Table 3.2-14 provide explanations for the differences.

In Table 3.2-14, the ratios of $[SF_{p-res-avg} \times (Bv_{wet} + ML_{prod-res} \times FAR) \times Sf_{p-f}]$ (with RESRAD) to $[CF_{res-soil} \times (Bv_{wet} + MLF) \times Sf_f]$ (with the PRG Calculator) as listed in the second from last column are almost the same as the ratios of cancer risk (RESRAD parent and short-lived progenies) to PRG listed in the last column, except for C-14 and H-3. This consistency confirms that the differences in cancer risks (RESRAD parent and short-lived progenies versus PRG) can be explained with the ratios of the intermediate variables used in the calculations.

For Ac-227 and Pb-210, one of the causes for the differences in cancer risks is the difference in slope factors used. As pointed out in Section 3.2.1, the PRG Calculator fails to include the Sf_f of the immediate short-lived progenies.

For C-14, H-3, I-129, and Tc-99, one of the causes of the differences in cancer risks is the difference between $SF_{p-res-avg}$ (with RESRAD) and $CF_{res-soil}$ (with the PRG Calculator). The PRG Calculator does not consider the loss of radionuclides in soil through leaching and evaporation for H-3, which can result in potential cancer risks being greatly overestimated.

TABLE 3.2-13 Comparison of Produce Ingestion Cancer Risks at the Current Time for the Resident Scenario[a]

Parent Nuclide	Cancer Risk RESRAD Result (total)	Cancer Risk RESRAD Result (parent and its short-lived progenies)	Cancer Risk PRG Result	Calculated Ratio (RESRAD total/PRG)	Calculated Ratio (RESRAD parent and short-lived progenies/PRG)
Ac-227	2.46E-07	2.46E-07	2.57E-05	9.56E-03	9.56E-03
Am-241	1.45E-09	1.45E-09	2.01E-05	7.23E-05	7.23E-05
C-14	3.47E-08	3.47E-08	6.78E-06	5.12E-03	5.12E-03
Co-60	2.76E-08	2.76E-08	9.96E-07	2.77E-02	2.77E-02
Cs-137	4.18E-07	4.18E-07	4.74E-06	8.82E-02	8.82E-02
H-3	4.65E-09	4.65E-09	1.02E-07	4.56E-02	4.56E-02
I-129	6.35E-09	6.35E-09	3.03E-05	2.10E-04	2.10E-04
Np-237	1.36E-07	1.36E-07	1.42E-05	9.61E-03	9.61E-03
Pa-231	1.41E-06	1.29E-06	3.60E-05	3.91E-02	3.59E-02
Pb-210	1.31E-05	1.31E-05	1.28E-04	1.03E-01	1.03E-01
Pu-239	9.74E-10	9.74E-10	2.67E-05	3.65E-05	3.65E-05
Pu-241	2.86E-11	7.27E-12	2.00E-07	1.43E-04	3.64E-05
Ra-226	1.03E-05	4.37E-06	8.29E-05	1.25E-01	5.28E-02
Ra-228	3.89E-06	3.76E-06	7.07E-05	5.50E-02	5.31E-02
Sr-90	3.82E-06	3.82E-06	1.48E-05	2.58E-01	2.58E-01
Tc-99	1.76E-07	1.76E-07	3.28E-06	5.37E-02	5.37E-02
Th-230	1.78E-07	1.29E-07	1.84E-05	9.65E-03	6.99E-03
U-234	2.94E-07	2.94E-07	1.50E-05	1.96E-02	1.96E-02
U-235	3.01E-07	3.01E-07	1.53E-05	1.97E-02	1.97E-02
U-238	3.72E-07	3.72E-07	1.89E-05	1.97E-02	1.97E-02

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios in the last column are shown in red if they are very different from 1.

For all radionuclides, except for C-14, H-3, and Tc-99, the primary reason for the significant difference in cancer risk is the very different factors used to relate the concentration in produce to the concentration in soil for the resuspension mechanism; $(ML_{prod-res} \times FAR)$ used by RESRAD is several orders of magnitude lower than the MLF used by the PRG Calculator. As discussed in Section 3.2.5, the PRG Calculator does not adjust the MLF with an absorption fraction or translocation factor, thus the contribution to cancer risk from the resuspension mechanism could be greatly overestimated. On the other hand, the value of $(ML_{prod-res} \times FAR)$ used by RESRAD in this comparison was based on wind erosion; should other processes, such as rain splash or plowing, be considered, the value of $(ML_{prod-res} \times FAR)$ should be much higher.

TABLE 3.2-14 Comparison of Intermediate Variables Used for the Produce Ingestion Exposure Calculations[a]

Parent Nuclide	RESRAD and PRG Bv_{wet}	PRG MLF	RESRAD $ML_{prod-res} \times FAR$	Ratio $(Bv_{wet} + ML_{prod-res} \times FAR)$ / $(Bv_{wet} + MLF)$	Ratio $SF_{p-res-avg}$ / $CF_{res-soil}$	Ratio RESRAD Sf_{p-f} / PRG Sf_f	Ratio $[SF_{p-res-avg} \times (Bv_{p-wet} + ML_{prod-res} \times FAR) \times Sf_{p-f}]$ / $[CF_{res-soil} \times (Bv_{wet} + MLF) \times Sf_f]$	Ratio of Cancer Risk (RESRAD parent and short-lived progenies/ PRG)
Ac-227	1.00E-03	2.60E-01	1.21E-06	3.84E-03	9.36E-01	2.66E+00	9.56E-03	9.56E-03
Am-241	1.91E-05	2.60E-01	1.21E-06	7.81E-05	9.26E-01	1.00E+00	7.23E-05	7.23E-05
C-14	5.50E+00	2.60E-01	–[b]	–	9.86E-03	1.00E+00	–[b]	5.12E-03
Co-60	7.40E-03	2.60E-01	1.21E-06	2.77E-02	9.99E-01	1.00E+00	2.77E-02	2.77E-02
Cs-137	2.52E-02	2.60E-01	1.21E-06	8.84E-02	1.00E+00	1.00E+00	8.83E-02	8.82E-02
H-3	4.80E+00	–	–	–	6.00E-02	1.00E+00	–	4.56E-02
I-129	5.48E-04	2.60E-01	1.21E-06	2.11E-03	9.77E-02	1.00E+00	2.06E-04	2.10E-04
Np-237	2.52E-03	2.60E-01	1.21E-06	9.60E-03	9.98E-01	1.00E+00	9.59E-03	9.61E-03
Pa-231	1.00E-02	2.60E-01	1.21E-06	3.70E-02	9.69E-01	1.00E+00	3.59E-02	3.59E-02
Pb-210	9.57E-03	2.60E-01	1.21E-06	3.55E-02	9.86E-01	2.92E+00	1.02E-01	1.03E-01
Pu-239	8.27E-06	2.60E-01	1.21E-06	3.65E-05	9.99E-01	1.00E+00	3.64E-05	3.65E-05
Pu-241	8.27E-06	2.60E-01	1.21E-06	3.65E-05	9.99E-01	1.01E+00	3.68E-05	3.64E-05
Ra-226	1.48E-02	2.60E-01	1.21E-06	5.39E-02	9.78E-01	1.00E+00	5.27E-02	5.28E-02
Ra-228	1.48E-02	2.60E-01	1.21E-06	5.39E-02	9.88E-01	1.00E+00	5.32E-02	5.31E-02
Sr-90	9.57E-02	2.60E-01	1.21E-06	2.69E-01	9.55E-01	1.00E+00	2.57E-01	2.58E-01
Tc-99	1.13E+00	2.60E-01	1.21E-06	8.13E-01	6.61E-02	1.00E+00	5.37E-02	5.37E-02
Th-230	1.83E-03	2.60E-01	1.21E-06	6.99E-03	1.00E+00	1.00E+00	6.99E-03	6.99E-03
U-234	5.39E-03	2.60E-01	1.21E-06	2.03E-02	9.69E-01	1.00E+00	1.97E-02	1.96E-02
U-235	5.39E-03	2.60E-01	1.21E-06	2.03E-02	9.69E-01	1.00E+00	1.97E-02	1.97E-02
U-238	5.39E-03	2.60E-01	1.21E-06	2.03E-02	9.69E-01	9.91E-01	1.95E-02	1.97E-02

[a] Ratios in the last two columns are highlighted with a yellow background if they are very different from each other. Ratios of the intermediate variables (listed in the 5th, 6th, and 7th columns) are shown in red if their values are very different from 1.

[b] A dash indicates not applicable.

RESRAD implements special models for H-3 and C-14. The PRG Calculator also models H-3 and C-14 differently from other radionuclides. However, the equations used by the PRG Calculator are not available; thus further investigation into the modeling differences could not be conducted.

3.3 COMPARISON OF WATER-DEPENDENT PATHWAYS

Table 3.3-1 lists the SSLs obtained with the PRG Calculator and the SCGs derived with the RESRAD results of the maximum cancer risks from all water-dependent pathways within 1,000 years. The PRG Calculator derived two sets of SSLs, one based on the partition method and the other based on the mass-limit method. The greater SSL for each radionuclide was selected as the final value, that is, Final SSL, for comparison with the SCG derived with the RESRAD results. For some reason, the PRG Calculator does not produce results for H-3. Two sets of SCGs were also derived; one based on RESRAD's default K_ds and the other based on the PRG Calculator's default K_ds. To differentiate them, the SCGs derived based on the PRG Calculator's default K_ds are termed SCG′s in Table 3.3-1. In addition to the values of SSLs and SCGs, the ratios of SCGs/SCG′s to Final SSLs are also listed in the table. The ratios of less than0.1 or greater than 10 are highlighted with a yellow background. Figure 3.3-1 is a graphic illustration of the ratios. To improve clarity of the figure, the range of ratios presented was set to 1×10^{-4} to 1×10^{8}; therefore, if a ratio was greater than 1×10^{8}, it was plotted as 1×10^{8} in the figure.

For most radionuclides, the SCG and SCG′ derived with RESRAD results are greater or much greater (more than a few orders of magnitude) than the Final SSL, indicating that the potential cancer risks associated with the water-dependent pathways calculated by RESRAD are much lower than those considered by the PRG Calculator (based on the same initial soil concentration for each radionuclide). For the few radionuclides whose SCG or SCG′ is smaller than the Final SSL, the difference between SCG/SCG′ and the Final SSL is within an order of magnitude, except for Pa-231. The most significant risk contributing pathway, that is, the most influential to determine the SSLs or SCGs, is the ingestion of water pathway, except for the SSLs of C-14, Ra-226, and Tc-99. For C-14 and Ra-226, the most critical pathway that determines the SSL is the inhalation of volatile pathway. For Tc-99, the SSL is most influenced by the ingestion of produce pathway.

According to the RESRAD results obtained with the RESRAD default K_ds, the maximum cancer risk associated with the water-dependent pathways would occur at the current time (starting at $t = 0$ for 26 years) only for I-129 and Tc-99. For Co-60, Cs-137, and Ra-228, the radionuclides would never reach the groundwater aquifer; therefore, there is no limitation to the initial soil concentration; that is, SCG is infinitely large. When the RESRAD calculations were performed with the PRG Calculator's default K_ds, for most radionuclides, the maximum cancer risk would occur at an earlier time (than would the maximum cancer risk calculated with the RESRAD's default K_ds.) The PRG Calculator assumes that the contamination in soil extends to the groundwater aquifer; it derives the SSLs based only on the cancer risks calculated for the current time.

TABLE 3.3-1 Comparison of SSLs and SCGs Corresponding to a Target Cancer Risk Level of 1 × 10^{-6}, Based on Exposures Associated with Water-dependent Pathways within 1,000 Years for the Resident Scenario[a]

Parent Nuclide	PRG Calculator			RESRAD (with RESRAD K_ds)			RESRAD (with PRG K_ds)		
	SSL Mass-limit Method (pCi/g)	SSL Partition Method (pCi/g)	Final SSL[b]	SCG (pCi/g)	Ratio (SCG/Final SSL)	Time of Peak Risk (yr)	SCG′ (pCi/g)	Ratio (SCG′/Final SSL)	Time of Peak Risk (yr)
Ac-227	5.71E-03	1.14E+00	1.14E+00	1.68E+01	1.48E+01	184	No limit	∞	NA[c]
Am-241	6.99E-03	3.46E-03	6.99E-03	6.20E-02	8.87E+00	412	7.39E-03	1.06E+00	84
C-14	1.25E-02[d]	1.48E-03[d]	1.25E-02[d]	9.36E-01	7.48E+01	2	4.02E+00	3.21E+02	3
Co-60	1.88E-01	1.06E+01	1.06E+01	No limit	∞	NA	No limit	∞	NA
Cs-137	3.28E-02	3.93E-02	3.93E-02	No limit	∞	NA	1.97E+00	5.03E+01	107
H-3	NA	NA	NA	1.12E+01	NA	0	1.12E+01	NA	2
I-129	4.65E-03	1.14E-04	4.65E-03	1.30E-03	2.79E-01	3	1.30E-03	2.79E-01	2
Np-237	1.01E-02	4.87E-04	1.01E-02	6.71E+01	6.64E+03	1,000	2.86E-03	2.83E-01	2
Pa-231	4.03E-03	9.47E-01	9.47E-01	5.95E-03	6.28E-03	1,000	No limit	∞	NA
Pb-210	1.25E-03	2.20E-02	2.20E-02	5.08E+10	2.31E+12	844	No limit	∞	NA
Pu-239	5.23E-03	3.20E-03	5.23E-03	2.32E+05	4.44E+07	1,000	5.94E-03	1.14E+00	109
Pu-241	7.89E-01	4.82E-01	7.89E-01	1.87E+00	2.37E+00	435	2.19E-01	2.78E-01	88
Ra-226	9.00E-06[d]	1.28E-06[d]	9.00E-06[d]	1.15E-02	1.28E+03	1,000	6.32E-04	7.03E+01	15
Ra-228	2.64E-03	3.75E-04	2.64E-03	No limit	∞	NA	3.84E-03	1.45E+00	10
Sr-90	1.29E-02	1.83E-03	1.29E-02	3.66E+02	2.84E+04	275	6.27E-03	4.86E-01	13
Tc-99	1.15E-01[e]	2.81E-03[e]	1.15E-01[e]	6.99E-02	6.08E-01	0	6.99E-02	6.08E-01	0
Th-230	7.68E-03	1.82E-02	1.82E-02	1.04E-01	5.72E+00	1,000	2.29E-02	1.26E+00	380
U-234	9.77E-03	6.99E-04	9.77E-03	1.14E-01	1.17E+01	1,000	2.82E-03	2.89E-01	4.9
U-235	9.60E-03	6.86E-04	9.60E-03	8.20E-02	8.54E+00	1,000	2.76E-03	2.87E-01	4.9
U-238	7.87E-03	5.63E-04	7.87E-03	9.42E-02	1.20E+01	1,000	2.28E-03	2.90E-01	4.9

TABLE 3.3-1 (Cont.)

---

[a] The SSL (based on the mass-limit method or the partition method) that determines the final value (i.e., Final SSL), is shown in red. The ratio of SCG or SCG' to Final SSL that is less than 0.1 or greater than 10 has a yellow background. Unless noted, the most critical pathway determining SSL or SCG is the ingestion of water pathway.

[b] Final SSL—the larger one between the SSL mass-limit method and the SSL partition method.

[c] NA = not available or not applicable.

[d] The most critical pathway determining the SSL is the inhalation of volatile pathway.

[e] The most critical pathway determining the SSL is the ingestion of produce pathway.

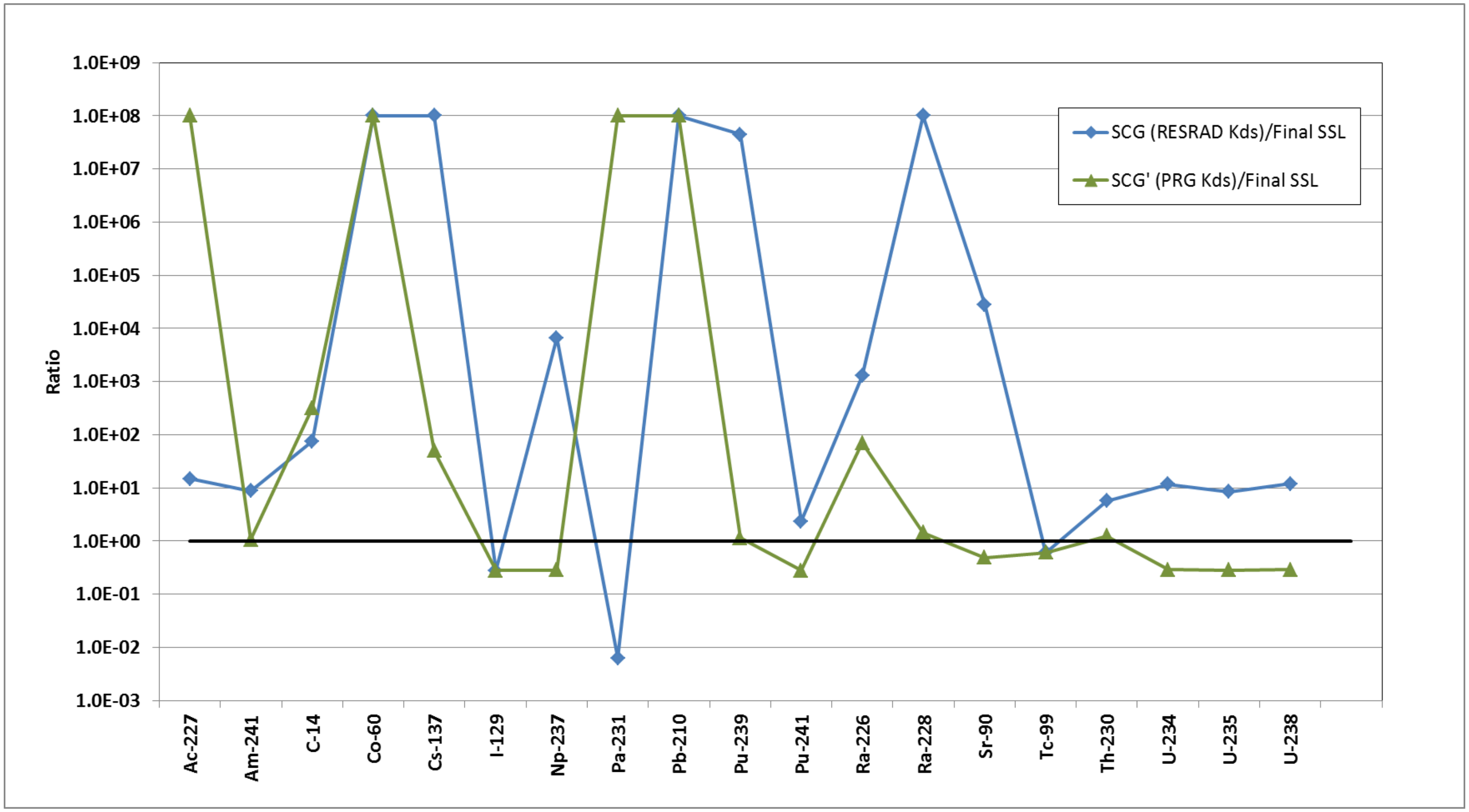

FIGURE 3.3-1 Ratios of SCG/SCG′ to Final SSL for the Resident Scenario (Note: For the purpose of plotting, when the ratio exceeded 1E+08, a value of 1E+08 was used.)

Investigation of the data and equations used in the PRG Calculator revealed the main reasons for the huge differences between SSLs and SCGs/SCG′s:

1. For some radionuclides, the contributions of cancer risk from short-lived progenies are not accounted for by the PRG Calculator;

2. For many radionuclides, the default K_ds chosen by the PRG Calculator are much smaller than those reported in the literature, resulting in much higher estimates of radionuclide concentrations in leachate;

3. The time required for radionuclides to reach the groundwater table through unsaturated zones and then to reach a well at a downgradient location and the associated radiological decay and ingrowth are not considered by the PRG Calculator to derive the SSLs;

4. The PRG Calculator does not consider long-lived progenies, which can outweigh the parent nuclide in terms of risk contribution, because they can dissolve more extensively in water or have a higher cancer risk potential (i.e., slope factor) than the parent nuclides;

5. The source depletion time used in deriving the SSL with the mass-limit method cannot be easily determined, and there is no provision in the PRG Calculator that can be used to determine the value; and

6. The cancer risks associated with the inhalation of volatile pathway for C-14 and radon precursors are incorrectly calculated with the wrong slope factors.

The following sections provide more detailed discussions on each of the findings.

3.3.1 Consideration of Short-lived Progenies

Section 3.2.1 pointed out that for some radionuclides, the PRG Calculator fails to account for the cancer risk contributions from short-lived progenies. According to the slope factors used for the parent nuclides as listed in Table 3.2-1, for Ac-227, the food ingestion and water ingestion slope factors used by the PRG Calculator are 2.66 and 2.42 times, respectively, lower than those used by RESRAD (which include contributions from short-lived progenies). Therefore, the potential cancer risk associated with the water-dependent pathways could be underestimated by the PRG Calculator by a factor of more than 2 for Ac-227. The underestimation in cancer risks could result in deriving SSLs which are more than 2 times greater than what they are supposed to be.

The same situation happens to Pb-210, for which the food ingestion and water ingestion slope factors used by the PRG Calculator are about 3 times lower than those used by RESRAD. This could result in deriving SSLs which are about 3 times overestimated.

3.3.2 Consideration of Radionuclide Concentrations in Leachate

Both the PRG Calculator and RESRAD use the K_d parameter to determine the concentration of a radionuclide in soil water based on a known soil concentration. For many radionuclides, the default K_ds selected by the PRG Calculator are much smaller than those reported in the literature and those used in RESRAD (see Table 3.2-3 for the comparison of K_ds). The smaller K_ds would yield much higher radionuclide concentrations in soil water that leaves the contaminated zone (i.e., leachate) and result in higher cancer risks associated with the water-dependent pathways.

Table 3.3-2 compares leachate concentrations calculated with the default K_ds of the PRG Calculator versus those calculated with the default K_ds of RESRAD, based on a soil concentration of 1 pCi/g. As can been seen with the ratios listed in the last column, the leachate concentrations of Cs-137, Np-237, Pu-239, Pu-241, Ra-226, Ra-228, Strontium-90 (Sr-90), Th-230, and the three uranium isotopes (U-234, U-235, and U-238) could be greatly overestimated (a factor of 25 or more) by the PRG Calculator with its default K_ds, which could lead to the derivation of overly conservative SSLs.

3.3.3 Consideration of Transport Time

To derive SSLs, the PRG Calculator assumes that the contaminated zone extends all the way to the groundwater table so that radionuclides in leachate would be discharged to the groundwater aquifer without any delay in time. The assumption that no unsaturated zone lies beneath the contaminated zone but above the groundwater table rarely matches actual site conditions. At many sites, unsaturated zones are present. During the transport through the unsaturated zones, radiological decay and ingrowth would continue. Thus the concentrations of parent nuclides in soil water when discharging to the groundwater aquifer would be less than when exiting the contaminated zone, if the K_ds for the unsaturated zones are the same as the K_d for the contaminated zone. The decrease in concentration would depend on the transport time through the unsaturated zones (which depends on the K_ds) relative to the radiological half-life of the parent nuclide. For radionuclides with large K_ds, the transport time through the unsaturated zones may be greater than 1,000 years, which is the time frame considered by RESRAD in this comparison. For radionuclides with a radiological decay half-life much shorter than the transport time, they may decay away before reaching the groundwater table.

After being discharged to the groundwater aquifer, radionuclides would continue to transport from the discharge point to the location of a downgradient well where groundwater is pumped out for use. The transport in the groundwater aquifer also takes time, during which radiological decay and ingrowth would continue. The PRG Calculator does not consider the requirement of time for radionuclides to reach a well from the discharge point, nor does it account for the radiological decay and ingrowth during the transport.

TABLE 3.3-2 Comparison of Leachate Concentrations Calculated with Default K_ds of the PRG Calculator and RESRAD for a Soil Concentration of 1 pCi/g[a]

Parent Nuclide	K_d (g/cm^3)		Leachate Concentration (pCi/L)		Ratio of Leachate Conc. (RESRAD/PRG)
	PRG Calculator	RESRAD	PRG Calculator	RESRAD	
Ac-227	1,700	20	5.88E-01	4.95E+01	8.41E+01
Am-241	4	20	2.38E+02	4.95E+01	2.08E-01
C-14	0.8	0	9.91E+02	4.78E+03	4.83E+00
Co-60	480	1,000	2.08E+00	1.00E+00	4.80E-01
Cs-137	10	4,600	9.80E+01	2.17E-01	2.22E-03
H-3	0	0	4.78E+03	4.78E+03	1.00E+00
I-129	0	0.1	4.78E+03	3.24E+03	6.76E-01
Np-237	0.2	821	2.44E+03	1.22E+00	4.98E-04
Pa-231	2,000	50	5.00E-01	1.99E+01	3.98E+01
Pb-210	150	100	6.66E+00	9.98E+00	1.50E+00
Pu-239	5	2,000	1.92E+02	5.00E-01	2.60E-03
Pu-241	5	2,000	1.92E+02	5.00E-01	2.60E-03
Ra-226	1	70	8.27E+02	1.42E+01	1.72E-02
Ra-228	1	70	8.27E+02	1.42E+01	1.72E-02
Sr-90	1	30	8.27E+02	3.31E+01	4.00E-02
Tc-99	0	0	4.78E+03	4.78E+03	1.00E+00
Th-230	20	60,000	4.95E+01	1.67E-02	3.37E-04
U-234	0.4	50	1.64E+03	1.99E+01	1.21E-02
U-235	0.4	50	1.64E+03	1.99E+01	1.21E-02
U-238	0.4	50	1.64E+03	1.99E+01	1.21E-02

[a] Ratios in the last column that are less than 0.1 are shown in red.

Tables 3.3-3 and 3.3-4 list the transport times calculated by RESRAD for radionuclides to move through the unsaturated zone of 4 m and in the groundwater aquifer for 44.72 m to reach the well located at the edge of the contaminated zone as considered in this comparison. The transport distance in the groundwater aquifer would range from 0 to 44.72 m, depending on where radionuclides are discharged at the groundwater table. The decreases in soil water concentrations expected for parent nuclides during the transport were calculated and are also shown in Tables 3.3-3 and 3.3-4. The decrease is expressed as the ratio of soil water concentration at the end of the transport to that at the beginning of the transport. For transport in the groundwater aquifer, the listed ratios are the average values considering different transport distances within the range of 0 to 44.72 m. The ratios did not take into consideration the dilution in the groundwater aquifer, which is accounted for by both the PRG Calculator and RESRAD with a dilution factor. The results in Table 3.3-3 were obtained with the RESRAD default K_ds,

TABLE 3.3-3 Estimated Transport Times and Associated Decreases in Radioactivity for Parent Nuclides Based on RESRAD Default K_ds[a]

Parent Nuclide	Transport Time (yr)		Ratio of Concentration in Soil Water		
	Unsaturated Zone (4 m)	Groundwater Aquifer (44.72 m)	Unsaturated Zone (4 m)	Groundwater Aquifer (0–44.72 m)	Unsaturated. Zone + Groundwater Aquifer
Ac-227	1.66E+02	3.40E+02	5.10E-03	9.25E-02	4.72E-04
Am-241	1.66E+02	3.40E+02	7.67E-01	7.71E-01	5.91E-01
C-14	1.72E+00	4.47E+00	1.00E+00	1.00E+00	1.00E+00
Co-60	8.22E+03	1.68E+04	~ 0	4.55E-04	~ 0
Cs-137	3.78E+04	7.72E+04	~ 0	5.64E-04	~ 0
H-3	1.72E+00	4.47E+00	9.08E-01	8.84E-01	8.03E-01
I-129	2.54E+00	6.15E+00	1.00E+00	1.00E+00	1.00E+00
Np-237	6.75E+03	1.38E+04	9.98E-01	9.98E-01	9.96E-01
Pa-231	4.13E+02	8.43E+02	9.91E-01	9.91E-01	9.82E-01
Pb-210	8.23E+02	1.68E+03	6.99E-12	1.91E-02	1.33E-13
Pu-239	1.64E+04	3.35E+04	6.24E-01	6.42E-01	4.01E-01
Pu-241	1.64E+04	3.35E+04	~ 0	6.17E-04	~ 0
Ra-226	5.77E+02	1.18E+03	7.79E-01	7.83E-01	6.10E-01
Ra-228	5.77E+02	1.18E+03	~ 0	~ 0	~ 0
Sr-90	2.48E+02	5.08E+02	2.53E-03	8.17E-02	2.06E-04
Tc-99	1.72E+00	4.47E+00	1.00E+00	1.00E+00	1.00E+00
Th-230	4.93E+05	1.01E+06	1.08E-02	1.08E-01	1.17E-03
U-234	4.13E+02	8.43E+02	9.99E-01	9.99E-01	9.98E-01
U-235	4.13E+02	8.43E+02	1.00E+00	1.00E+00	1.00E+00
U-238	4.13E+02	8.43E+02	1.00E+00	1.00E+00	1.00E+00

[a] Transport time through the unsaturated zone is highlighted with a yellow background if it is greater than 1,000 years. The ratio of concentration in soil water is shown in red if it is less than 0.1.

which were assigned to the contaminated zone, unsaturated zone, and saturated zone where the groundwater aquifer is located. The results in Table 3.3-4 were obtained with the default K_ds of the PRG Calculator.

According to the transport times listed in Table 3.3-3, Co-60, Cs-137, Np-237, Pu-239, Pu-241, and Th-230 would not appear in the groundwater (as parent nuclides) within 1,000 years. If the time frame was extended so that it was longer than the transport times required by these radionuclides to move through the unsaturated zone, Co-60, Cs-137, and Pu-241 would still not appear in the groundwater because they would decay away during the transport (indicated by the ratios which are zeros). For Pu-239, however, the radioactivity would decrease by 60% and for Th-230, the radioactivity would decrease by more than 99% when they

TABLE 3.3-4 Estimated Transport Times and Associated Decreases in Radioactivity for Parent Nuclides Based on PRG Calculator Default K_ds[a]

Parent Nuclide	Transport Time (yr)		Ratio of Concentration in Soil Water		
	Unsaturated Zone (4 m)	Groundwater Aquifer (44.72 m)	Unsaturated Zone (4 m)	Groundwater Aquifer (0–44.72 m)	Unsaturated Zone + Groundwater Aquifer
Ac-227	1.40E+04	2.85E+04	~ 0	1.10E-03	~ 0
Am-241	3.46E+01	7.16E+01	9.46E-01	9.45E-01	8.94E-01
C-14	8.29E+00	1.79E+01	9.99E-01	9.99E-01	9.98E-01
Co-60	3.95E+03	8.05E+03	~ 0	9.48E-04	~ 0
Cs-137	8.39E+01	1.72E+02	1.45E-01	2.48E-01	3.60E-02
H-3	1.72E+00	4.47E+00	9.08E-01	8.84E-01	8.03E-01
I-129	1.72E+00	4.47E+00	1.00E+00	1.00E+00	1.00E+00
Np-237	3.36E+00	7.83E+00	1.00E+00	1.00E+00	1.00E+00
Pa-231	1.64E+04	3.35E+04	7.06E-01	7.16E-01	5.05E-01
Pb-210	1.23E+03	2.52E+03	~ 0	1.27E-02	~ 0
Pu-239	4.28E+01	8.83E+01	9.99E-01	9.99E-01	9.98E-01
Pu-241	4.28E+01	8.83E+01	1.27E-01	2.31E-01	2.92E-02
Ra-226	9.93E+00	2.12E+01	9.96E-01	9.95E-01	9.91E-01
Ra-228	9.93E+00	2.12E+01	3.01E-01	3.59E-01	1.08E-01
Sr-90	9.93E+00	2.12E+01	7.87E-01	7.83E-01	6.16E-01
Tc-99	1.72E+00	4.47E+00	1.00E+00	1.00E+00	1.00E+00
Th-230	1.66E+02	3.40E+02	9.98E-01	9.98E-01	9.97E-01
U-234	5.00E+00	1.12E+01	1.00E+00	1.00E+00	1.00E+00
U-235	5.00E+00	1.12E+01	1.00E+00	1.00E+00	1.00E+00
U-238	5.00E+00	1.12E+01	1.00E+00	1.00E+00	1.00E+00

[a] Transport time through the unsaturated zone is highlighted with a yellow background if it is greater than 1,000 years. The ratio of concentration in soil water is shown in red if it is less than 0.1.

reach the location of the downgradient well. For Ac-227, Am-241, Pb-210, Ra-226, Ra-228, and Sr-90, even though the transport time required for moving through the unsaturated zone is less than 1,000 years, they would decay completely or significantly by the time they reach the groundwater table. Similar observations can be made with the calculation results listed in Table 3.3-4.

The results in Tables 3.3-3 and 3.3-4 underscore the importance of considering the transport times required by radionuclides to move through the unsaturated zone(s) and in the groundwater aquifer and the associated radiological decay and ingrowth when modeling the potential radiation exposure associated with the water-dependent pathways. The PRG Calculator does not factor into account the transport time and the associated radiological decay; therefore, the potential cancer risk associated with water-dependent pathways for a parent nuclide could be greatly overestimated, if the contribution from its long-lived progenies is relatively small.

The above observations also show the flaw in the EPA's guidance that "...To avoid unnecessary inconsistency between radiological and chemical risk assessment at the same site, users should generally use the same model for chemical and radionuclide risk assessment..." (EPA 2014). Decay during transport does not occur with chemicals, while it is a well-known and understood scientific fact for radionuclides, and should be taken into account in the fate and transport modeling of radionuclides.

3.3.4 Consideration of Long-lived Progenies

The PRG Calculator lacks the capability to track the formation of long-lived progenies which can be generated by the decay of parent nuclides in the contaminated zone, as well as during transport through the unsaturated zone and in the groundwater aquifer. Because long-lived progenies may dissolve in water more extensively than the parent nuclide (i.e., with smaller K_ds), not only their concentrations in soil water may be greater than those of the parent nuclide, they may also move faster through the unsaturated zone(s) and reach the groundwater table and eventually the downgradient location of a well earlier than the parent nuclide. Therefore, long-lived progenies may be significant cancer risk contributors, and, sometimes, they outweigh the parent nuclide in terms of risk contribution. The negligence of long-lived progenies by the PRG Calculator could result in the derivation of SSLs that are not protective of human health based on the TR level.

The importance of considering long-lived progenies in deriving SSLs can be demonstrated with the cancer risk results calculated by RESRAD for the water-dependent pathways (Table 3.3-5.) For Np-237, Pu-239, Pu-241, and Th-230, the maximum cancer risks projected for them within 1,000 years would all be contributed by their progenies. For Pa-231 and Ra-226, their long-lived progenies, Ac-227 and Pb-210, respectively, contributed more than 80% of the projected maximum cancer risk within 1,000 years. For U-235, about 30% of the maximum cancer risk would come from its long-lived progeny, Ac-227.

3.3.5 Consideration of Source Depletion Time

When deriving the SSLs with the partition method, the PRG Calculator assumes that the contaminated zone is very thick and extends all the way to the groundwater table. Therefore, concentrations of radionuclides in the leachate would stay constant (determined by K_ds) and not decrease with time. When the K_d of a parent nuclide is small, this method may violate the principle of mass balance by allowing more radionuclides to dissolve in water (over the exposure duration) than the total inventory in the contaminated zone. Another method employed by the PRG Calculator to determine SSLs is the mass-limit method. This mass-limit method allows the specification of a source depletion time and calculates a constant leachate concentration by evenly distributing the radionuclide inventory in the contaminated zone to the infiltration water over the specified depletion time. The default depletion time is 70 years for all radionuclides.

TABLE 3.3-5 Comparison of Cancer Risks from Both the Parent and Long-lived Progenies with Cancer Risks from the Parent Only—Water-dependent Pathways at the Time of Maximum Total Risk within 1,000 Years—Based on a Soil Concentration of 1 pCi/g and RESRAD K_ds

Parent Nuclide	Time of Max. Total Risk (yr)	Water-dependent Pathways									Significant Risk Contributing Progenies
		Ingestion of Water			Ingestion of Produce			All Pathways			
		Cancer Risk – Total	Cancer Risk – Parent	Ratio (Parent/ Total)[a]	Cancer Risk – Total	Cancer Risk – Parent	Ratio (Parent/ Total)[a]	Cancer Risk – Total	Cancer Risk – Parent	Ratio (Parent/ Total)[a]	
Ac-227	184	5.17E-08	5.17E-08	1	7.76E-09	7.76E-09	1	5.95E-08	5.95E-08	1	–[b]
Am-241	412	1.41E-05	1.41E-05	1	2.03E-06	2.03E-06	1	1.61E-05	1.61E-05	1	–
C-14	2	7.95E-07	7.95E-07	1	1.70E-08	1.70E-08	1	8.12E-07	8.12E-07	1	–
Co-60	NA[c]	NA	NA	NA	NA	NA	NA	NA	NA	NA	–
Cs-137	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	–
H-3	0	8.63E-08	8.63E-08	1	2.93E-09	2.93E-09	1	8.92E-08	8.92E-08	1	–
I-129	3	6.72E-04	6.72E-04	1	9.80E-05	9.80E-05	1	7.70E-04	7.70E-04	1	–
Np-237	1,000	1.29E-08	0.00E+00	0	1.96E-09	0.00E+00	0	1.49E-08	0.00E+00	0	U-233
Pa-231	1,000	1.46E-04	1.78E-05	0.12	2.19E-05	2.60E-06	0.12	1.68E-04	2.04E-05	0.12	Ac-227
Pb-210	844	1.72E-17	1.72E-17	1	2.48E-18	2.48E-18	1	1.97E-17	1.97E-17	1	–
Pu-239	1,000	3.74E-12	0.00E+00	0	5.67E-13	0.00E+00	0	4.31E-12	0.00E+00	0	U-235, Ac-227
Pu-241	435	4.67E-07	0.00E+00	0	6.73E-08	0.00E+00	0	5.34E-07	0.00E+00	0	Am-241
Ra-226	1,000	7.56E-05	1.30E-05	0.17	1.10E-05	1.94E-06	0.18	8.66E-05	1.49E-05	0.17	Pb-210
Ra-228	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	–
Sr-90	275	2.39E-09	2.39E-09	1	3.46E-10	3.46E-10	1	2.74E-09	2.74E-09	1	–
Tc-99	0	1.22E-05	1.22E-05	1	2.07E-06	2.07E-06	1	1.43E-05	1.43E-05	1	–
Th-230	1,000	8.39E-06	0.00E+00	0	1.22E-06	0.00E+00	0	9.61E-06	0.00E+00	0	Pb-210, Ra-226
U-234	1,000	7.54E-06	7.42E-06	0.98	1.14E-06	1.12E-06	0.98	8.68E-06	8.54E-06	0.98	–
U-235	1,000	1.06E-05	7.55E-06	0.71	1.61E-06	1.15E-06	0.71	1.22E-05	8.70E-06	0.71	Ac-227
U-238	1,000	9.19E-06	9.17E-06	1	1.42E-06	1.42E-06	1	1.06E-05	1.06E-05	1	–

TABLE 3.3-5 (Cont.)

[a] Ratios that are lower than 0.75 are shown in red.

[b] A dash = none.

[c] NA = not applicable because radionuclides would not reach the groundwater.

In addition to the water infiltration rate and thickness of contaminated zone, the leach rate of a radionuclide also depends on its interaction with soil particles and soil water. Therefore, the source depletion time would vary among radionuclides, and, in many cases, it is difficult to provide a reasonable estimate unless a computer model such as RESRAD is used. The PRG Calculator has no provision or guidance for estimating the source depletion time.

The source depletion time can be defined as the time required for the initial inventory in the contaminated zone to reduce to a small percentage (e.g., 1%) due to leaching (including radiological decay), and it can be estimated with the RESRAD calculation results. Table 3.3-6 lists the source depletion times estimated for the 20 radionuclides studied in this comparison. They were obtained by considering that the radionuclide inventory in the contaminated zone was reduced to less than 1% of the initial value; the results were obtained with the default K_ds of the PRG Calculator. According to the listed values, for many radionuclides, the source depletion time is less than 70 years. Therefore, if the default source depletion time of 70 years is used with the mass-limit method, the concentrations of these radionuclides in the leachate would be underestimated and lead to the derivation of SSLs which may not be protective of human health based on the specified target cancer risk level.

3.3.6 Consideration of Inhalation of Volatiles

The PRG Calculator considers radiation exposures from the inhalation of C-14 or radon that volatilize from water used in household activities and contaminated with C-14 or radon precursors. A volatilization factor is used to relate the indoor air concentration of C-14 and radon to the water concentration of C-14 and Ra-224 (Rn-220 precursor) or Ra-226 (Rn-222 precursor), respectively. The potential cancer risk associated with the inhalation of volatile pathway is supposed to be calculated with the inhalation slope factor of C-14 in gas form and the inhalation slope factors for radon (Rn-220 or Rn-222). However, the slope factors used by the

TABLE 3.3-6 Source Depletion Times Required To Reduce Radionuclide Inventory to Less Than 1%

Parent Nuclide	Source Depletion Time (yr)	Parent Nuclide	Source Depletion Time (yr)
Ac-227	145	Pu-239	65
Am-241	151	Pu-241	65
C-14	2	Ra-226	46
Co-60	35	Ra-228	22
Cs-137	133	Sr-90	37.4
H-3	2	Tc-99	8.8
I-129	8.8	Th-230	764
Np-237	15.7	U-234	23.6
Pa-231	> 1,000	U-235	23.6
Pb-210	145	U-238	23.6

PRG Calculator are for C-14 in solid form, Ra-224 and Ra-226. This misuse of slope factors would result in overestimating the potential cancer risk by several orders of magnitude and provides an explanation for why the SSLs derived for C-14 and Ra-226 by the PRG Calculator are much lower than the SCGs calculated based on the RESRAD results (see Table 3.3-1). Table 3.3-7 compares the inhalation slope factors of C-14 in solid form and in gas form, radon and its progenies, and radon precursors.

3.3.7 Comparison of Modeling for Groundwater Concentration

The modeling of potential cancer risks associated with water-dependent pathways resulting from soil contamination can be divided into two parts. In the first part, the relationship between the groundwater concentration and the initial soil concentration is established; in the second part, the concentration of radionuclide in biota or biota product (e.g., plant, meat, or milk) is related to the concentration in groundwater, and then the intake of radionuclides from each pathway is evaluated with the concentration in biota or biota product. In this section, the first part of the modeling is investigated by comparing the groundwater concentrations calculated with the

TABLE 3.3-7 Comparison of Inhalation Slope Factors of C-14, Radon, Radon Progenies, and Radon Precursors

Nuclide	Inhalation Class[a]	Slope Factor (1/pCi)
C-14	S	1.69E-11[b]
C-14	G	1.99E-14
Ra-226	S	2.82E-08[b]
Rn-222		3.19E-11
Po-218[c]		0
Pb-214[c]	S	4.00E-11
Bi-214[c]	S	3.10E-11
Ra-224	M	1.13E-8[b]
Rn-220		0
Po-216[d]		0
Pb-212[d]	M	6.40E-10
Bi-212[d]	M	8.44E-11

[a] Inhalation class is for the listed slope factor, which is the largest one for the radionuclide. S = slow, M = medium, and G = gas.

[b] The slope factor used by the PRG Calculator for calculating the risk associated with the inhalation of volatile pathway.

[c] Short-lived progenies of Rn-222.

[d] Short-lived progenies of Rn-220.

partition method of the PRG Calculator and by RESRAD. Although RESRAD calculates groundwater concentrations for both parent nuclides and their long-lived progenies, only the concentrations of parent nuclides are used for comparison because the PRG Calculator does not model groundwater concentrations for long-lived progenies. The potential cancer risk contributed by long-live progenies could be significant, and the issues with deriving SSLs without considering their contributions should be recognized (see the discussion in Section 3.3.4).

The equations of the partition method that the PRG Calculator uses to relate the groundwater concentration to the soil concentration are as follows:

$$C_{res-GW-avg} = \frac{C_{res-leachate-avg}}{DAF}$$

$$C_{res-leachate-avg} = C_{leachate}(0) \times CF_{res-soil} = C_{leachate}(0) \times \frac{(1 - e^{-\lambda \times ED_r})}{\lambda \times ED_r}$$

$$C_{leachate}(0) = \frac{C_{soil}(0)}{(K_d + \frac{\theta_w}{\rho_b})} \times 1000$$

where

$C_{res-GW-avg}$	=	average groundwater concentration (of parent nuclide) over the exposure duration of residents (pCi/L);
$C_{res-leachate-avg}$	=	average leachate concentration over the exposure duration of residents (pCi/L);
DAF	=	dilution and attenuation factor in groundwater aquifer;
$C_{leachate}(0)$	=	leachate concentration at the current time, that is, $t = 0$ (pCi/L);
$CF_{res-soil}$	=	correction factor for soil concentration for resident exposure;
ED_r	=	exposure duration of residents (yr);
λ	=	radiological decay constant (1/yr);
$C_{soil}(0)$	=	initial soil concentration (pCi/g);
K_d	=	soil-water partition coefficient (L/kg or cm^3/g);
θ_w	=	water-filled soil porosity (L_{water}/L_{soil});

ρ_b = dry soil bulk density (kg/L); and

$1{,}000$ = conversion factor (g/kg).

The PRG Calculator assumes that soil contamination extends to the groundwater table and divides the leachate concentration by a dilution and attenuation factor, DAF, to obtain the groundwater concentration. The DAF is calculated by considering the total amount of infiltration water discharging to the groundwater aquifer and the amount of groundwater flowing into the mixing zone where it mixes homogeneously with the infiltration water.

The calculations performed by RESRAD to determine parent nuclide concentrations in well water can be described with the following equations:

$$C_{well}(t) = \frac{C_{leachate}(0) \times \ STF_{avg}(t)}{f_{GW}}$$

When $t < t_{uz}$, $\quad STF_{avg}(t) = 0$

When $t_{uz} \le t < t_{uz} + t_{sz}$, $\quad STF_{avg}(t) = \dfrac{ID(t_{uz}) \times \int_0^{t_1} SF(t') \times ID(t_1 - t')dt'}{t_{sz}}$ and $t_1 = t - t_{uz}$

When $t \ge t_{uz} + t_{sz}$, $\quad STF_{avg}(t)$

$$= \frac{ID(t_{uz}) \times SF(t - t_{uz} - t_{sz}) \times \int_0^{t_1} SF(t') \times ID(t_1 - t')dt'}{t_{sz}}$$

and $t_1 = t_{sz}$

$$C_{leachate}(0) = \frac{C_{soil}(0)}{(K_d + \frac{\theta_w}{\rho_b})} \times 1000$$

where

$C_{well}(t)$ = well water concentration at time *t* (pCi/L);

$STF_{avg}\,(t)$ = average source and transport to groundwater correction factor at time *t*;

f_{GW} = dilution factor for groundwater screened within the depth of a well;

t_{uz} = transport time through the unsaturated zone (yr);

t_{sz} = transport time in the saturated zone from the upgradient to the downgradient edge of the contaminated zone (yr);

$ID(t_{uz})$ = radiological decay correction factor for the transport time period through the unsaturated zone;

$ID(t_1 - t')$ = radiological decay correction factor for the time period $(t_1 - t')$;

$SF(t')$ = source factor at time t';

$SF(t - t_{uz} - t_{sz})$ = source factor at time $(t - t_{uz} - t_{sz})$; and

t_1 = time period for integration (yr).

RESRAD considers the loss of radionuclide inventory in the contaminated zone through radiological decay and leaching, while the PRG Calculator considers only radiological decay; therefore, the decrease with time of the parent nuclide concentration in the leachate is greater with RESRAD than with the PRG Calculator. RESRAD also considers the loss of radioactivity when radionuclides transport through the unsaturated zone and in the groundwater aquifer. The distance radionuclides transport in the groundwater aquifer to a well located at the downgradient edge of the contaminated zone varies with the discharge location of the radionuclides at the groundwater table. The variation is factored into account when the average source and transport to groundwater correction factor, $STF_{avg}(t)$, is calculated, which is used with the dilution factor for groundwater, f_{GW}, to obtain the average concentration of groundwater pumped out from a well at time t. The value of f_{GW} is dependent on the pumping rate of groundwater, the screening depth of the well, as well as the flow rate of groundwater.

Comparing the above two sets of equations, if the initial soil concentration of a parent nuclide, $C_{soil}(0)$, is 1 pCi/g, the ratio of the well water concentration at time t, $C_{well}(t)$, from RESRAD, to the average groundwater concentration over the exposure duration of the resident, $C_{res-GW-avg}$, from the PRG Calculator, would equal the ratio of $[C_{leachate}(0) \times STF_{avg}(t)/f_{GW}]$ with the RESRAD code to $[C_{leachate}(0) \times CF_{res-soil}/DAF]$ with the PRG Calculator. Table 3.3-8 compares the well water concentrations. The well water concentrations listed under “RESRAD Results” were calculated by RESRAD with the RESRAD default K_ds. The groundwater concentrations listed under “PRG Results” were obtained by dividing the tap water PRG (pCi/L) by the risk-based SSL (pCi/g) calculated by the PRG Calculator. Except for Pa-231, the maximum well water concentrations within 1,000 years from RESRAD are lower than the average groundwater concentrations over the exposure duration of a resident from the PRG Calculator. According to the RESRAD results, Co-60, Cs-137, Np-237, Pu-239, Pu-241, Ra-228, and Th-230 would not be observed in the groundwater within 1,000 years, either because they would decay away during the transport in the unsaturated zone or because it would take longer than 1,000 years for these radionuclides to reach the groundwater table.

TABLE 3.3-8 Comparison of the Maximum Well Water Concentrations from RESRAD (based on RESRAD K_ds) with the Average Groundwater Concentrations from the PRG Calculator – Based on a Soil Concentration of 1 pCi/g

Parent Nuclide	RESRAD Results		PRG Results	Ratio (RESRAD well water conc./PRG GW conc.)[a]
	Time of Max. Well Water Conc. (yr)	Max. Well Water Conc. (pCi/L)	Average Groundwater Conc. (pCi/L)	
Ac-227	195	5.74E-03	1.67E-01	3.43E-02
Am-241	425	7.11E+00	9.71E+01	7.32E-02
C-14	5.90	2.02E+02	4.15E+02	4.87E-01
Co-60	1,000	0	2.46E-01	0
Cs-137	1,000	0	3.07E+01	0
H-3	4	5.01E+02	NA[b]	NA
I-129	8	8.63E+02	2.08E+03	4.14E-01
Np-237	1,000	0	1.04E+03	0
Pa-231	1,000	5.33E+00	2.09E-01	2.55E+01
Pb-210	854	3.46E-13	1.90E+00	1.83E-13
Pu-239	1,000	0	8.01E+01	0
Pu-241	1,000	0	4.57E+01	0
Ra-226	1,000	1.73E+00	3.45E+02	5.02E-03
Ra-228	1,000	0	1.06E+02	0
Sr-90	285	1.72E-03	2.58E+02	6.67E-06
Tc-99	6	1.23E+03	2.08E+03	5.93E-01
Th-230	1,000	0	2.07E+01	0
U-234	1,000	5.43E+00	6.95E+02	7.82E-03
U-235	1,000	5.45E+00	6.94E+02	7.85E-03
U-238	1,000	5.45E+00	6.94E+02	7.86E-03

[a] GW = groundwater.

[b] NA = not available or not applicable.

Table 3.3-9 compares the intermediate variables and their ratios. The ratios of the intermediate variables would provide explanations for the differences in groundwater concentrations because the product of the ratios agrees well (within 5%) with the ratio of groundwater concentrations (see the last two columns in the table). The greater deviation seen with I-129 and Tc-99 than with other radionuclides could be attributed to the less precise well water concentrations (from RESRAD) reported for these two radionuclides than for other radionuclides. This is because for these two radionuclides, the well water concentration changed sharply over a short period of time after the first entry of these radionuclides to the groundwater

TABLE 3.3-9 Comparison of Intermediate Variables Used for the Groundwater Concentration Calculations (RESRAD Results Based on Its Default K_ds)[a]

Parent Nuclide	RESRAD $STF_{avg}\ (t_{max})$	PRG CF_{avg}	Ratio STF_{avg}/CF_{avg}	Ratio Leachate Conc. RESRAD/ PRG	Ratio RESRAD f_{GW} / PRG DAF	Ratio $(STF_{avg} \times RESRAD\ Leachate\ Conc. / f_{GW}) / (CF_{avg} \times PRG\ Leachate\ Conc. / DAF)$	Ratio (RESRAD well water conc./PRG GW conc).[b]
Ac-227	1.59E-04	6.80E-01	2.33E-04	8.41E+01	5.66E-01	3.47E-02	3.43E-02
Am-241	1.95E-01	9.79E-01	1.99E-01	2.08E-01	5.66E-01	7.34E-02	7.32E-02
C-14	5.73E-02	9.98E-01	5.74E-02	4.83E+00	5.66E-01	4.90E-01	4.87E-01
Co-60	0	2.84E-01	0	4.80E-01	5.66E-01	0	0
Cs-137	0	7.53E-01	0	2.22E-03	5.66E-01	0	0
H-3	1.42E-01	NA[c]	NA	NA	5.66E-01	NA	NA
I-129	3.62E-01	1.00E+00	3.62E-01	6.76E-01	5.66E-01	4.33E-01	4.14E-01
Np-237	0	1.00E+00	0	4.98E-04	5.66E-01	0	0
Pa-231	3.64E-01	1.00E+00	3.64E-01	3.98E+01	5.66E-01	2.56E+01	2.55E+01
Pb-210	4.81E-14	6.85E-01	7.02E-14	1.50E+00	5.66E-01	1.86E-13	1.83E-13
Pu-239	0	1.00E+00	0	2.60E-03	5.66E-01	0	0
Pu-241	0	5.69E-01	0	2.60E-03	5.66E-01	0	0
Ra-226	1.65E-01	9.94E-01	1.66E-01	1.72E-02	5.66E-01	5.05E-03	5.02E-03
Ra-228	0	3.04E-01	0	1.72E-02	5.66E-01	0	0
Sr-90	7.01E-05	7.43E-01	9.43E-05	4.00E-02	5.66E-01	6.67E-06	6.67E-06
Tc-99	3.50E-01	1.00E+00	3.50E-01	1.00E+00	5.66E-01	6.19E-01	5.93E-01
Th-230	0	1.00E+00	0	3.37E-04	5.66E-01	0	0
U-234	3.71E-01	1.00E+00	3.71E-01	1.21E-02	5.66E-01	7.94E-03	7.82E-03
U-235	3.72E-01	1.00E+00	3.72E-01	1.21E-02	5.66E-01	7.97E-03	7.85E-03
U-238	3.72E-01	1.00E+00	3.72E-01	1.21E-02	5.66E-01	7.97E-03	7.86E-03

[a] The ratio of the intermediate variables (in the 4th, 5th, and 6th columns) that is the most significant cause for the difference in groundwater concentration is shown in red.

[b] GW = groundwater.

[c] NA = not available or not applicable.

table, as a consequence of 0 K_d. The most significant cause of the difference in groundwater concentrations is shown in red in the table.

As indicated by the ratios of the intermediate variables listed in Table 3.3-9, for Pa-231, Ra-226, U-234, U-235, and U-238, the most significant cause of the difference in groundwater concentration calculated by RESRAD and the PRG Calculator is the difference in the leachate concentration used for the calculation, which resulted from the use of different K_ds. For the other radionuclides (except for H-3), the most significant cause of the difference in groundwater concentration is the difference in STF_{avg} versus CF_{avg}. RESRAD considers the loss of radionuclide inventory in the contaminated zone through leaching and the change in radioactivity during the transport through the unsaturated zone and in the groundwater aquifer, while the PRG Calculator does not consider either of these conditions.

Another set of maximum well water concentrations calculated by RESRAD with the PRG Calculator's default Kd_s was obtained. Table 3.3-10 compares these well water concentrations with the groundwater concentrations from the PRG Calculator. According to the RESRAD results, Ac-227, Co-60, Pa-231, and Pb-210 would not be observed in the groundwater within 1,000 years, either because they would decay away during the transport in the unsaturated zone or because it would take longer than 1,000 years for these radionuclides to reach the groundwater table. Table 3.3-11 compares the intermediate variables and their ratios that provide explanations for the differences in groundwater concentrations shown in Table 3.3-10.

As shown by the ratios of intermediate variables listed in Table 3.3-10, for all radionuclides (except for H-3), the difference in STF_{avg} versus CF_{avg} is more significant than the difference in f_{GW} versus DAF.

3.3.8 Comparison of Cancer Risk Modeling for Each Exposure Pathway

The two water-dependent pathways selected for consideration by RESRAD for this comparison were the ingestion of water and ingestion of produce pathways. In addition to the two pathways considered by RESRAD, the PRG Calculator also considers the inhalation of volatile and the water immersion pathways. The inhalation of volatile pathway is applicable only when the tap water, which was assumed to be groundwater in this comparison, used for household activities is contaminated with C-14 and radon precursors. The issue with the modeling of this pathway has been discussed in Section 3.3.6. Potential radiation exposure from the water immersion pathway is negligible. Based on the results obtained with the PRG Calculator for this comparison, the cancer risk associated with this pathway accounted for less than 0.005% of the total cancer risk from all the water-dependent pathways.

TABLE 3.3-10 Comparison of the Maximum Well Water Concentrations from RESRAD (Based on PRG Calculator K_ds) with the Average Groundwater Concentrations from the PRG Calculator – Based on a Soil Concentration of 1 pCi/g

	RESRAD Results		PRG Results	
Parent Nuclide	Time of Max. Well Water Conc. (yr)	Well Water Conc. (pCi/L)	Groundwater Conc. (pCi/L)	Ratio (RESRAD well water conc./PRG GW conc.)[a]
Ac-227	1,000	0	1.67E-01	0
Am-241	106	6.22E+01	9.71E+01	6.40E-01
C-14	26.00	1.26E+01	4.15E+02	3.04E-02
Co-60	1,000	0	2.46E-01	0
Cs-137	119.00	0.781	3.07E+01	2.54E-02
H-3	4.35	5.04E+02	NA[b]	NA
I-129	6.19	1.25E+03	2.08E+03	6.01E-01
Np-237	10.82	6.89E+02	1.04E+03	6.62E-01
Pa-231	1,000	0	2.09E-01	0
Pb-210	1,000	0	1.90E+00	0
Pu-239	130.77	59.5	8.01E+01	7.43E-01
Pu-241	59.64	1.2497	4.57E+01	2.74E-02
Ra-226	31.02	2.47E+02	3.45E+02	7.17E-01
Ra-228	16.01	18.91	1.06E+02	1.79E-01
Sr-90	26.24	1.22E+02	2.58E+02	4.73E-01
Tc-99	6.16	1.25E+03	2.08E+03	6.01E-01
Th-230	505.41	1.54E+01	2.07E+01	7.46E-01
U-234	16.10	4.82E+02	6.95E+02	6.94E-01
U-235	16.10	4.82E+02	6.94E+02	6.94E-01
U-238	16.10	4.82E+02	6.94E+02	6.95E-01

[a] GW = groundwater.

[b] NA = not available or not applicable.

TABLE 3.3-11 Comparison of Intermediate Variables Used for the Groundwater Concentration Calculations (RESRAD Results Based on PRG CalculatorK_ds)[a]

Parent Nuclide	RESRAD STF_{avg} (t_{max})	PRG CF_{avg}	Ratio STF_{avg}/CF_{avg}	Ratio Leachate Conc. RESRAD/PRG	Ratio RESRAD f_{GW} / PRG DAF	Ratio $(STF_{avg} \times RESRAD\ Leachate\ Conc. / f_{GW}) / (CF_{avg} \times PRG\ Leachate\ Conc. / DAF)$	Ratio (RESRAD well water conc./PRG GW conc.)[b]
Ac-227	0	6.80E-01	0	1.00E+00	5.66E-01	00	0
Am-241	3.56E-01	9.79E-01	3.64E-01	1.00E+00	5.66E-01	6.43E-01	6.40E-01
C-14	1.63E-02	9.98E-01	1.63E-02	1.00E+00	5.66E-01	2.88E-02	3.04E-02
Co-60	0	2.84E-01	0	1.00E+00	5.66E-01	0	0
Cs-137	1.08E-02	7.53E-01	1.43E-02	1.00E+00	5.66E-01	2.53E-02	2.54E-02
H-3	1.43E-01	NA[c]	NA	1.00E+00	5.66E-01	NA	NA
I-129	3.56E-01	1.00E+00	3.56E-01	1.00E+00	5.66E-01	6.29E-01	6.01E-01
Np-237	3.83E-01	1.00E+00	3.83E-01	1.00E+00	5.66E-01	6.76E-01	6.62E-01
Pa-231	0	1.00E+00	0	1.00E+00	5.66E-01	0	0
Pb-210	0	6.85E-01	0	1.00E+00	5.66E-01	0	0
Pu-239	4.21E-01	1.00E+00	4.21E-01	1.00E+00	5.66E-01	7.44E-01	7.43E-01
Pu-241	8.84E-03	5.69E-01	1.55E-02	1.00E+00	5.66E-01	2.74E-02	2.74E-02
Ra-226	4.06E-01	9.94E-01	4.08E-01	1.00E+00	5.66E-01	7.22E-01	7.17E-01
Ra-228	3.08E-02	3.04E-01	1.01E-01	1.00E+00	5.66E-01	1.79E-01	1.79E-01
Sr-90	2.00E-01	7.43E-01	2.70E-01	1.00E+00	5.66E-01	4.76E-01	4.73E-01
Tc-99	3.55E-01	1.00E+00	3.55E-01	1.00E+00	5.66E-01	6.28E-01	6.01E-01
Th-230	4.23E-01	1.00E+00	4.23E-01	1.00E+00	5.66E-01	7.48E-01	7.46E-01
U-234	3.99E-01	1.00E+00	3.99E-01	1.00E+00	5.66E-01	7.05E-01	6.94E-01
U-235	3.99E-01	1.00E+00	3.99E-01	1.00E+00	5.66E-01	7.05E-01	6.94E-01
U-238	3.99E-01	1.00E+00	3.99E-01	1.00E+00	5.66E-01	7.05E-01	6.95E-01

[a] The ratio of the intermediate variables (in the 4th, 5th, and 6th columns) that is the most significant cause for the difference in groundwater concentration is shown in red.

[b] GW = groundwater.

[c] NA = not available or not applicable.

The modeling of the cancer risk associated with the ingestion of water pathway is straightforward; that is, by multiplying the average water concentration over the exposure duration, the total amount of water ingested over the exposure duration, and the slope factor for water ingestion. When the total amount of water ingested and the slope factor used by RESRAD and the PRG Calculator were the same, the difference in cancer risk calculated by RESRAD and the PRG Calculator can be explained by the difference in the average water concentration (associated with an initial soil concentration of 1 pCi/g) used for the calculation. The comparison of the modeling for groundwater concentration is discussed in detail in Section 3.3.7. According to the cancer risk results obtained for this comparison, the ingestion of water pathway is the most important water-dependent pathway. Based on the PRG Calculator's results, the risk from the ingestion of water pathway accounted for 64% to 79% of the total risk for all the radionuclides studied except for C-14, H-3, Ra-226, and Tc-99. On the basis of the RESRAD results obtained with the RESRAD default K_ds, the cancer risk from the ingestion of water pathway accounted for 86% to 98% of the maximum total risk within 1,000 years for all the radionuclides studied except for Co-60, Cs-137, and Ra-228.

The difference in cancer risk calculated for the ingestion of produce pathway by RESRAD and the PRG Calculator can be explained by the modeling differences in (1) projecting groundwater concentration (based on the initial soil concentration, 1 pCi/g used in this comparison), and (2) relating the produce concentration to the concentration in the irrigation water. The first modeling difference is the main cause of the difference in cancer risk. Therefore, the second modeling difference is briefly discussed here. The PRG Calculator considers that radionuclides in the irrigation water would accumulate in soils for 30 years (the default case), and then some of the accumulation would be taken up by vegetation through two mechanisms: (1) root absorption and (2) resuspension. The root uptake multiplier (Bv_{wet}) and the resuspension multiplier (MLF) discussed in Section 3.2.5 are used to relate the concentration in vegetation to the accumulated soil concentration due to irrigation. In addition to the above two mechanisms, the radionuclides that are deposited on the foliage during irrigation could be retained on the foliage and absorbed by vegetation; this is the third mechanism, foliage deposition, considered by the PRG Calculator. When relating the concentration in produce to the concentration in irrigation water, RESRAD considers only the first and third mechanisms that the PRG Calculator considers. The equations used by RESRAD for these two mechanisms are similar to those used by the PRG Calculator. Because RESRAD does not consider the resuspension mechanism and the default resuspension multiplier used by the PRG Calculator is overly conservative (see discussion in Section 3.2.5), the concentrations of radionuclides in produce calculated by RESRAD would be smaller than those calculated by the PRG Calculator, given the same radionuclide concentration in the irrigation water.

3.4 COMPARISON OF THE COMBINATION OF WATER-INDEPENDENT AND WATER-DEPENDENT PATHWAYS

The PRG Calculator analyzes radiation exposures associated with the water-independent pathways and water-dependent pathways separately to derive the Total Soil PRG and SSL, respectively, for a radionuclide of concern. To ensure protection of human health based on a target cancer risk level, in some cases, the total Soil PRG should be limited by the SSL, if the

SSL is smaller than the total Soil PRG (the final PRG is called the Final Soil PRG in this section.) However, the PRG Calculator does not provide the information needed to determine whether the above adjustment for the Total Soil PRG should be performed for a specific contaminated site. To determine the need for adjustment, in addition to the knowledge of whether there is a groundwater aquifer underlying the contaminated zone, the decision makers also need to know (1) when radionuclides would reach the groundwater aquifer, relative to the time frame considered for human health protection, and (2) if radionuclides would reach the groundwater aquifer within the considered time frame, what the groundwater concentrations would be after the delay in time. The above information can be obtained with the RESRAD code. The RESRAD code performs dynamic analysis to project the change of radiation exposures and cancer risks over the considered time frame. It integrates the radiation exposures and cancer risks from the water-independent and the water-dependent pathways to determine the maximum total cancer risk within the considered time frame; therefore, the SCG derived for a radionuclide of concern based on the maximum total cancer risk (the Final SCG in this section) does not require additional adjustment like the Total Soil PRG does.

The calculation results for the water-independent and water-dependent pathways obtained for this comparison were combined to determine the Final Soil PRGs and Final SCGs as presented in Table 3.4-1. The Final Soil PRGs were obtained by limiting the Total Soil PRGs with the SSLs if the SSLs were smaller (Note: The SSLs used in this section are the Final SSLs discussed in Section 3.3 and presented in Table 3.3-1.) The Final SCGs were derived with the maximum total cancer risks over all the water-independent and water-dependent pathways within 1,000 years, the assumed time frame for human health protection for this comparison. There were two sets of Final SCGs, the first set was derived with the maximum cancer risk calculated with the RESRAD's default K_ds, and the second set was derived with the maximum cancer risk calculated with the PRG Calculator's default K_ds. The second set was termed SCG' in Table 3.4-1 to differentiate it from the first set. The ratio between the Final SCG or Final SCG' to the Final Soil PRG was also calculated and listed in the table. Figure 3.4-1 is a graphic illustration of the calculated ratios.

For most radionuclides, the Final SCG or SCG′ derived with the RESRAD results were greater or much greater (up to 3 orders of magnitude) than the Final Soil PRG, indicating that the maximum total cancer risks within 1,000 years over all pathways calculated by RESRAD were much lower than both the cancer risks for the water-independent and water-dependent pathways considered by the PRG Calculator (based on the same initial soil concentration for each radionuclide). For the few radionuclides whose Final SCG or SCG′ is smaller than the Final Soil PRG, the difference between the Final SCG/SCG′ and the Final Soil PRG is within an order of magnitude. Detailed discussions on the modeling differences between the PRG Calculator and the RESRAD code that lead to the differences between the Final SCGs/SCG's and Final Soil PRGs can be found in Sections 3.2 and 3.3.

Because the cancer risks associated with the water-independent pathways and water-dependent pathways are analyzed separately by the PRG Calculator, the Final Soil PRG is equivalent to either the Total Soil PRG or SSL. In RESRAD modeling, the cancer risks associated with the water-independent pathways and water-dependent pathways are analyzed in the same run and they are added to determine the total cancer risk, so the Final SCG/SCG' is

TABLE 3.4-1 Comparison of the Final Soil PRGs and Final SCGs Considering both Water-independent and Water-dependent Pathways

Parent Nuclide	PRG Calculator			RESRAD (with RESRAD K_ds)				RESRAD (with PRG K_ds)			
	Total Soil PRG (pCi/g) (Water-independent)	SSL (pCi/g) (Water-dependent)	Final Soil PRG (pCi/g)	SCG (pCi/g) (Water-independent)	SCG (pCi/g) (Water-dependent)	Final SCG (pCi/g)	Ratio (Final SCG/Final Soil PRG)	SCG' (pCi/g) (Water-independent)	SCG' (pCi/g) (Water-dependent)	Final SCG' (pCi/g)	Ratio (Final SCG'/Final Soil PRG)
Ac-227	3.86E-02	1.14E+00	3.86E-02	1.07E-01	1.68E+01	1.07E-01	2.78E+00	1.01E-01	–[a]	1.01E-01	2.61E+00
Am-241	4.88E-02	6.99E-03	6.99E-03	2.33E+00	6.20E-02	6.20E-02	8.86E+00	3.09E+00	7.39E-03	7.39E-03	1.06E+00
C-14	1.47E-01	1.25E-02	1.25E-02	2.87E+01	9.36E-01	9.26E-01	7.41E+01	2.69E+01	4.02E+00	3.56E+00	2.85E+02
Co-60	3.73E-02	1.06E+01	3.73E-02	3.64E-02	–	3.64E-02	9.76E-01	3.64E-02	–	3.64E-02	9.76E-01
Cs-137	5.36E-02	3.93E-02	3.93E-02	6.54E-02	–	6.53E-02	1.66E+00	7.49E-02	1.97E+00	7.49E-02	1.90E+00
H-3	2.32E-01	NA[b]	2.32E-01	1.82E+02	1.12E+01	1.06E+01	4.55E+01	1.82E+02	1.12E+01	1.06E+01	4.55E+01
I-129	3.27E-02	4.65E-03	4.65E-03	2.39E+01	1.30E-03	1.30E-03	2.79E-01	3.54E+01	1.30E-03	1.30E-03	2.79E-01
Np-237	4.90E-02	1.01E-02	1.01E-02	1.40E-01	6.71E+01	1.40E-01	1.39E+01	1.09E+00	2.86E-03	2.86E-03	2.83E-01
Pa-231	2.69E-02	9.47E-01	2.69E-02	8.04E-02	5.95E-03	5.90E-03	2.19E-01	5.85E-02	–	5.85E-02	2.18E+00
Pb-210	7.72E-03	2.20E-02	7.72E-03	5.89E-02	5.08E+10	5.89E-02	7.63E+00	5.87E-02	–	5.87E-02	7.60E+00
Pu-239	3.70E-02	5.23E-03	5.23E-03	3.22E+00	2.32E+05	3.22E+00	6.17E+02	4.30E+00	5.94E-03	5.94E-03	1.14E+00
Pu-241	4.97E+00	7.89E-01	7.89E-01	8.72E+01	1.87E+00	1.87E+00	2.37E+00	1.58E+02	2.19E-01	2.20E-01	2.78E-01
Ra-226	6.92E-03	9.00E-06	9.00E-06	1.23E-02	1.15E-02	1.03E-02	1.14E+03	3.49E-02	6.32E-04	6.29E-04	6.98E+01
Ra-228	1.24E-02	2.64E-03	2.64E-03	3.20E-02	–	3.20E-02	1.21E+01	5.54E-02	3.84E-03	3.79E-03	1.43E+00
Sr-90	6.63E-02	1.29E-02	1.29E-02	2.48E-01	3.66E+02	2.47E-01	1.92E+01	5.94E-01	6.27E-03	6.26E-03	4.85E-01
Tc-99	3.04E-01	1.15E-01	1.15E-01	5.65E+00	6.99E-02	6.91E-02	6.01E-01	5.66E+00	6.99E-02	6.91E-02	6.01E-01
Th-230	5.37E-02	1.82E-02	1.82E-02	5.86E-02	1.04E-01	3.75E-02	2.06E+00	1.70E+00	2.29E-02	2.28E-02	1.25E+00
U-234	6.61E-02	9.77E-03	9.77E-03	2.07E+00	1.14E-01	1.14E-01	1.17E+01	1.05E+01	2.82E-03	2.80E-03	2.87E-01
U-235	5.22E-02	9.60E-03	9.60E-03	2.02E-01	8.20E-02	7.87E-02	8.20E+00	1.02E+00	2.76E-03	2.75E-03	2.87E-01
U-238	5.00E-02	7.87E-03	7.87E-03	6.61E-01	9.42E-02	9.31E-02	1.18E+01	3.35E+00	2.28E-03	2.28E-03	2.90E-01

[a] A dash indicates no limitation.

[b] NA= not available.

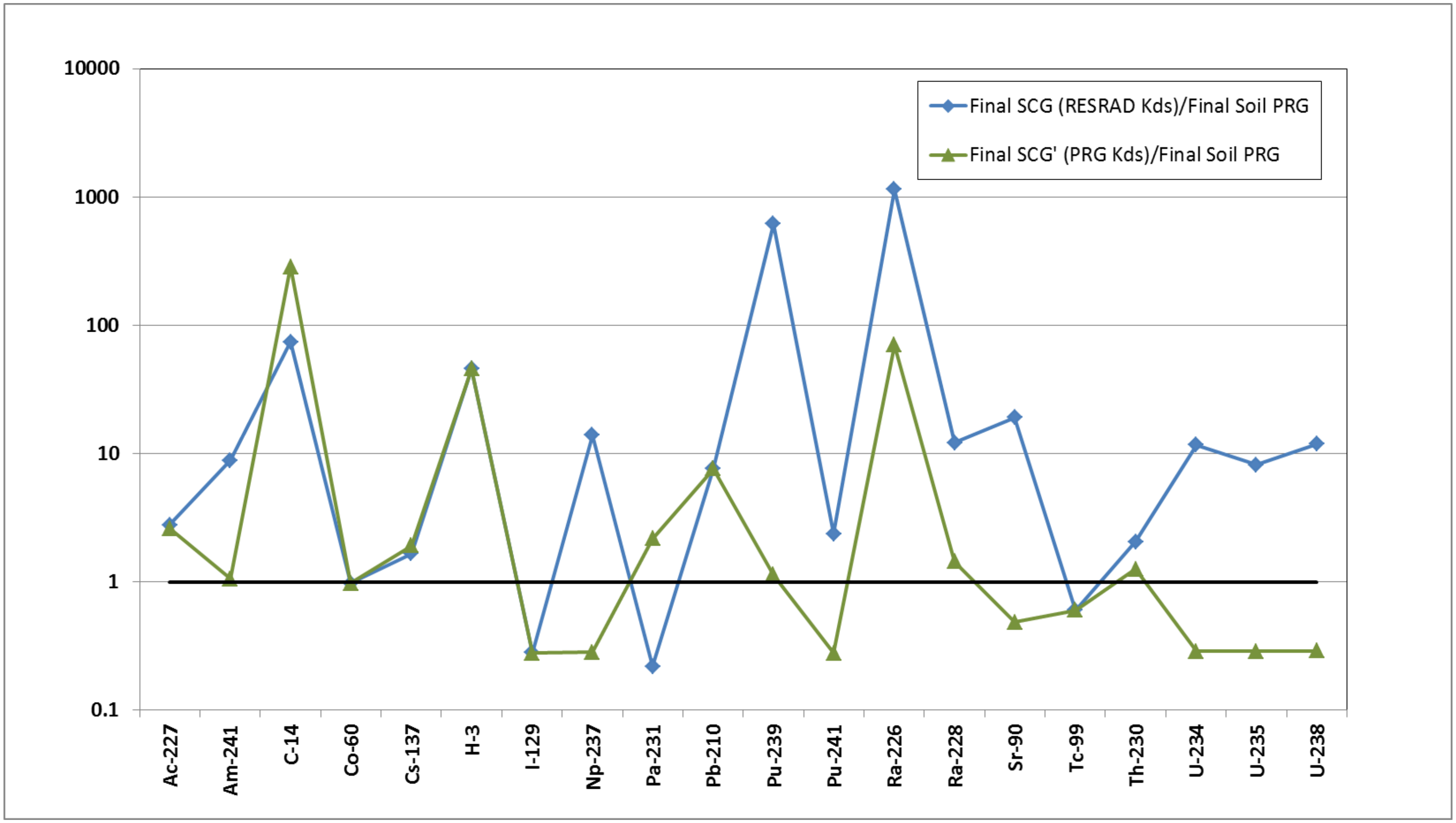

FIGURE 3.4-1 Ratios of Final SCG/SCG′ to Final Total Soil PRG for the Resident Scenario

lower than both the SCGs/SCG's for the water-independent pathways and water-dependent pathways. However, one of the SCGs/SCG's might have a dominant influence on the Final SCG/SCG', meaning that the cancer risk from the pathways it represents (either water-dependent or water-independent) constitutes more than 90% of the maximum total cancer risk from all pathways, then the Final SCG or SCG' would be very close to the dominant SCG or SCG'. In Table 3.4-1, the Total Soil PRGs or SSLs that determine the Final Soil PRGs are shown in red, as are the SCGs/SCG's that have a dominant influence on the Final SCGs/SCG's.

Comparing the results listed under "PRG Calculator" with those listed under "RESRAD (with PRG K_ds)" in Table 3.4-1, for most radionuclides, the exposure pathways (either water-dependent or water-independent) that determine the Final Soil PRG are consistent with the exposure pathways that dominate the Final SCG'.

For example, for Ac-227, the Final Soil PRG is determined by the Total Soil PRG (i.e., by the water-independent pathways), which is consistent with the Final SCG' being dominated by the SCG' for the water-independent pathways.

However, for Cs-137 and H-3, the consistency in dominant pathways (water-independent or water-dependent) is not observed. For Cs-137, the Final Soil PRG is determined by the SSL, because the PRG Calculator neglects the transport time required for Cs-137 to reach the groundwater aquifer which, in this comparison, is long enough for Cs-137 dissolving in the leachate to decay away prior to reaching the groundwater aquifer. The RESRAD code considers the transport time required and the associated radiological decay; therefore, the Final SCG' is dominated by the SCG' for the water-independent pathways rather than by the SCG' for the water-dependent pathways. For H-3, the Final Soil PRG is determined by the Total Soil PRG, because the PRG Calculator, for some reason, does not calculate the SSL. The Total Soil PRG for H-3 is determined primarily by the inhalation exposure to HTO that would evaporate from the contaminated zone to the air. In the form of HTO, H-3 would transport through the unsaturated zone quickly to reach the groundwater aquifer. Therefore, the potential exposure associated with the water-dependent pathways could be significant, relative to the exposure associated with the water-independent pathways, which is shown by the RESRAD results.

For C-14, the Final SCG' is more than 10% lower than the SCG' for the water-dependent pathways, because the water-independent pathways contribute more than 10% of the maximum total cancer risk. If the cancer risks from water-independent and -dependent pathways are not combined as they are handled in the PRG Calculator, the maximum total cancer risk could be underestimated, leading to the derivation of a Final SCG' or Final Total PRG that is not protective of human health. The Final SCG' for C-14 is highlighted with a yellow background to indicate that the associated maximum cancer risk is influenced by both the water-independent pathways and water-dependent pathways.

Comparing the results listed under "PRG Calculator" with those listed under "RESRAD (with RESRAD K_ds)" in Table 3.4-1, the exposure pathways (either water-dependent or water-independent) that determine the Final Soil PRG are not always consistent with the exposure pathways that dominate the Final SCG. The inconsistency is observed for Cs-137 and H-3, as well as for Np-237, Pa-231, Pu-239, Ra-228, and Sr-90. The inconsistency underscores the important role played by the K_d parameter in both the PRG Calculator and the RESRAD modeling. For Ra-226 and Th-230, both the water-independent and water-dependent pathways are important for determining the Final SCG, thus the Final SCG is highlighted with a yellow background. For Ra-226, about 10% of the maximum total cancer risk was contributed by the water-independent pathways and 90% by the water-dependent pathways. For Th-230, the contributions to the maximum total cancer risk from the water-independent and water-dependent pathways were 64% and 36%, respectively.

The change in the total cancer risk over time and the contributions from both the water-dependent and water-independent pathways are analyzed by RESRAD, which are reported in tables as well as illustrated in graphics. Figures 3.4-2 to 3.4-5 are some examples. These graphic presentations would enhance the understanding of the influence from various physical processes on the projected cancer risk over time. The understanding gained would assist decision makers in choosing proper management strategies for a contaminated site to protect human health. Using Figure 3.4-2 as an example, the graphic shows the potential cancer risk that could be incurred by residents who move into a contaminated site (with 30 pCi/g of Cs-137 in soil) at different times. Based on a target cancer risk of 1×10^{-4}, the site would need remediation if it were to be released without any restriction. A different management strategy than remediation is to impose institutional control for a period of time. According to the projection of cancer risk, the institutional control should be implemented for at least 67 years, if no other measure were implemented (e.g., adding a cover layer to the contaminated soil). Choosing a target cancer risk of 3×10^{-4}, the institutional control should be implemented for just 19 years.

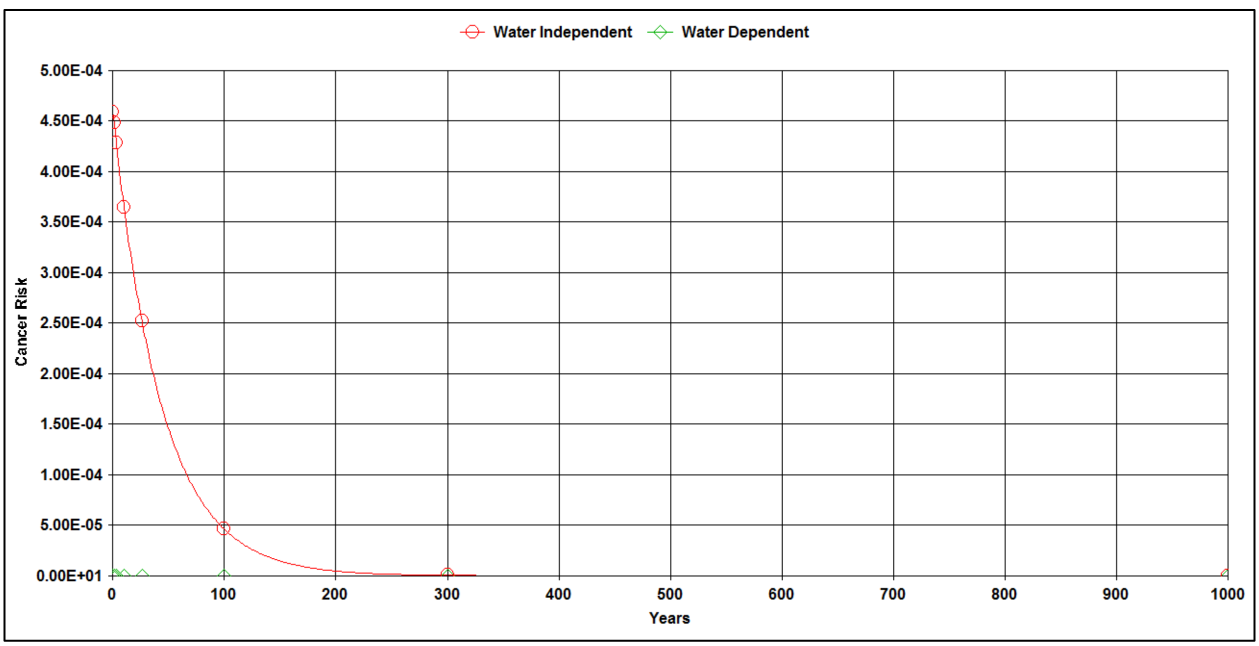

FIGURE 3.4-2 Cancer Risk Calculated by RESRAD for 30 pCi/g of Cs-137 in Soil from the Water-independent and Water-dependent Pathways – Based on the RESRAD Default K_ds

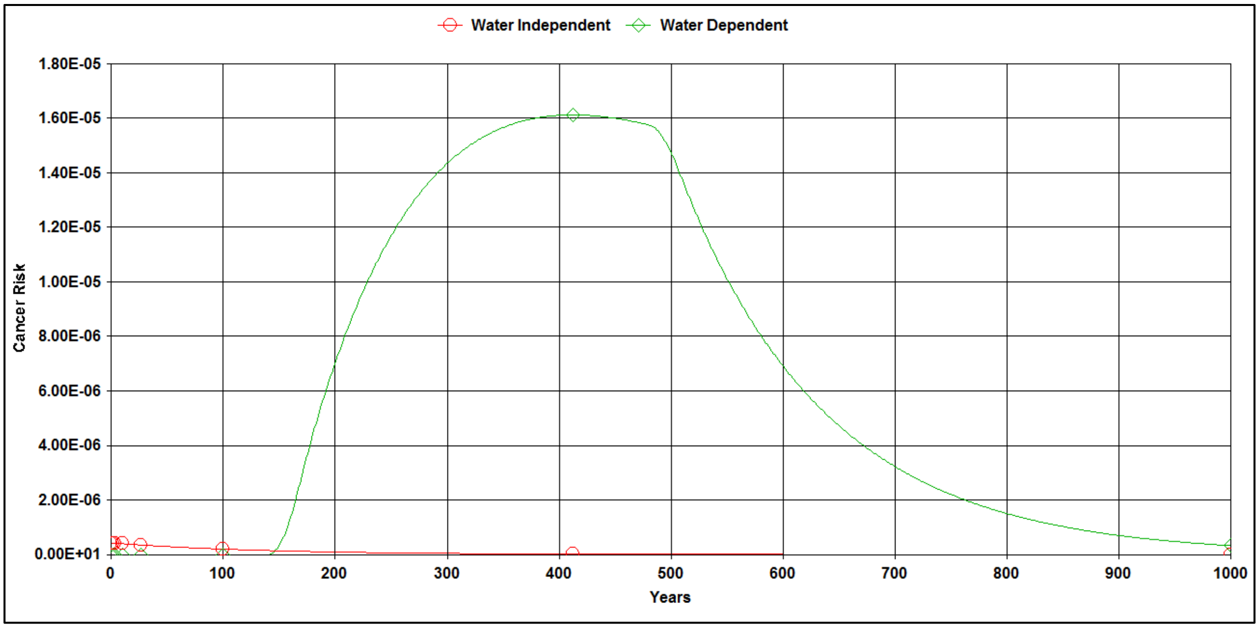

FIGURE 3.4-3 Cancer Risk Calculated by RESRAD for 1 pCi/g of Am-241 in Soil from the Water-independent and Water-dependent Pathways – Based on the RESRAD Default K_ds

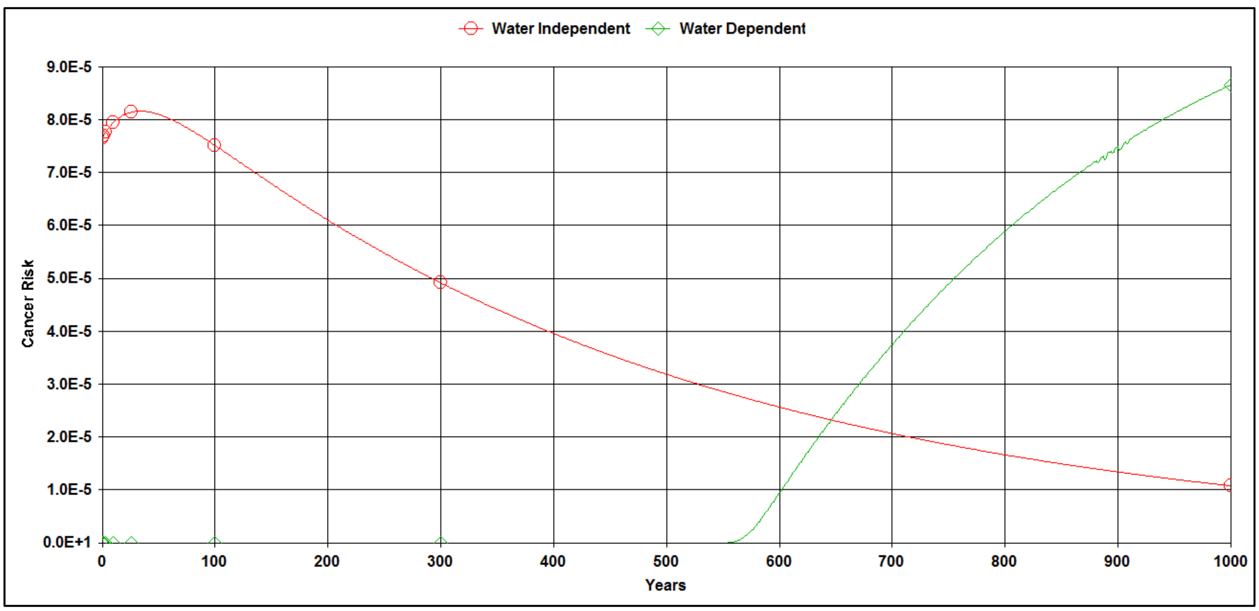

FIGURE 3.4-4 Cancer Risk Calculated by RESRAD for 1 pCi/g of Ra-226 in Soil from the Water-independent and Water-dependent Pathways – Based on the RESRAD Default K_ds

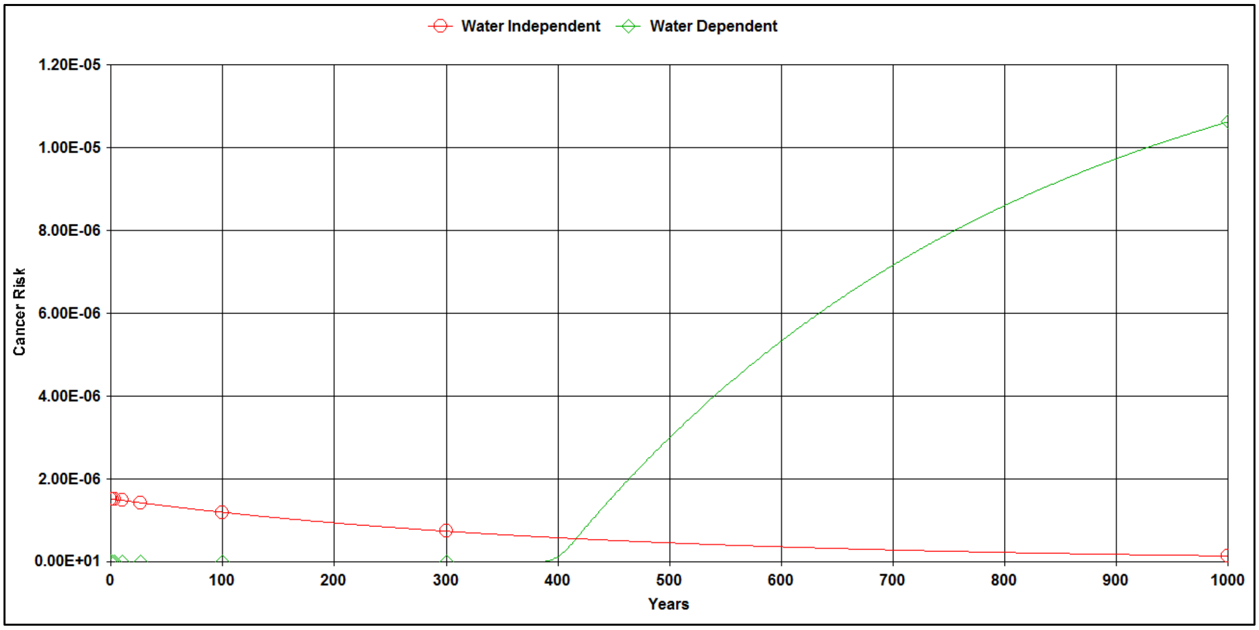

FIGURE 3.4-5 Cancer Risk Calculated by RESRAD for 1 pCi/g of U-238 in Soil from the Water-independent and Water-dependent Pathways – Based on the RESRAD Default K_ds

This page intentionally left blank.

4 COMPARISON OF RESRAD AND THE DCC CALCULATOR

The EPA DCC Calculator is used to calculate radiological dose similar to the PRG Calculator for radiological risk assessment. First, the DCC Calculator is compared with the PRG Calculator in Section 4.1, and then a comparison of the DCC Calculator with RESRAD is presented in Section 4.2. For this comparison, the DCC and PRG Calculators were accessed multiple times from January to March 2015.

4.1 COMPARISON OF THE PRG AND DCC CALCULATORS

The comparison includes the comparison of scenarios and media available for selection, models used in different exposure pathways, and general input parameters used in the calculations. The scenarios and media are compared in Section 4.1.1. The radionuclide-specific parameters are compared in Section 4.1.2.

4.1.1 Scenarios and Media

Table 4.1-1 compares the scenarios and media available for selection in the PRG and DCC Calculators. All the contaminated media can be simultaneously selected in the PRG Calculator for a selected scenario, but this option does not work in the DCC Calculator. Two site-specific construction worker scenarios—Recreator and Soil to Groundwater—are not available in the DCC Calculator. No media selection is available in the DCC Calculator for the Farmer Scenario. Currently, certain selection options are not available in the DCC Calculator (Accessed on March 19, 2015), such as selection of the Farmer Scenario and Soil to Groundwater media option for the Resident Scenario.

4.1.2 Comparison of Model and Input Parameters in the PRG and DCC Calculators

For this comparison in the PRG Calculator, the Farmer Scenario and Combined Soil and Biota media were selected; in the DCC Calculator, the Farmer Scenario was selected and there was no option for selecting any media. The PRG Calculator has the option to select multiple media simultaneously. Biota from both Soil and Water Media can also be selected in the PRG Calculator; in that case, the PRG Calculator also provides intercept PRG values for produce, fish, and beef, and diary is listed separately. The PRG/DCC from exposure to soil contamination is the sum of fraction of PRGs/DCCs derived for the soil inhalation; direct external exposure; and soil, produce, egg, poultry, fish, beef, dairy, and swine ingestion exposure pathways. The PRG/DCC Calculators estimate individual exposure pathways, and from these values the total soil PRG/DCC values are calculated. Similar equations are used in estimating soil PRGs and DCCs for the Farmer Scenario as shown in Figures 4.1-1 and 4.1-2.

In this comparison exercise, only the exposure pathways available in the RESRAD code were investigated. Figures 4.1-3 and 4.1-4 show the parameters common to all exposure route

TABLE 4.1-1 Comparison of Scenarios and Media Available in the PRG and DCC Calculators

PRG Calculator		DCC Calculator	
Scenario	Media	Scenario	Media
Resident	Soil, air, 2-D external exposure, tap water, and fish	Resident	Soil, air, 2-D external exposure, tap water, and fish
Composite worker	Soil, air, 2-D external exposure	Composite worker	Soil, air, 2-D external exposure
Outdoor worker	Soil, air, 2-D external exposure	Outdoor worker	Soil, air, 2-D external exposure
Indoor worker	Soil, air, 2-D external exposure	Indoor worker	Soil, air, 2-D external exposure
Construction worker—standard unpaved road vehicle traffic (site-specific only)	Soil, air, 2-D external exposure	NA[a]	NR[b]
Construction worker—wind erosion and other construction activities (site-specific only)	Soil, air, 2-D external exposure	NA	NR
Recreator (site-specific only)	Soil, air, 2-D external exposure, surface water, game and fowl	NA	NR
Farmer	Air, biota direct, combined soil and biota, combined water and biota, biota from both soil and water	Farmer	No selection available
Soil to groundwater	No selection available	NA	NR

[a] NA = not available or not applicable.

[b] NR = not required.

$$PRG_{soil\text{-}f\text{-}tot}\,(pCi/g) = \cfrac{1}{\frac{1}{PRG_{soil\text{-}f\text{-}sol\text{-}ing}} + \frac{1}{PRG_{soil\text{-}f\text{-}sol\text{-}inh}} + \frac{1}{PRG_{soil\text{-}f\text{-}sol\text{-}ext}} + \frac{1}{PRG_{soil\text{-}f\text{-}prod\text{-}ing}} + \frac{1}{PRG_{soil\text{-}f\text{-}egg\text{-}ing}} + \frac{1}{PRG_{soil\text{-}f\text{-}po\text{-}ing}} + \frac{1}{PRG_{soil\text{-}f\text{-}fish\text{-}ing}} + \frac{1}{PRG_{soil\text{-}f\text{-}beef\text{-}ing}} + \frac{1}{PRG_{soil\text{-}f\text{-}dairy\text{-}ing}} + \frac{1}{PRG_{soil\text{-}f\text{-}sw\text{-}ing}}}$$

FIGURE 4.1-1 Equation Used in the PRG Calculator for Estimating the Total Soil PRG

$$DCC_{soil\text{-}f\text{-}tot}\left(\frac{pCi}{g}\right)=\frac{1}{\frac{1}{DCC_{soil\text{-}f\text{-}sol\text{-}ing}}+\frac{1}{DCC_{soil\text{-}f\text{-}sol\text{-}inh}}+\frac{1}{DCC_{soil\text{-}f\text{-}sol\text{-}ext}}+\frac{1}{DCC_{soil\text{-}f\text{-}prod\text{-}ing}}+\frac{1}{DCC_{soil\text{-}f\text{-}egg\text{-}ing}}+\frac{1}{DCC_{soil\text{-}f\text{-}po\text{-}ing}}+\frac{1}{DCC_{soil\text{-}f\text{-}fish\text{-}ing}}+\frac{1}{DCC_{soil\text{-}f\text{-}beef\text{-}ing}}+\frac{1}{DCC_{soil\text{-}f\text{-}dairy\text{-}ing}}+\frac{1}{DCC_{soil\text{-}f\text{-}sw\text{-}ing}}}$$

FIGURE 4.1-2 Equation Used in the DCC Calculator for Estimating the Total Soil DCC

Parameters Common to all Exposure Route Equations

Value	Parameter	Value	Parameter
40	ED_f (exposure duration - farmer) yr	24	ET_f (exposure time - farmer) hr
34	$ED_{f\text{-}a}$ (exposure duration - farmer adult) yr	24	$ET_{f\text{-}a}$ (exposure time - farmer adult) hr
6	$ED_{f\text{-}c}$ (exposure duration - farmer child) yr	24	$ET_{f\text{-}c}$ (exposure time - farmer child) hr
350	EF_f (exposure frequency - farmer) day/yr	40	t_f (time - farmer) yr
350	$EF_{f\text{-}a}$ (exposure frequency - farmer adult) day/yr	1.0E-6	TR (target cancer risk) unitless
350	$EF_{f\text{-}c}$ (exposure frequency - farmer child) day/yr		

FIGURE 4.1-3 Parameters Common to all Soil Exposure Route Equations in the PRG Calculator

Parameters Common to all Soil Exposure Route Equations

Value	Parameter	Value	Parameter
Select a slab size	Slab size for ACF		
1	DF_w (dilution factor for drinking water)	1	DL (dose limit) mrem
1.5	ρ (soil bulk density) kg/L	1	ED_f (exposure duration – farmer) yr
0.3	S (fraction water content) L water/L pore space	1	$ED_{f\text{-}a}$ (exposure duration – adult farmer) yr
0.5	σ (total soil porosity) L water/L pore space	1	$ED_{f\text{-}c}$ (exposure duration – child farmer) yr
0.85	$AAF_{f\text{-}a}$ (annual age fraction – adult farmer)	350	EF_f (exposure frequency – farmer) day/yr
0.15	$AAF_{f\text{-}c}$ (annual age fraction – child farmer)	0.4	GSF_i (gamma shielding factor – indoor)
0.9	ACF (area correction factor)	1	t_f (time – farmer) yr

FIGURE 4.1-4 Parameters Common to all Soil Exposure Route Equations in the DCC Calculator

equations used in the PRG and DCC Calculators, respectively. The values highlighted in blue are either the values that cannot be changed, or the values that are calculated from other parameters.

The PRG Calculator uses target cancer risk in the calculations, and the DCC Calculator uses dose limit in the calculations. The PRG Calculator has an exposure duration of 40 years compared with a 1-year exposure duration in the DCC Calculator. In the PRG Calculator, the adult spends 34 years on the site and the child spends 6 years on the site. In the DCC Calculator, the adult spends 85% of his/her time and the child spends 15% of his/her time on site for an exposure duration of 1 year. However, the exposure frequency in both the PRG and DCC Calculators is 350 days.

Figures 4.1-5 and 4.1-6 show the PEF equations and parameters used in the PRG and DCC Calculators, respectively. The equations and parameters are exactly the same in both; however, the PRG Calculator lists the estimated PEF value and uses dispersion constants A, B, and C.

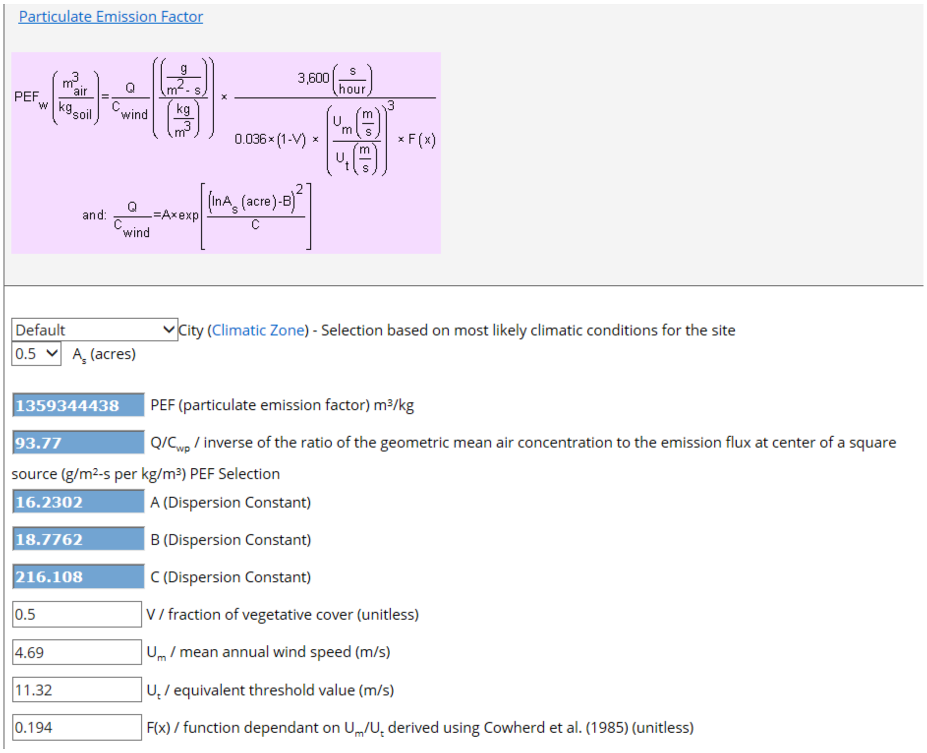

FIGURE 4.1-5 Particle Emission Factor Equation and Parameters in the PRG Calculator

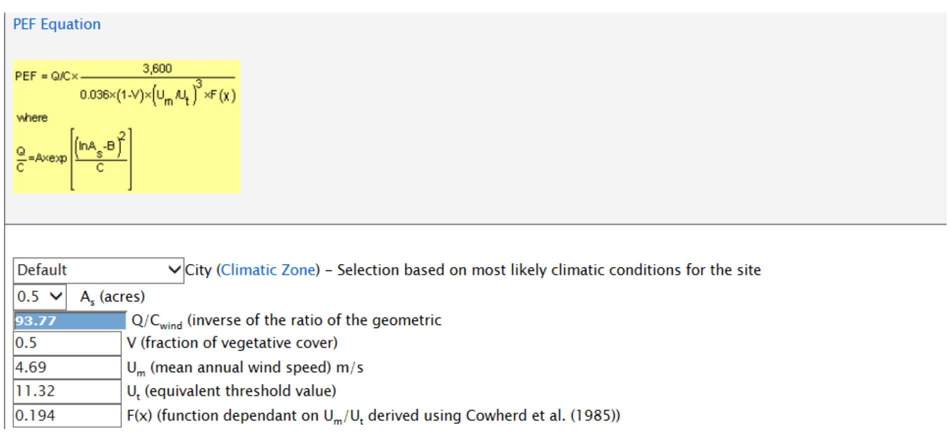

FIGURE 4.1-6 Particle Emission Factor Equation and Parameters in the DCC Calculator

Figures 4.1-7 and 4.1-8 show the equations and parameters for soil external exposure, ingestion, and inhalation used in the PRG and DCC Calculators, respectively.

There is basically no difference in the equations and parameters used in the PRG and the DCC Calculators for soil ingestion, soil inhalation, and external exposure pathways in the Farmer Scenario.

For all exposure pathways, the PRG Calculator uses Slope Factors (SFs), and the DCC Calculator uses Dose Conversion Factors (DCFs). Both the PRG and DCC Calculators apply decay correction over the exposure duration. However, the exposure duration is 40 years in the PRG Calculator and 1 year in the DCC Calculator.

Figures 4.1-9 and 4.1-10 show the equations and parameters used for estimating the exposure from the consumption of produce in the PRG and DCC Calculators, respectively. The PRG Calculator considers root uptake and foliar deposition for estimating plant contamination. The DCC Calculator only considers root uptake for estimating plant contamination. The values of the produce ingestion rates in the PRG Calculator and the DCC Calculator are also different. Table 4.1-2 lists the produce ingestion rates used in the PRG and DCC Calculators. Moreover, the default produce ingestion rates units given in the DCC Calculator are in mg/d instead of the kg/yr values used in the equations.

Figures 4.1-11 and 4.1-12 show the equations and parameters used for estimating the exposure from consumption of fish. In the PRG Calculator, fish are swimming directly in the leachate; K_d values and the bioaccumulation factor are used to estimate the fish concentration. In the DCC Calculator, contamination extends to the groundwater table; the groundwater concentration is estimated from the $K_d$value and soil properties in the contaminated zone; a dilution factor is used to estimate the surface water concentration, and the bioaccumulation factor is used in estimating the fish concentration. The values of the fish ingestion rates used in the PRG Calculator (adult 57.2 kg/yr [156.6 g/d] and child 12.0 kg/yr [32.8 g/d]) and the DCC Calculator (adult 45.8 kg/yr [125.5 g/d] and child 6.4 kg/yr [17.5 g/d]) are different.

Figures 4.1-13 and 4.1-14 show the equations and parameters used for estimating the exposure from consumption of beef. In the PRG Calculator, beef is contaminated from the ingestion of contaminated fodder and soil. In the DCC Calculator, beef is contaminated from the ingestion of contaminated fodder, soil, and water. In the DCC Calculator, contamination extends to the groundwater table; the groundwater concentration is estimated from the K_d value and soil properties in the contaminated zone; and a dilution factor for drinking water (default = 1) is used. The beef transfer factor is used to convert the daily contamination intake to the beef concentration in both the PRG and DCC Calculators. The beef fodder ingestion rate and beef soil ingestion rate in both the PRG and DCC Calculators are the same. The values of the beef ingestion rates used in the PRG Calculator (adult 65.6 kg/yr [179.7 g/d] and child 14.6 kg/yr [40.1 g/d]) and the DCC Calculator (adult 50.2 kg/yr [137.5 g/d] and child 4.7 kg/yr [12.9 g/d]) are different.

Soil External Exposure

$$PRG_{f\text{-soil-ext}}(pCi/g)=\frac{TR\times t_f\,(yr)\times\lambda\left(\frac{1}{yr}\right)}{\left(1\text{-}e^{-\lambda t_f}\right)\times SF_{ext\text{-}sv}\left(\frac{risk/yr}{pCi/g}\right)\times EF\left(\frac{350\ days}{yr}\right)\times\left(\frac{1\ yr}{365\ days}\right)\times ED_f\,(40\ yr)\times\left[\left(ET_{fo}\left(\frac{12.168\ hr}{day}\right)\times\left(\frac{1\ day}{24\ hrs}\right)\times GSF_o\,(1.0)\right)+\left(ET_{fi}\left(\frac{10.008\ hr}{day}\right)\times\left(\frac{1\ day}{24\ hrs}\right)\times GSF_i\,(0.4)\right)\right]\times ACF_{ext\text{-}sv}}$$

Soil Ingestion

$$PRG_{f\text{-soil-ing}}(pCi/g)=\frac{TR\times t_f\,(yr)\times\lambda\left(\frac{1}{yr}\right)}{\left(1\text{-}e^{-\lambda t_f}\right)\times SF_s\left(\frac{risk}{pCi}\right)\times IFS_{f\text{-adj}}\,(1{,}610{,}000\ mg)\times\left(\frac{g}{1000\ mg}\right)}$$

where:

$$IFS_{f\text{-adj}}\,(1{,}610{,}000\ mg)=\left(\begin{array}{l}\left(EF_{f\text{-c}}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-c}}\,(6\ yr)\times IRS_{f\text{-c}}\left(\frac{200\ mg}{day}\right)\right)+\\ \left(EF_{f\text{-a}}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-a}}\,(34\ yr)\times IRS_{f\text{-a}}\left(\frac{100\ mg}{day}\right)\right)\end{array}\right)$$

Soil Inhalation

$$PRG_{f\text{-soil-inh}}(pCi/g)=\frac{TR\times t_f\,(yr)\times\lambda\left(\frac{1}{yr}\right)}{\left(1\text{-}e^{-\lambda t_f}\right)\times SF_i\left(\frac{risk}{pCi}\right)\times IFA_{f\text{-adj}}\left(259{,}000\ m^3\right)\times\frac{1}{PEF\left(\frac{m^3}{kg}\right)}\times\left(\frac{1000\ g}{kg}\right)}$$

where:

$$IFA_{f\text{-adj}}\left(259{,}000\ m^3\right)=\left(\begin{array}{l}\left(EF_{f\text{-c}}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-c}}\,(6\ yr)\times ET_{f\text{-c}}\left(\frac{24\ hrs}{day}\right)\times\left(\frac{1\ day}{24\ hrs}\right)\times IRA_{f\text{-c}}\left(\frac{10\ m^3}{day}\right)\right)+\\ \left(EF_{f\text{-a}}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-a}}\,(34\ yr)\times ET_{f\text{-a}}\left(\frac{24\ hrs}{day}\right)\times\left(\frac{1\ day}{24\ hrs}\right)\times IRA_{f\text{-a}}\left(\frac{20\ m^3}{day}\right)\right)\end{array}\right)$$

- [Select a slab size] Slab size for ACF
- [Select a soil thickness cover layer] Select cover layer thickness for GSF_o (gamma shielding factor - outdoor)
- **40** ED_f (exposure duration - farmer) yr
- 34 $ED_{f\text{-}a}$ (exposure duration - farmer adult) yr
- 6 $ED_{f\text{-}c}$ (exposure duration - farmer child) yr
- **350** EF_f (exposure frequency) day/yr
- 350 $EF_{f\text{-}a}$ (exposure frequency - farmer adult) day/yr
- 350 $EF_{f\text{-}c}$ (exposure frequency - farmer child) day/yr
- 24 $ET_{f\text{-}a}$ (exposure time - farmer adult) hr/day
- 24 $ET_{f\text{-}c}$ (exposure time - farmer child) hr/day
- 10.008 $ET_{f\text{-}i}$ (indoor exposure time fraction) hr/day

- 12.168 $ET_{f\text{-}o}$ (outdoor exposure time fraction) hr/day
- 0.4 GSF_i (gamma shielding factor - indoor)
- **259000** $IFA_{f\text{-}adj}$ (age-adjusted soil inhalation factor) m^3
- **1610000** $IFS_{f\text{-}adj}$ (age-adjusted soil ingestion factor) mg
- 20 $IRA_{f\text{-}a}$ (inhalation rate - farmer adult) m^3/day
- 10 $IRA_{f\text{-}c}$ (inhalation rate - farmer child) m^3/day
- 100 $IRS_{f\text{-}a}$ (soil ingestion rate - farmer adult) mg/day
- 200 $IRS_{f\text{-}c}$ (soil ingestion rate - farmer child) mg/day
- **40** t_f (time - farmer) yr
- **1.0E-6** TR (target cancer risk) unitless

FIGURE 4.1-7 Equations and Parameters for Soil Ingestion, Inhalation, and External Exposure in the PRG Calculator

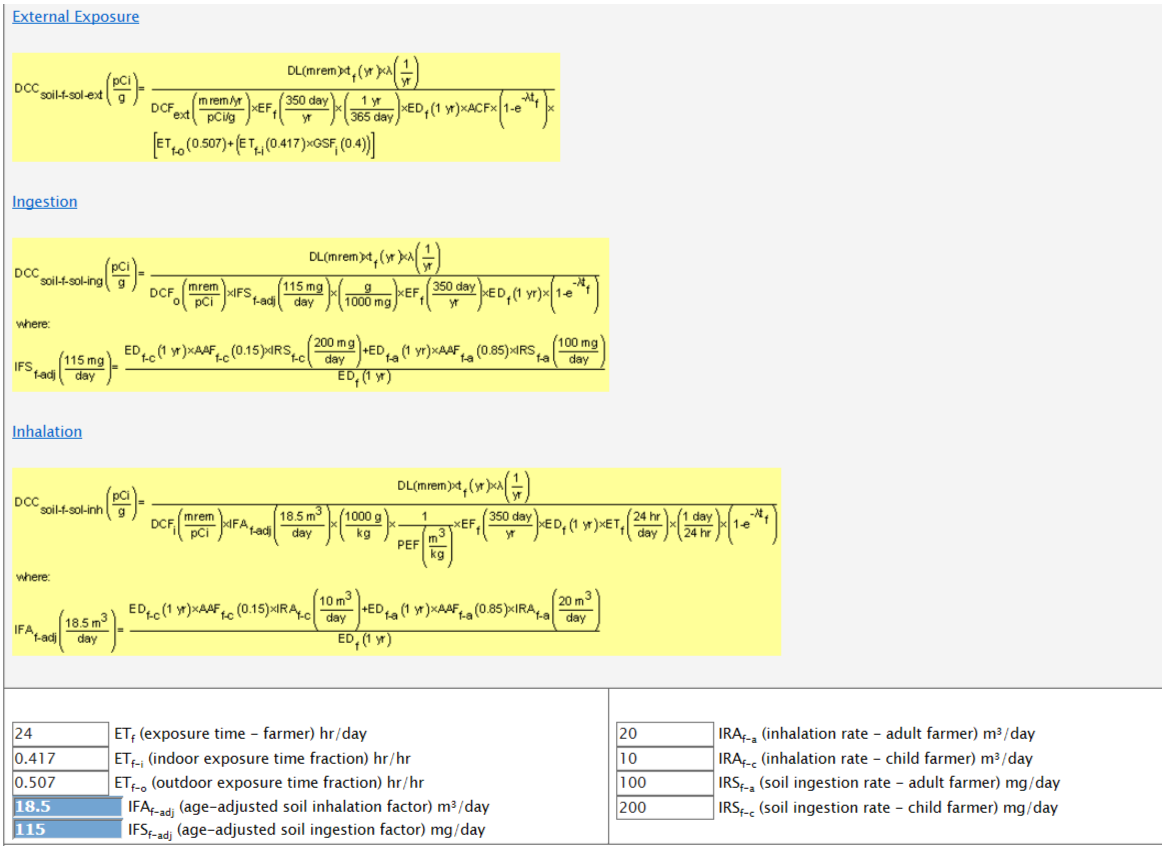

FIGURE 4.1-8 Equations and Parameters for Soil Ingestion, Inhalation, and External Exposure in the DCC Calculator

TABLE 4.1-2 Produce Ingestion Rates in the PRG and DCC Calculators

Parameter	PRG	DCC
Adult fruit ingestion rate (g/d)	178.1	56.2 (= 20.5 × 1,000/365)
Child fruit ingestion rate (g/d)	68.1	14.8 (= 5.4 × 1,000/365)
Adult vegetable ingestion rate (g/d)	126.2	28.5 (=10.4 × 1,000/365)
Child vegetable ingestion rate (g/d)	41.7	10.4 (= 3.8 × 1,000/365)

Produce Consumption - back calculated to soil

$$PRG_{soil\text{-}f\text{-}prod\text{-}ing}(pCi/g) = \frac{PRG_{f\text{-}prod\text{-}ing}(pCi/g)}{\left(R_{upv} + R_{es}\right)} \times \left(\frac{t_r(yr) \times \lambda\left(\frac{1}{yr}\right)}{\left(1 - e^{-\lambda t_r}\right)}\right)$$

where

$R_{upv} = Bv_{wet}$; $R_{es} = MLF\,(0.26)$

Produce Consumption - direct

$$PRG_{f\text{-}prod\text{-}ing}(pCi/g) = \frac{TR}{SF_f\left(\frac{risk}{pCi}\right) \times \left(IFF_{f\text{-}adj}(2{,}262{,}400\ g) + IFV_{f\text{-}adj}(1{,}589{,}350\ g)\right) \times CPF_f(1)}$$

where:

$$IFF_{f\text{-}adj}(2{,}262{,}400\ g) = \left(EF_{f\text{-}c}\left(\frac{350\ day}{yr}\right) \times ED_{f\text{-}c}(6\ yr) \times IRF_{f\text{-}c}\left(\frac{68.1\ g}{day}\right)\right) + \left(EF_{f\text{-}a}\left(\frac{350\ day}{yr}\right) \times ED_{f\text{-}a}(34\ yr) \times IRF_{f\text{-}a}\left(\frac{178.1\ g}{day}\right)\right)$$

and

$$IFV_{f\text{-}adj}(1{,}589{,}350\ g) = \left(EF_{f\text{-}a}\left(\frac{350\ day}{yr}\right) \times ED_{f\text{-}c}(6\ yr) \times IRV_{f\text{-}c}\left(\frac{41.7\ g}{day}\right)\right) + \left(EF_{f\text{-}a}\left(\frac{350\ day}{yr}\right) \times ED_{f\text{-}a}(34\ yr) \times IRV_{f\text{-}a}\left(\frac{126.2\ g}{day}\right)\right)$$

1	CPF_f (contaminated produce fraction) unitless	1589350	$IFV_{f\text{-}adj}$ (age-adjusted vegetable ingestion factor) g
34	$ED_{f\text{-}a}$ (exposure duration - farmer adult) yr	178.1	$IRF_{f\text{-}a}$ (fruit ingestion rate - farmer adult) g/day
6	$ED_{f\text{-}c}$ (exposure duration - farmer child) yr	68.1	$IRF_{f\text{-}c}$ (fruit ingestion rate - farmer child) g/day
350	$EF_{f\text{-}a}$ (exposure frequency - farmer adult) day/yr	126.2	$IRV_{f\text{-}a}$ (vegetable ingestion rate - farmer adult) g/day
350	$EF_{f\text{-}c}$ (exposure frequency - farmer child) day/yr	41.7	$IRV_{f\text{-}c}$ (vegetable ingestion rate - farmer child) g/day
2262400	$IFF_{f\text{-}adj}$ (age-adjusted fruit ingestion factor) g	0.26	$MLF_{produce}$ (produce plant mass loading factor) unitless

FIGURE 4.1-9 Equations and Parameters for Consumption of Produce in the PRG Calculator

Produce Consumption

$$DCC_{soil\text{-}f\text{-}prod\text{-}ing}\left(\frac{pCi}{g}\right) = \frac{DL(mrem) \times t_f(yr) \times \lambda\left(\frac{1}{yr}\right)}{\left(IFF_{f\text{-}adj}\left(\frac{18.235\ kg}{yr}\right) + IFV_{f\text{-}adj}\left(\frac{9.41\ kg}{yr}\right)\right) \times EF_f\left(\frac{350\ day}{yr}\right) \times \left(\frac{1\ yr}{365\ day}\right) \times ED_f(1\ yr) \times TF_p\left(\frac{\frac{pCi}{gram\text{-}plant}}{\frac{pCi}{gram\text{-}soil}}\right) \times CPF_f(1.0) \times \left(\frac{1000\ g}{kg}\right) \times DCF_o\left(\frac{mrem}{pCi}\right) \times \left(1 - e^{-\lambda t_f}\right)}$$

where:

$$IFF_{f\text{-}adj}\left(\frac{18.235\ kg}{yr}\right) = \frac{ED_{f\text{-}c}(1\ yr) \times AAF_{f\text{-}c}(0.15) \times IRF_{f\text{-}c}\left(\frac{5.4\ kg}{yr}\right) + ED_{f\text{-}a}(1\ yr) \times AAF_{f\text{-}a}(0.85) \times IRF_{f\text{-}a}\left(\frac{20.5\ kg}{yr}\right)}{ED_f(1\ yr)}$$

$$IFV_{f\text{-}adj}\left(\frac{9.41\ kg}{yr}\right) = \frac{ED_{f\text{-}c}(1\ yr) \times AAF_{f\text{-}c}(0.15) \times IRV_{f\text{-}c}\left(\frac{3.8\ kg}{yr}\right) + ED_{f\text{-}a}(1\ yr) \times AAF_{f\text{-}a}(0.85) \times IRV_{f\text{-}a}\left(\frac{10.4\ kg}{yr}\right)}{ED_f(1\ yr)}$$

1	CPF_f (contaminated plant fraction – farmer)	5.4	$IRF_{f\text{-}c}$ (fruit consumption rate – child farmer) mg/day
18.235	$IFF_{f\text{-}adj}$ (age-adjusted fruit ingestion factor) mg-yr/kg-day	10.4	$IRV_{f\text{-}a}$ (vegetable consumption rate – adult farmer) mg/day
9.41	$IFV_{f\text{-}adj}$ (age-adjusted vegetable ingestion factor) mg-yr/kg-day	3.8	$IRV_{f\text{-}c}$ (vegetable consumption rate – child farmer) mg/day
20.5	$IRF_{f\text{-}a}$ (fruit consumption rate – adult farmer) mg/day		

FIGURE 4.1-10 Equations and Parameters for Consumption of Produce in the DCC Calculator

Fish Consumption - back calculated to soil

$$PRG_{soil\text{-}f\text{-}fish\text{-}ing}(pCi/g)=\frac{PRG_{f\text{-}fish\text{-}ing}(pCi/g)\times Kd\left(\frac{L}{kg}\right)}{BCF\left(\frac{L}{kg}\right)}\times\left(\frac{t_r(yr)\times\lambda\left(\frac{1}{yr}\right)}{\left(1-e^{-\lambda t_r}\right)}\right)$$

Fish Consumption - direct

$$PRG_{f\text{-}fish\text{-}ing}(pCi/g)=\frac{TR}{SF_f\left(\frac{risk}{pCi}\right)\times IFFI_{f\text{-}adj}(1{,}932{,}420\ g)\ \times CF_{fish}(1)}$$

where:

$$IFFI_{f\text{-}adj}(1{,}932{,}420\ g)=\left(EF_{f\text{-}c}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-}c}(6\ yr)\times IRFI_{f\text{-}c}\left(\frac{32.8\ g}{day}\right)\right)+\left(EF_{f\text{-}a}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-}a}(34\ yr)\times IRFI_{f\text{-}a}\left(\frac{156.6\ g}{day}\right)\right)$$

1	CF_{fish} (fish contaminated fraction) unitless	156.6	$IRFI_{f\text{-}a}$ (fish ingestion rate - farmer adult) g/day
1932420	$IFFI_{f\text{-}adj}$ (age-adjusted fish ingestion factor) g	32.8	$IRFI_{f\text{-}c}$ (fish ingestion rate - farmer child) g/day

FIGURE 4.1-11 Equations and Parameters for Consumption of Fish in the PRG Calculator

Fish Consumption

$$DCC_{soil\text{-}f\text{-}fish\text{-}ing}\left(\frac{pCi}{g}\right)=\frac{DL(mrem)\times t_f(yr)\times\lambda\left(\frac{1}{yr}\right)}{IFFI_{f\text{-}adj}\left(\frac{39.89\ kg}{yr}\right)\times\left(\frac{1000\ g}{kg}\right)\times DCF_o\left(\frac{mrem}{pCi}\right)\times EF_f\left(\frac{350\ day}{yr}\right)\times\left(\frac{1\ yr}{365\ day}\right)\times ED_f(1\ yr)\times TF_f\left(\frac{L}{kg}\right)\times\frac{1}{\left(K_d\left(\frac{L}{kg}\right)+\sigma(0.5)\times\left(\frac{S(0.3)}{\rho\left(\frac{1.5\ kg}{L}\right)}\right)\right)}\times\frac{A_s\left(10^4\ m^2\right)}{A_w\left(10^5\ m^2\right)}\times\left(1-e^{-\lambda t_f}\right)}$$

where:

$$IFFI_{f\text{-}adj}\left(\frac{39.89\ kg}{yr}\right)=\frac{ED_{f\text{-}c}(1\ yr)\times AAF_{f\text{-}c}(0.15)\times IRFI_{f\text{-}c}\left(\frac{6.4\ kg}{yr}\right)+ED_{f\text{-}a}(1\ yr)\times AAF_{f\text{-}a}(0.85)\times IRFI_{f\text{-}a}\left(\frac{45.8\ kg}{yr}\right)}{ED_f(1\ yr)}$$

10000	A_s (surface area of contaminated site) m^2	45.8	$IRFI_{f\text{-}a}$ (fish ingestion rate – adult farmer) kg/yr
100000	A_w (surface area of watershed) m^2	6.4	$IRFI_{f\text{-}c}$ (fish ingestion rate – child farmer) kg/yr
39.89	$IFFI_{f\text{-}adj}$ (age-adjusted fish ingestion rate) kg/yr		

FIGURE 4.1-12 Equations and Parameters for Consumption of Fish in the DCC Calculator

Beef Consumption - back calculated to soil

$$PRG_{soil\text{-}f\text{-}beef\text{-}ing}(pCi/g)=\frac{PRG_{f\text{-}beef\text{-}ing}(pCi/g)}{TF_{beef}\left(\frac{day}{kg}\right)\times\left[\left(Q_{p\text{-}beef}\left(\frac{11.77\ kg}{day}\right)\times f_{p\text{-}beef}(1)\times f_{s\text{-}beef}(1)\times\left(R_{upp}+R_{es}\right)\right)+\left(Q_{s\text{-}beef}\left(\frac{0.39\ kg}{day}\right)\times f_{p\text{-}beef}(1)\right)\right]}\times\left(\frac{t_r(yr)\times\lambda\left(\frac{1}{yr}\right)}{\left(1-e^{-\lambda t_r}\right)}\right)$$

where:

$$R_{upp}=Bv_{dry}\qquad R_{es}=MLF(0.25)$$

Beef Consumption - direct

$$PRG_{f\text{-}beef\text{-}ing}(pCi/g)=\frac{TR}{SF_f\left(\frac{risk}{pCi}\right)\times IFB_{f\text{-}adj}(2{,}222{,}640\ g)\ \times CF_{beef}(1)}$$

where:

$$IFB_{f\text{-}adj}(2{,}222{,}640\ g)=\left(EF_{f\text{-}c}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-}c}(6\ yr)\times IRB_{f\text{-}c}\left(\frac{40.1\ g}{day}\right)\right)+\left(EF_{f\text{-}a}\left(\frac{350\ day}{yr}\right)\times ED_{f\text{-}a}(34\ yr)\times IRB_{f\text{-}a}\left(\frac{179.7\ g}{day}\right)\right)$$

Value	Parameter
1	CF_{beef} (beef contaminated fraction) unitless
2222640	$IFB_{f\text{-}adj}$ (age-adjusted beef ingestion factor) g
179.7	$IRB_{f\text{-}a}$ (beef ingestion rate - farmer adult) g/day
40.1	$IRB_{f\text{-}c}$ (beef ingestion rate - farmer child) g/day
1	$f_{p\text{-}beef}$ (animal on-site fraction) unitless
1	$f_{s\text{-}beef}$ (fraction of year animal on site) unitless
0.25	MLF_{beef} (plant mass loading factor) unitless
11.77	$Q_{p\text{-}beef}$ (beef fodder intake rate) kg/day
0.39	$Q_{s\text{-}beef}$ (beef soil intake rate) kg/day

FIGURE 4.1-13 Equations and Parameters for Consumption of Beef in the PRG Calculator

Beef Consumption

$$DCC_{soil\text{-}f\text{-}beef\text{-}ing}\left(\frac{pCi}{g}\right)=\frac{DL(mrem)\times t_f(yr)\times\lambda\left(\frac{1}{yr}\right)}{DCF_o\left(\frac{mrem}{pCi}\right)\times\left(1-e^{-\lambda t_f}\right)\times\left(\frac{1000\ g}{kg}\right)\times IFB_{f\text{-}adj}\left(\frac{43.375\ kg}{yr}\right)\times EF_f\left(\frac{350\ day}{yr}\right)\times\left(\frac{1\ yr}{365\ day}\right)\times ED_f(1\ yr)\times\left(\begin{array}{l}\left(TF_{beef}\left(\frac{day}{kg}\right)\times FI_{beef}\left(\frac{11.77\ kg}{day}\right)\times TF_p\left(\frac{\frac{pCi}{gram\text{-}plant}}{\frac{pCi}{gram\text{-}soil}}\right)\right)+\left(TF_{beef}\left(\frac{day}{kg}\right)\times FI_{beef\text{-}s}\left(\frac{0.39\ kg}{day}\right)\right)+\\ \left(TF_{beef}\left(\frac{day}{kg}\right)\times FI_{beef\text{-}w}\left(\frac{53\ L}{day}\right)\times\frac{1}{\left(K_d\left(\frac{L}{kg}\right)+\sigma(0.5)\times\left(\frac{S(0.3)}{\rho\left(\frac{1.5\ kg}{L}\right)}\right)\right)}\times\frac{1}{DF_w}\right)\end{array}\right)}$$

where:

$$IFB_{f\text{-}adj}\left(\frac{43.375\ kg}{yr}\right)=\frac{ED_{f\text{-}c}(1\ yr)\times AAF_{f\text{-}c}(0.15)\times IRB_{f\text{-}c}\left(\frac{4.7\ kg}{yr}\right)+ED_{f\text{-}a}(1\ yr)\times AAF_{f\text{-}a}(0.85)\times IRB_{f\text{-}a}\left(\frac{50.2\ kg}{yr}\right)}{ED_f(1\ yr)}$$

Value	Parameter
43.375	$IFB_{f\text{-}adj}$ (age-adjusted beef ingestion rate) kg/yr
11.77	FI_{beef} (beef fodder ingestion rate) kg/day
0.39	$FI_{beef\text{-}s}$ (beef soil ingestion rate) kg/day
53	$FI_{beef\text{-}w}$ (beef water ingestion rate) kg/day
50.2	$IRB_{f\text{-}a}$ (beef ingestion rate - adult farmer) kg/yr
4.7	$IRB_{f\text{-}c}$ (beef ingestion rate - child farmer) kg/yr

FIGURE 4.1-14 Equations and Parameters for Consumption of Beef in the DCC Calculator

Figures 4.1-15 and 4.1-16 show the equations and parameters used for estimating the exposure from consumption of dairy products. In the PRG Calculator, dairy is contaminated from the ingestion of contaminated fodder and soil. In the DCC Calculator, dairy is contaminated from the ingestion of contaminated fodder, soil, and water. In the DCC Calculator, contamination extends to the groundwater table; the groundwater concentration is estimated from the K_d value and soil properties in the contaminated zone; and a dilution factor for drinking water (default = 1) is used. The milk transfer factor is used to convert the daily contamination intake to dairy concentration in both the PRG and DCC Calculators. The dairy fodder ingestion rate and the dairy soil ingestion rate in both the PRG and DCC Calculators are the same. The values of the dairy ingestion rates used in the PRG Calculator (adult 162.6 kg/yr [445.6 g/d] and child 127.6 kg/yr [349.5 g/d]) and the DCC Calculator (adult 224.4 kg/yr [614.8 g/d] and child 96.9 kg/yr [265.5 g/d]) are different.

Table 4.1-3 summarizes the differences observed in the PRG and DCC Calculators for the Farmer Scenario.

Dairy Consumption - back calculated to soil

$$PRG_{soil\text{-}f\text{-}dairy\text{-}ing}(pCi/g) = \frac{PRG_{f\text{-}dairy\text{-}ing}(pCi/g)}{TF_{dairy}\left(\frac{day}{L\ milk}\right) \times \rho_m \left(\frac{1.03\ kg}{1\ L\ milk}\right)^{-1} \times \left[\left(Q_{p\text{-}dairy}\left(\frac{16.9\ kg}{day}\right) \times f_{p\text{-}dairy}(1) \times f_{s\text{-}dairy}(1) \times \left(R_{upp} + R_{es}\right)\right) + \left(Q_{s\text{-}dairy}\left(\frac{0.41\ kg}{day}\right) \times f_{p\text{-}m}(1)\right)\right]} \times \left(\frac{t_r(yr) \times \lambda\left(\frac{1}{yr}\right)}{\left(1 - e^{-\lambda t_r}\right)}\right)$$

where:

$R_{upp} = Bv_{dry}$ $\quad R_{es} = MLF(0.25)$

Dairy Consumption - direct

$$PRG_{f\text{-}dairy\text{-}ing}(pCi/g) = \frac{TR}{SF_f\left(\frac{risk}{pCi}\right) \times IFD_{f\text{-}adj}(6{,}036{,}590\ g) \times CF_{dairy}(1)}$$

where:

$$IFD_{f\text{-}adj}(6{,}036{,}590\ g) = \left(EF_{f\text{-}c}\left(\frac{350\ day}{yr}\right) \times ED_{f\text{-}c}(6\ yr) \times IRD_{f\text{-}c}\left(\frac{349.5\ g}{day}\right)\right) + \left(EF_{f\text{-}a}\left(\frac{350\ day}{yr}\right) \times ED_{f\text{-}a}(34\ yr) \times IRD_{f\text{-}a}\left(\frac{445.6\ g}{day}\right)\right)$$

1	CF_{dairy} (dairy contaminated fraction) unitless	1	$f_{p\text{-}dairy}$ (animal on-site fraction) unitless
6036590	$IFD_{f\text{-}adj}$ (age-adjusted dairy ingestion factor) g	1	$f_{s\text{-}dairy}$ (fraction of year animal on site) unitless
445.6	$IRD_{f\text{-}a}$ (dairy ingestion rate - farmer adult) g/day	0.25	MLF_{dairy} (plant mass loading factor) unitless
349.5	$IRD_{f\text{-}c}$ (dairy ingestion rate - farmer child) g/day	16.9	$Q_{p\text{-}dairy}$ (dairy fodder intake rate) kg/day
1.03	ρ_m (density of milk) kg/L	0.41	$Q_{s\text{-}dairy}$ (dairy soil intake rate) kg/day

FIGURE 4.1-15 Equations and Parameters for Consumption of Dairy in the PRG Calculator

Dairy Consumption

$$DCC_{soil\text{-}f\text{-}dairy\text{-}ing}\left(\frac{pCi}{g}\right)=\frac{DL(mrem)\times t_f(yr)\times\lambda\left(\frac{1}{yr}\right)}{DCF_o\left(\frac{mrem}{pCi}\right)\times\left(1-e^{-\lambda t_f}\right)\times\left(\frac{1000\ g}{kg}\right)\times IFD_{f\text{-}adj}\left(\frac{205.275\ kg}{yr}\right)\times EF_f\left(\frac{350\ day}{yr}\right)\times\left(\frac{1\ yr}{365\ day}\right)\times ED_f(1\ yr)\times\left(\left(TF_{dairy}\left(\frac{day}{kg}\right)\times FI_{dairy}\left(\frac{16.9\ kg}{day}\right)\times TF_p\left(\frac{\frac{pCi}{gram\text{-}plant}}{\frac{pCi}{gram\text{-}soil}}\right)\right)+\left(TF_{dairy}\left(\frac{day}{kg}\right)\times FI_{dairy\text{-}s}\left(\frac{0.41\ kg}{day}\right)\right)+\left(TF_{dairy}\left(\frac{day}{kg}\right)\times FI_{dairy\text{-}w}\left(\frac{92\ L}{day}\right)\times\frac{1}{\left(K_d\left(\frac{L}{kg}\right)+\sigma(0.5)\times\left(\frac{S(0.3)}{\rho\left(\frac{1.5\ kg}{L}\right)}\right)\right)}\times\frac{1}{DF_w}\right)\right)}$$

where:

$$IFD_{f\text{-}adj}\left(\frac{205.275\ kg}{yr}\right)=\frac{ED_{f\text{-}c}(1\ yr)\times AAF_{f\text{-}c}(0.15)\times IRD_{f\text{-}c}\left(\frac{96.9\ kg}{yr}\right)+ED_{f\text{-}a}(1\ yr)\times AAF_{f\text{-}a}(0.85)\times IRD_{f\text{-}a}\left(\frac{224.4\ kg}{yr}\right)}{ED_f(1\ yr)}$$

16.9	FI_{dairy} (dairy fodder ingestion rate kg/day	224.4	$IRD_{f\text{-}a}$ (dairy ingestion rate – adult farmer) kg/yr
0.41	$FI_{dairy\text{-}s}$ (dairy soil ingestion rate) kg/day	96.9	$IRD_{f\text{-}c}$ (dairy ingestion rate – child farmer) kg/yr
92	$FI_{dairy\text{-}w}$ (dairy water ingestion rate) kg/day	205.275	$IFD_{f\text{-}adj}$ (age–adjusted dairy ingestion rate) kg/yr

FIGURE 4.1-16 Equations and Parameters for Consumption of Dairy in the DCC Calculator

4.2 COMPARISON OF THE DCC CALCULATOR AND RESRAD

In this section, the calculations of different exposure scenarios and pathways in the DCC Calculator are compared with the RESRAD code. For this comparison, the RESRAD (onsite) code Version 7.0 (www.evs.anl.gov/resrad) and the EPA DCC Calculator (http://epa-dccs.ornl.gov/cgi-bin/dose_search) were used. The comparison focused on the soil concentrations for radionuclides corresponding to a target radiation dose of 1 mrem/yr. The comparison was performed for the Outdoor Worker, Resident, and Farmer Scenarios. For this comparison, 21 commonly used radionuclides in dose/risk assessment were selected. Some of the detailed information on selected radionuclide decay schemes and input parameters are included in Appendix B. Table B.1 lists the properties of radionuclides selected for comparison. Figures B.1 through B.4 show the decay schemes of the selected radionuclides. Radionuclide- and element-specific input parameters are compared in Tables B.2 and B.3.

For the comparison, the default settings of the DCC Calculator were maintained, including the DCs and transfer factors. The input values used in the RESRAD code were changed as much as possible to match the input values used in the DCC Calculator. Table B.4 lists the DCFs used in both codes. In actual calculations, different inhalation class type DCFs are used in the DCC Calculator for Ac-227, Ac-228, C-14, H-3, I-129, Pa-231, Pa-233, Pa-234, and yttrium (Y-90) compared with the inhalation class type listed in DCC Calculator output results (Table B.4). There is also a slight (<0.5%) difference in external DCFs due to rounding errors (Table B.4).

TABLE 4.1-3 Differences in the PRG and DCC Calculators for the Farmer Scenario (Selected Combined Soil and Biota Media in the PRG Calculator)[a]

Pathway	PRG	DCC
Calculation method	Uses target cancer risk level and slope factors.	Uses target dose limit and dose conversion factors.
Exposure duration	Adult spends 34 years on site and child spends 6 years on site from the total exposure duration of 40 years. For the exposure duration of 40 years, the decay correction is applied.	An adult spends 85% of his/her time on site and a child spends 15% of his/her time on site for the total exposure duration of 1 year. For the exposure duration of 1 year, the decay correction is applied.
Soil ingestion, inhalation, and external exposure	No difference.	No difference.
Produce consumption	Produce is contaminated from root uptake and foliar deposition. Produce ingestion rates are different (see Table 4.1-2).	Produce is contaminated only from root uptake. Produce ingestion rates are different (see Table 4.1-2).
Estimation of leachate concentration	K_d values are used for estimating leachate concentration.	Not required.
Estimation of groundwater concentration	Not required.	The contamination extends to the groundwater table; the groundwater concentration is estimated from the K_d value and soil properties in the contaminated zone.
Estimation of surface water concentration	Not required.	A dilution factor is used to estimate the surface water concentration from the groundwater concentration.
Fish consumption	Fish are swimming directly in the leachate, and the bioaccumulation factor is used to estimate the fish concentration. Fish ingestion rates of 57.2 kg/yr (156.6 g/d) are used for an adult and 12.0 kg/yr (32.8 g/d) for a child.	Fish are swimming in the surface water body, and the bioaccumulation factor is used in estimating the fish concentration. Fish ingestion rates of 45.8 kg/yr (125.5 g/d) are used for an adult and 6.4 kg/yr (17.5 g/d) for a child.
Beef consumption	Beef is contaminated from the ingestion of contaminated fodder and soil. Beef ingestion rates of 65.6 kg/yr (179.7 g/d) are used for an adult and 14.6 kg/yr (40.1 g/d) for a child.	Beef is contaminated from the ingestion of contaminated fodder, soil, and water. Beef ingestion rates of 50.2 kg/yr (137.5 g/d) are used for an adult and 4.7 kg/yr (12.9 g/d) for a child.
Diary consumption	Dairy is contaminated from the ingestion of contaminated fodder and soil. Dairy ingestion rates of 162.6 kg/yr (445.6 g/d) are used for an adult and 127.6 kg/yr (349.5 g/d) for a child.	Dairy is contaminated from the ingestion of contaminated fodder, soil, and water. Dairy ingestion rates of 224.4 kg/yr (614.8 g/d) are used for an adult and 96.9 kg/yr (265.5 g/d) for a child

[a] If biota from both soil and water media are selected in the PRG Calculator, the “intercept” PRG values for produce, fish, beef, and diary are also listed separately.

4.2.1 Effect of Modeling Assumptions on the Results

The RESRAD code allows users to select any cutoff half-life. The DCC Calculator has the option to select +D or +E. For +D, the cutoff half-life selected is 100 years, and for +E, the cutoff half-life selected is 1,000 years. Table B.5 lists the expected DCFs with different cutoff half-lives and compares them with the actual values used in the code. Footnotes in the table list the discrepancies observed. In the RESRAD code, depending on the cutoff half-life selected, DCFs of daughter products with half-lives less than the cutoff half are automatically added along with the parent radionuclide, and the DCFs used are listed in the summary report. No discrepancies were noted in the RESRAD code in the way DCFs are handled. Table 4.2-1 summarizes the discrepancies in the DCC Calculator for the 21 radionuclides selected for the analysis when a cutoff half-life of 6 months is selected in RESRAD for the analysis. Ac-227, Pa 231, Pb-210, Pu-241, and Th-228 all include decay products with less than a 100-year half-life; however, +D or +E are not available for analysis in the DCC Calculator. For Ac-227 and Th-228, the external dose would be underestimated in the DCC Calculator by 3 orders of magnitude. For Pb-210, all pathway doses would be different. For Pu-241, Ra-226, Ra-228, Sr-90, and U-238, the contributions of daughter products are not added correctly in the DCC Calculator. DCFs for Pa-231, Ra-226, and Ra-228 would change when a cutoff half-life of 100 years is used instead of 6 months.

4.2.2 Outdoor Worker Scenario Comparison

The Outdoor Worker Scenario considers three exposure pathways: (1) direct exposure to external radiation from the contaminated soil, (2) internal radiation from inhalation of contaminated dust, and (3) internal radiation from incidental ingestion of soil. RESRAD (onsite) Version 7.0 was used to calculate the potential radiation dose for the outdoor worker. The period

TABLE 4.2-1 Effect of DCFs on the Analysis

Radionuclide	Ratio (RESRAD/DCC) DCFs		
	Ingestion	Inhalation	External
Ac-227+D	1.10	1.08	4190
Pb-210+D	2.74	4.08	3.79
Pu-241+D	0.998	1	3.23
Ra-226+D	0.997	1	0.883
Ra-228+D	0.832	0.057	1
Sr-90+D	1.09	1.04	1.01
Th-228+D	1.99	1.08	1350
U-235+D	NA[a]	NA	1
U-238+D	1.07	1.01	0.881

[a] DCFs are not available in the DCC Calculator.

considered for this analysis was 1,000 years. For this comparison, the element-specific parameters were set at the DCC default values listed in Table B.3. The other RESRAD input parameters used for this comparison are listed in Table B.6. The RESRAD code provides individual exposure pathway dose contribution to the total dose. The individual pathway dose was used to estimate soil concentration that will result in a 1-mrem/yr dose.

Table B.7 compares the soil DCCs and the RESRAD-estimated SCGs for individual exposure pathways that result in a 1-mrem/yr dose for the Outdoor Worker Scenario. For some radionuclides, the peak occurs at later times. Table B.7 lists the results from RESRAD for all radionuclides at time 0 and also lists the results for the radionuclides when the peak dose occurs at later times. The differences greater than 10% are highlighted in red. The explanation of the differences is provided in the Remarks column in the table. As shown in Table B.7, the DCC Calculator underestimated results for many radionuclides.

Differences in the external exposure are due to the differences in the ACF used in the DCC Calculator and RESRAD code. Table B.2 in Appendix B compares the ACFs used. For some radionuclides, differences were observed due to the leaching of contaminant from the contaminated zone to a deeper soil layer. Another run with RESRAD was performed by increasing the K_d value and lowering the infiltration rate (Table B.8). Table 4.2.2 shows the ratio of DCC/RESRAD results for the Outdoor Worker Scenario using high K_d and low infiltration in the RESRAD run. The differences greater than 10% are highlighted in red. For I-129, Np-237, and Tc-99, now there is practically no difference in the DCC and RESRAD results. The effect of short-lived progeny and the buildup of long-lived progeny on the DCC values is explored in Section 4.2.3.

Figure 4.2-1 shows the effect of K_d values on the yearly average soil concentration in the contaminated zone in the RESRAD code. For radionuclides with K_d values less than or equal to 0.1, the yearly average soil concentration will be about 0.8 times lower compared with the values without any infiltration or leaching in the RESRAD code. This results in lowering the DCC soil concentrations compared with the SCG values. Table 4.2-3 shows the effect of K_d for the radionuclides included in this study. Figure 4.2-2 shows the results for the Outdoor Worker Scenario after removing the K_d effect in the RESRAD code (i.e., using high Kd and low infiltration). Peak dose for all radionuclides from the RESRAD run was used in the plot. RESRAD has a special model for H-3 and C-14; therefore, the results for C-14 and H-3 were not plotted. Table 4.2-4 summarizes the reasons for the differences in DCC and RESRAD ratios greater than 10% for individual pathways for the Outdoor Worker Scenario.

4.2.3 Time Integration and Decay Correction

RESRAD code estimates integrated yearly dose and includes the contributions of decay and ingrowth in calculating dose. The DCC Calculator estimates static dose at time 0 and applies a decay correction factor for 1 year of exposure. Table 4.2-5 compares the impact of these modeling assumptions on the estimated doses. The Outdoor Worker Scenario was used for this comparison; all the parameters were kept at Outdoor Worker Scenario parameter values. The

TABLE 4.2.2 Comparison of DCC and RESRAD Results for the Outdoor Worker Scenario

Radionuclide	Time of Dose in RESRAD	Ratio (DCC/SCG)[a]			
		Ingestion	Inhalation	External	Total
Ac-227	0	1.10E+00	1.09E+00	3.97E+03	4.97E+00
Am-241	0	1.00E+00	1.01E+00	1.01E+00	1.00E+00
C-14	0	2.90E-01	6.64E+05	3.10E-01	1.29E+00
Co-60	0	1.00E+00	1.01E+00	1.13E+00	1.13E+00
Cs-137+D	0	1.00E+00	1.01E+00	1.07E+00	1.07E+00
H-3	0	1.00E+00	2.32E-02	NA[b]	2.32E-02
I-129	0	9.98E-01	1.01E+00	1.02E+00	1.00E+00
Np-237+D	0	1.01E+00	1.01E+00	9.77E-01	9.79E-01
Pa-231	0	1.03E+00	1.04E+00	1.11E+00	1.06E+00
Pb-210	0	2.74E+00	4.13E+00	3.64E+00	2.75E+00
Pu-239	0	9.99E-01	1.01E+00	9.55E-01	1.00E+00
Pu-241	0	1.03E+00	1.05E+00	8.82E+00	1.05E+00
Ra-226+D	0	1.11E+00	1.04E+00	1.01E+00	1.02E+00
Ra-228+D	0	8.62E-01	2.13E-01	1.30E+00	1.28E+00
Sr-90+D	0	1.10E+00	1.05E+00	9.46E-01	9.80E-01
Tc-99	0	1.00E+00	1.01E+00	1.04E+00	1.01E+00
Th-228	0	1.99E+00	1.09E+00	1.30E+03	2.37E+02
Th-230	0	1.00E+00	1.01E+00	2.99E+00	1.03E+00
U-234	0	9.99E-01	1.01E+00	9.68E-01	1.00E+00
U-235+D	0	0.00E+00	0.00E+00	9.95E-01	1.02E+00
U-238+D	0	1.08E+00	1.02E+00	8.52E-01	8.75E-01
Pa-231	223	2.69E+00	2.71E+00	1.10E+01	5.76E+00
Pu-241	58	1.31E+00	1.47E+00	2.10E+02	1.85E+00
Ra-226+D	53	6.38E+00	2.03E+00	9.92E-01	1.05E+00
Ra-228+D	3	6.84E-01	6.03E-01	1.74E+00	1.68E+00
Th-230	1,000	4.53E+00	1.20E+00	3.28E+03	4.46E+01
U-234	1,000	1.11E+00	1.05E+00	5.13E+01	1.95E+00
U-235+D	1,000	0.00E+00	0.00E+00	1.05E+00	1.11E+00
U-238+D	1,000	1.08E+00	1.02E+00	8.52E-01	8.75E-01

[a] Differences in ratios (DCC/SCG) greater than 10% are shown in red type.

[b] NA = not available or not applicable.

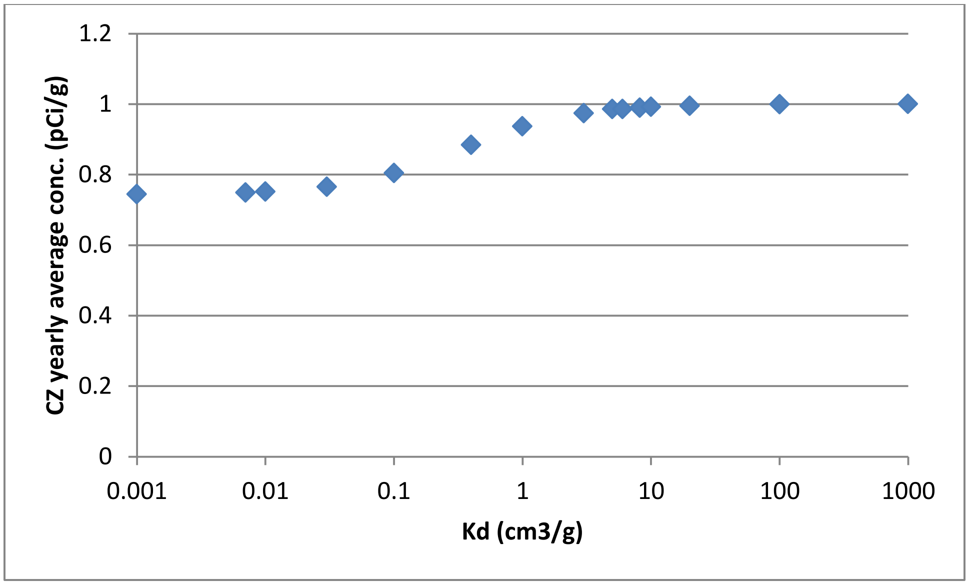

FIGURE 4.2-1 Effect of K_d on Yearly Average Contaminated Zone Soil Concentration

TABLE 4.2-3 Effect of K_d on the Concentration in the Contaminated Zone

Element	K_d (cm^3/g)	Average Soil Concentration. (pCi/g)
H	0	0.74
Tc	0.007	0.75
I	0.03	0.77
Co, Np	0.1	0.80
U	0.4	0.88
C	0.8	0.93
Sr	1	0.94
Ra	3	0.97
Pu	5	0.99
Pb	6	0.99
Am	8.2	0.99
Cs	10	0.99
Ac, Th	20	1.00

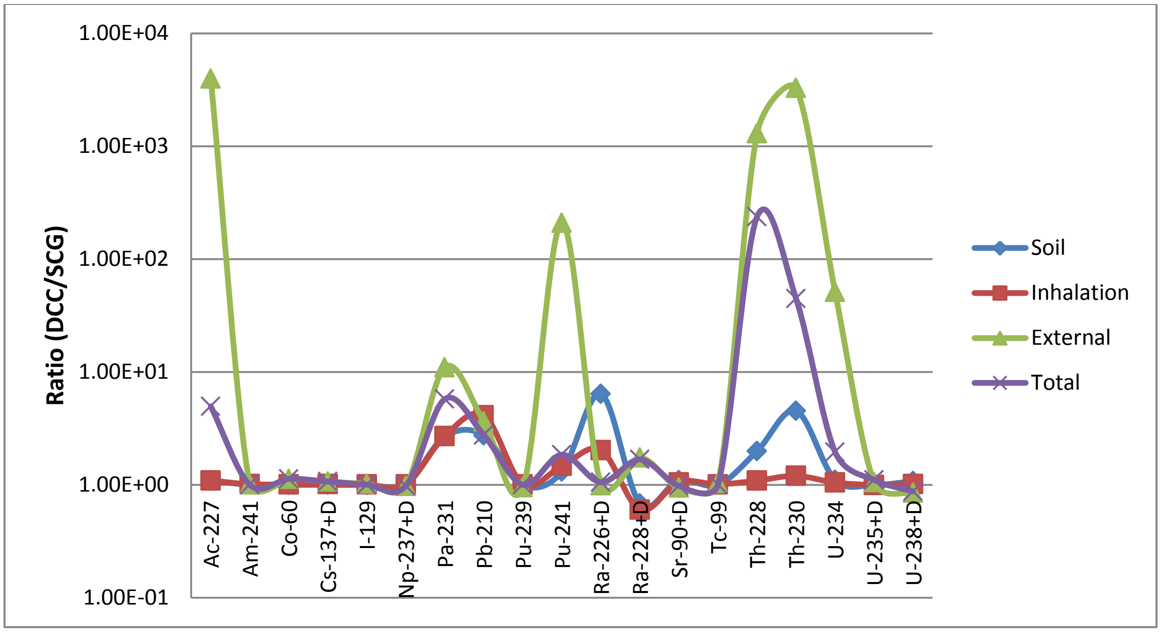

FIGURE 4.2-2 DCC/SCG Ratio for the Outdoor Worker Scenario

TABLE 4.2-4 Summary of Reasons for Differences (>10%) in DCC and RESRAD Results for the Outdoor Worker Scenario

Radionuclide	Difference >10%	Reason
Ac-227	External	Short-lived progeny not included in DCC
Co-60	External	Difference in ACF
Pa-231	All pathways	Buildup of long-lived progeny Ac-227
Pb-210	All pathways	Short-lived progeny Po-210 not included in DCC
Pu-241	All pathways	Buildup of long-lived progeny Am-241
Ra-226+D	Soil ingestion and inhalation	Buildup of long-lived progeny Pb-210
Ra-228+D	All pathways	Issues with DCFs in DCC
Th-228	Soil ingestion and external	Short-lived progeny not included in DCC
Th-230	All pathways	Buildup of long-lived progeny Ra-226
U-234	Soil ingestion and external	Buildup of long-lived progeny Th-230
U-235	Inhalation and soil ingestion	Issues with DCFs in DCC
U-238+D	External	Issues with DCFs in DCC

TABLE 4.2-5 Importance of Short-Lived Decay Products (Used Outdoor Worker Scenario Parameters in the RESRAD Run)

Radionuclide	No Integration[a]	1-yr Decay Corrected Dose (as is done in DCC)	1-yr Integrated Dose[b]	Ratio (integrated/ no integration)	Ratio (integrated/ decay corrected)
Ac-227	9.44E-02	9.29E-02	4.21E-01	4.46E+00	4.53E+00
Np-237	2.32E-02	2.32E-02	1.71E-01	7.36E+00	7.36E+00
Pb-210	5.79E-02	5.70E-02	1.09E-01	1.89E+00	1.92E+00
Pu-241	4.11E-04	4.01E-04	4.21E-04	1.02E+00	1.05E+00
Ra-226	2.91E-02	2.91E-02	1.97E+00	6.78E+01	6.78E+01
Ra-228	5.75E-02	5.41E-02	1.33E+00	2.32E+01	2.46E+01
Sr-90	2.46E-03	2.43E-03	9.93E-03	4.04E+00	4.09E+00
Th-228	7.90E-03	6.62E-03	1.55E+00	1.96E+02	2.34E+02
U-235	1.33E-01	1.33E-01	1.33E-01	9.96E-01	9.96E-01
U-238	3.80E-03	3.80E-03	2.69E-02	7.07E+00	7.07E+00

[a] Time integration parameter for dose set at 1 in the RESRAD run.

[b] Maximum dose from RESRAD run that includes contributions of decay and ingrowth.

cutoff half-life selected in this RESRAD run was 10 minutes. Initially, no daughter products were included with the principle radionuclide. Only radionuclides that have associated short-lived decay products (see Table B.1) were included for the comparison. The DCC Calculator can underestimate dose by 2 orders of magnitude. Similar differences were observed in other exposure scenarios.

The DCC Calculator estimates static dose at time 0 and applies a decay correction for the exposure duration. The RESRAD code estimates the peak dose over the period of dose estimation. As shown in Tables B.7 and B.8, for many radionuclides, peak dose occurs at later times due to the buildup of long-lived progeny. Table 4.2-6 compares the RESRAD results at time 0 with the results at the time of peak dose using the results shown in Table B.8 and shows the effect of buildup of long-lived progeny on estimated soil concentrations. The DCC Calculator can underestimate dose by as much as 40 times by not including long-lived progeny in dose calculations (see Th-230 results in Table 4.2-6).

4.2.4 Resident Scenario Comparison

The Resident Scenario considers four exposure pathways: (1) direct exposure to external radiation from the contaminated soil, (2) internal radiation from inhalation of contaminated dust, (3) ingestion of plants, and (4) internal radiation from incidental ingestion of soil. RESRAD (onsite) Version 7.0 was used to calculate the potential radiation dose for the resident scenario. The period considered for this analysis was 1,000 years. For this comparison, the element-specific parameters were set at the DCC default values listed in Table B.3. If the element-specific parameter value was not available in the DCC Calculator, the RESRAD parameter

TABLE 4.2-6 Effect of Buildup of Long-Lived Progeny

Radionuclide	Estimated SCG (pCi/g)		Ratio (time zero/peak dose time SCG)
	At Time Zero	At Peak Dose Time	
Pa-231	9.76E+00	1.79E+00	5.46E+00
Pu-241	2.36E+03	1.35E+03	1.75E+00
Ra-226+D	4.82E-01	4.64E-01	1.04E+00
Ra-228+D	7.26E-01	5.52E-01	1.31E+00
Th-230	5.46E+01	1.25E+00	4.35E+01
U-234	2.39E+02	1.22E+02	1.95E+00
U-235+D	7.17E+00	6.63E+00	1.08E+00
U-238+D	3.26E+01	3.26E+01	1.00E+00

default was retained. Table B.9 lists the other RESRAD input parameters used for this comparison. The DCC Calculator does not include the contribution of contaminated irrigation water to the plant dose. In the RESRAD code, the irrigation water was also assumed to be not contaminated for the plant dose estimation. The RESRAD code provides individual exposure pathway dose contributions to the total dose. The individual pathway dose was used to estimate the soil concentration that will result in a 1-mrem/yr dose.

Table B.10 compares the soil DCCs and RESRAD-estimated SCGs for individual exposure pathways that results in a 1-mrem/yr dose for the Resident Scenario. For some radionuclides, the peak occurs at later times. Table B.10 lists the results from RESRAD at time 0 and for the radionuclides when the peak occurs at later times; the results at the peak time are also shown. The differences greater than 10% are highlighted in red. The explanation of the differences is provided in the Remarks column in the table. The reason for the differences is the same as for the Outdoor Worker Scenario. The DCC Calculator does not include a foliar deposition mechanism in estimating the plant pathway dose; however, the foliar deposition contribution in the estimated plant SCGs is less than 0.1%. Figure 4.2-3 and Table B.11 show the results for the Resident Scenario after removing the differences due to K_d values and foliar deposition in the RESRAD results. Figure 4.2-3 does not include C-14 and H-3 because of the special model in the RESRAD code. Practically, there is no difference in the results obtained from the DCC Calculator and RESRAD for Am-241, Cs-137, I-129, Np-237+D, Pu-239, and Tc-99 for the Resident Scenario. Table 4.2-7 summarizes the reasons for the differences in the DCC/SCG ratio greater than 10% for individual pathways for the Resident Scenario.

4.2.5 Farmer Scenario Comparison

The Farmer Scenario considers 10 exposure pathways: (1) direct exposure to external radiation from the contaminated soil, (2) inhalation of contaminated dust, (3) ingestion of plants, (4) incidental ingestion of soil, (5) fish ingestion, (6) beef ingestion, (7) dairy ingestion, (8) egg ingestion, (9) poultry ingestion, and (10) swine ingestion. The RESRAD code does not include

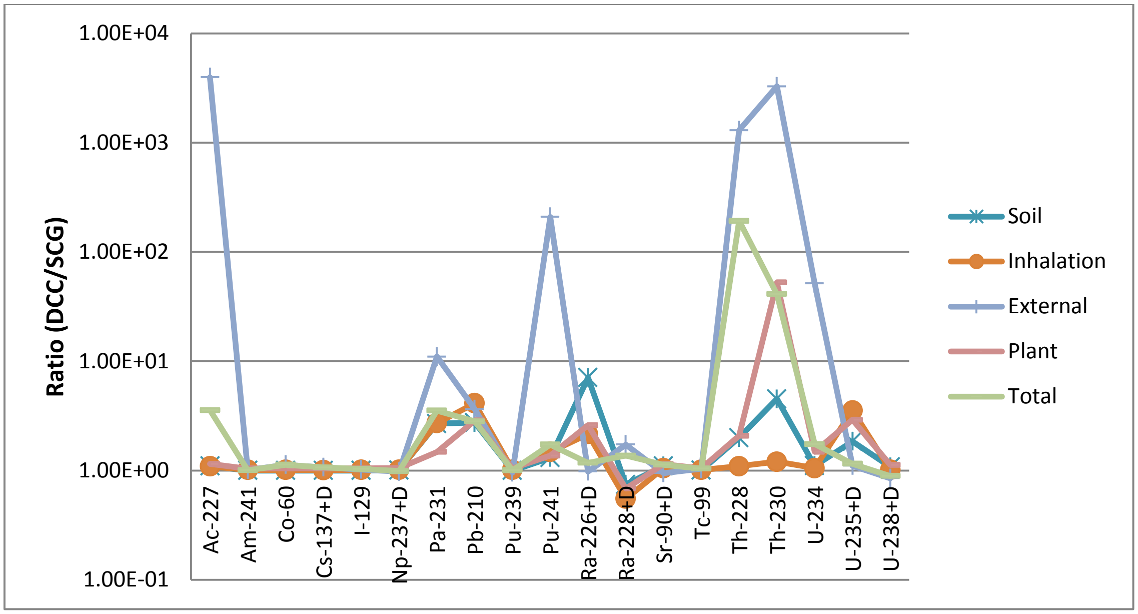

FIGURE 4.2-3 DCC/SCG Ratio for the Resident Scenario

TABLE 4.2-7 Summary of Reasons for Differences (>10%) in DCC and RESRAD Results for the Resident Scenario

Radionuclide	Difference >10%	Reason
Ac-227	External, soil, plant	Short-lived progeny not included in DCC
Co-60	External	Difference in ACF
Pa-231	All pathways	Buildup of long-lived progeny Ac-227
Pb-210	All pathways	Short-lived progeny Po-210 not included in DCC
Pu-241	External	Buildup of long-lived progeny Am-241
Ra-226+D	Soil	Buildup of long-lived progeny Pb-210
Ra-228+D	All pathways	Issues with DCFs in DCC
Sr-90+D	Soil, plant	Issue with DCFs in DCC
Th-228	Soil, external, plant	Short-lived progeny not included in DCC
Th-230	External, plant	Buildup of long-lived progeny Ra-226
U-234	Soil, external, plant	Buildup of long-lived progeny Th-230
U-235	Soil, inhalation, plant	Buildup of long-lived progeny Pa-231
U-238+D	External, plant	Issues with DCFs in DCC

the egg ingestion and swine ingestion pathways and does not have separate transfer factors for poultry; therefore, the egg, swine, and poultry ingestion pathways are not included in the comparison. RESRAD (onsite) Version 7.0 was used to calculate the potential radiation dose for the Farmer Scenario. The period considered for this analysis was 1,000 years. For this comparison, the element-specific parameters were set at the DCC default values listed in Table B.3. The other RESRAD input parameters used for this comparison are listed in

Table B.12. The RESRAD code provides individual exposure pathway dose contributions to the total dose. The individual pathway dose was used to estimate the soil concentration that will result in a 1-mrem/yr dose. For the external exposure, inhalation, dust ingestion, and plant ingestion pathways, the comparison was performed at time 0. For the fish, meat, and milk ingestion pathways, the comparison was performed at the time of the peak pathway dose.

Table B.13 compares the soil DCCs and RESRAD-estimated SCGs for the external exposure, inhalation, dust ingestion, and plant ingestion pathways that results in a 1-mrem/yr dose for the Farmer Scenario. The differences greater than 10% are highlighted in red. The explanation of the differences is provided in the Remarks column in the table. The reasons for the differences are the same as for the Resident Scenario.

Table B.14 lists the soil DCCs and SCGs for the fish, meat, and dairy ingestion pathways that results in a 1-mrem/yr dose for the Farmer Scenario. The estimated peak dose for the meat and milk pathways is the sum of the dose from the water-independent and water-dependent pathways. As noted in Table B.14, the peak pathway dose occurs at different times for each radionuclide. The DCC Calculator does not provide DCCs for Ac-227 and Pa-231.

Table B.15 provides the ratio of estimated DCC and SCGs values for the fish, meat, and dairy ingestion pathways and compares it with the ratio of estimated water concentration in the DCC Calculator and RESRAD code. For the fish ingestion pathway, the main difference in the results is because of the water concentration calculated in RESRAD and the DCC Calculator except for some radionuclides (Pb-210, Pu-241, Ra-226, Th-228, and Th-230) where the contributions of the progeny are not included in the DCC Calculator. Figure 4.2-4 shows the results for the fish, meat, and milk pathways in the Farmer Scenario.

As noted previously, the peak dose for the meat and milk pathways is the sum of the dose from the water-independent and water-dependent pathways. To explore the reasons for the differences, the meat and milk pathway doses in the RESRAD code were estimated by assuming that water consumed by meat and milk cows was not contaminated. For this comparison, DCCs were recalculated by eliminating the water ingestion contribution. Table B.16 provides the results of the comparison. The reasons for the differences are the same as those observed for the Outdoor Worker and Resident Scenarios—the effect of low K_d values in the RESRAD code and the contribution of progeny not being included in the DCC Calculator.

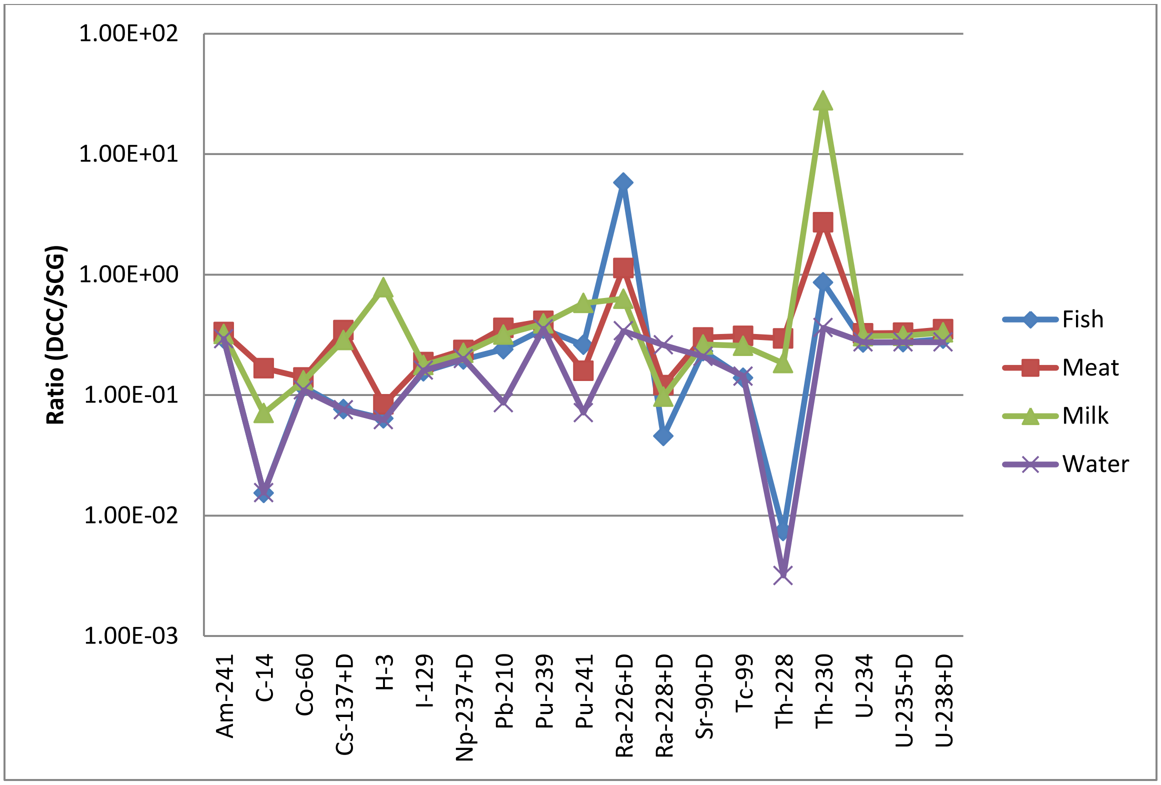

FIGURE 4.2-4 DCC/SCG Ratio for the Fish, Meat, and Milk Pathways in the Farmer Scenario

This page intentionally left blank.

5 SUMMARY AND RECOMMENDATIONS

The EPA's OSRTI misused the dose-to-risk conversion factor in its Superfund Guidance Memorandum in the recommendation to change the Superfund protective dose-based ARAR from 15 to 12 mrem/yr. The reduction of 3 mrem/yr is well within the noise and uncertainty of the low risks corresponding to the dose range.

RESRAD consistently calculates both dose and risk using exactly the same models and parameters. The EPA uses two different models to calculate radiological dose and risk. The DCC Calculator is used to calculate radiological dose, and the PRG Calculator is used for risk calculations. Not only do the PRG and DCC Calculators use different models and parameters, they also have inconsistent default scenarios and media for selection. For example, all contaminated media can be simultaneously selected in the PRG Calculator for a particular scenario, but this option is not available in the DCC Calculator.

The PRG Calculator does not handle radiological decay and ingrowth properly. The ingrowth of longer-lived progenies is ignored, and some short-lived progenies are not accounted for or not accurately accounted for. Furthermore, the PRG Calculator is not designed for realistic or site-specific analysis because many models (e.g., fish, produce, and special radionuclides) and parameters (e.g., K_ds, MLF) used are not realistic.

A comparison of the DCC and PRG Calculators identified many inconsistencies in these two tools used by the EPA for radiological dose and risk calculations, respectively. Two site-specific construction worker scenarios, the Recreator and the Soil to Groundwater Scenarios, are available in the PRG Calculator but not in the DCC Calculator. No media selection is available in the DCC Calculator for the Farmer Scenario. Currently, certain selection options are not available in the DCC Calculator such as selection of the Farmer Scenario. There are differences in the element-specific parameters such as K_d values; fish bioaccumulation factor; plant, meat, and milk transfer factors; and radionuclide-specific parameters such as ACF for the external exposure pathway used in the PRG and DCC Calculators. There are also differences in the pathway models used in the PRG and DCC Calculators for the plant, meat, milk, and fish ingestion pathways. Differences exist in the human intake rates used in the DCC and PRG Calculators for plants, meat, milk, and fish.

RESRAD has special models for special radionuclides such as radon, H-3, and C-14. For example, RESRAD has a special radon diffusion model to calculate radon and its daughters' inhalation dose and risk, but the radon inhalation pathway is not included in the PRG and DCC Calculators. RESRAD tracks radionuclide decay and ingrowth during transport in the environment, including source leaching, transport through the unsaturated and saturated zones, and so forth, whereas the DCC and PRG Calculators do not have this capability.

The calculations of the Outdoor Worker, Resident, and Farmer Scenarios in the DCC Calculator were compared with the RESRAD code. For this comparison, 21 commonly used radionuclides in dose/risk assessment and only the common pathways available were selected. For the comparison, the default settings of the DCC Calculator were maintained, including the

DCs and transfer factors. The input values used in the RESRAD code were changed as much as possible to match the input values used in the DCC Calculator. The RESRAD code allows users to select any cutoff half-life. The DCC Calculator has the option to select +D or +E. For +D, the cutoff half-life selected is 100 years and for +E, the cutoff half-life selected is 1,000 years. In the RESRAD code, depending on the cutoff half-life, selected DCFs of daughter products with half-lives less than the cutoff half-life are automatically added to the parent radionuclide. Whereas no discrepancies were noted during this comparison analysis regarding the way DCFs are handled in the RESRAD code, many discrepancies were observed in the DCC Calculator. For instance, for many radionuclides (Ac-227, Pa-231, Pb-210, Pu-241, and Th-228) that should have "short-lived" decay products with a half-life less than 100 years, the +D or +E options are not available for analysis in the DCC Calculator. For some other radionuclides (Ra-226, Ra-228, Sr-90, U-235, and U-238), the contribution of daughter products is not added correctly in the DCC Calculator.

The RESRAD code estimates integrated yearly dose, includes the contribution of decay and ingrowth in calculating dose, and estimates the peak dose over the period of dose estimation. The code has the capability to perform sensitivity analysis and uncertainty analysis. These features of the code can be used to identify sensitive parameters (Kamboj et. al. 2002, 2005). The DCC Calculator estimates static dose at time 0 and applies a decay correction factor for 1 year of exposure. This difference in modeling assumptions results in an underestimation of dose by the DCC Calculator for many radionuclides due to ignoring the contribution of the decay products' ingrowth during the 1-year exposure period. For the Outdoor Worker and Resident Scenarios, the DCC Calculator underestimated total dose by as much as 2 orders of magnitude for Th-228, and external dose was underestimated by as much as 3 orders of magnitude for Ac-227, Th-228, and Th-230. The DCC Calculator does not consider loss of radionuclides in soil through leaching. This difference in modeling assumptions between the DCC Calculator and RESRAD code results in an overestimation of dose for low K_d radionuclides (H-3, I-129, Tc-99, Np-237+D, and Co-60) by as much as 20%. Differences in the ACF used in the DCC Calculator and RESRAD code resulted, in general, in less than a 10% difference in external dose. The contribution of foliar deposition to the plant concentration in the RESRAD code was small; therefore, this modeling difference did not result in any noticeable differences in the plant dose for both codes. For the Farmer Scenario, the main difference in the result for ingestion of fish, meat, and milk was due to the difference in the water concentration calculated in RESRAD and the DCC Calculator.

The EPA PRG and DCC Calculators are online spreadsheet calculators available on the Internet. They are not available when the website is down or when it is under routine maintenance. There is no validation or benchmarking report available. The verification report for the PRG Calculator on the PRG website is of limited scope. A Google search on the Internet did not identify any user-published report or papers. In contrast, RESRAD code is widely used by more than 100 countries, and 1,000+ papers and reports and Ph.D. dissertations have been published using or citing the RESRAD family of codes. The EPA Science Advisory Board also reviewed RESRAD and approved its use for many radiation-regulation-related studies. The quality assurance and quality control of the EPA PRG and DCC Calculators need to be improved, and perhaps the EPA Science Advisory Board can conduct a review of the PRG and DCC Calculators.

This comparison study identified many inconsistencies between the PRG Calculator and the DCC Calculator. Even for screening purposes of deriving PRGs for radionuclides, both the PRG and DCC Calculators should be modified to improve their consistency when evaluating radionuclides for dose and risk calculations. Because the models implemented in the PRG and DCC Calculators are simple, static models, they are not appropriate for modeling the dynamic effects during time-dependent transport in the environment. It is recommended that the PRG and DCC Calculators be used only for screening purposes. Consistent with DOE and the NRC, the EPA should accept the RESRAD code as its primary recommended code/model for assessing doses or risk from residual radioactive material in soils and structures. Rather than investing more resources in updating and maintaining the inferior PRG Calculator, the EPA could work with DOE and other interested parties to develop a series of default templates for application to CERCLA reviews or screening assessments. The cost-savings from this effort could be used to improve the chemical models the EPA currently uses for screening.

This page intentionally left blank.

6 REFERENCES

Bellamy, M., et al., 2014, *Area Correction Factors for Contaminated Soil for Use in Risk and Dose Assessment Models*, ORNL/TM-2013/00, September, Oak Ridge National Laboratory, Oak Ridge, Tenn.

DOE (U.S. Department of Energy), 2011, *DOE Standard: Derived Concentration Technical Standard*, DOE-STD-1196-2011, April, Washington, D.C.

Eckerman, K.F., et al., 1999, *Federal Guidance Report No. 13, Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, Oak Ridge National Laboratory, Oak Ridge, Tenn., Sept., Office of Radiation Indoor Air Protection, U.S. Environmental Protection Agency, Washington, D.C. Available at http://www.epa.gov/radiation/federal/techdocs.html#report13.

EPA (U.S. Environmental Protection Agency), 1994, *Estimating Radiogenic Cancer Risks*, EPA 402-R-93-076, June, Washington, D.C.

EPA, 1999, Radiation Risk Assessment at CERCLA Sites: Q&A. Available at http://nepis.epa.gov/Exe/ZyNET.exe/P1000RP3.txt?ZyActionD=ZyDocument&Client=EPA&Index=1995%20Thru%201999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A\ZYFILES\INDEX%20DATA\95THRU99\TXT\00000021\P1000RP3.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h|-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=p|f&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=4.

EPA, l999c, cited in text box on page 6; same as Eckerman et al. 1999.

EPA, 2011, *Blue Book: EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population*, EPA 402-R-11-001, April, Office of Radiation and Indoor Air, Washington, D.C.

EPA, 2014, "Radiation Risk Assessment at CERCLA Sites: Q&A," Directive 9200.4-40, EPA 540-R-012-13, May.

EPA, 2015, *Preliminary Remediation Goals for Radionuclides: PRG User's Guide*. Available at http://epa-prgs.ornl.gov/radionuclides/prg_guide.html.

Gil-Garcia, C., K. Tagami, S. Uchida, A. Rigol, and M. Vidalm, 2009a, "New Best Estimates for Radionuclide Solid–Liquid Distribution Coefficients in Soils, Part 3: Miscellany of Radionuclides (Cd, Co, Ni, Zn, I, Se, Sb, Pu, Am, and Others)," *Journal of Environmental Radioactivity*, 100:704–715.

Gil-Garcia, C., A. Rigol, and M. Vidal, 2009b, "New Best Estimates for Radionuclide Solid–Liquid Distribution Coefficients in Soils, Part 1: Radio Strontium and Radio Cesium," *Journal of Environmental Radioactivity* 100:690–696.

HPS (Health Physics Society), 1993, *Uncertainty in Risk Assessment: Position Statement of the Health Physics Society*, Revised April 1995, February 2013. Available at https://hps.org/documents/riskassessment_ps008-2.pdf.

HPS, 1996, *Radiation Risk in Perspective: Position Statement of the Health Physics Society,* Reaffirmed March 2001, Revised 2010. Available at https://hps.org/documents/radiationrisk.pdf.

ICRP (International Commission on Radiological Protection), 1977, *Recommendations of the ICRP*, ICRP Publication 26, Annals of the ICRP 1 (3), superseded by ICRP Publication 103, Pergamon Press, New York, N.Y.

ICRP, 1979–1982, *Limits for Intakes of Radionuclides by Workers*, ICRP Publication 30, Part 1 (and Supplement), Part 2 (and Supplement), Part 3 (and Supplements A and B), and Index, prepared by Committee 2, adopted by the Commission in July 1978, Annals of the ICRP, Pergamon Press, New York, N.Y.

ICRP, 1991, *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, Annals of the ICRP, Vol. 21(1–3), Pergamon Press, New York, N.Y.

ICRP, 2007, *The 2007 Recommendations of the International Commission on Radiological Protection,* ICRP Publication 103, Annals of the ICRP, Vol. 37, Nos. 2–4, Elsevier.

ICRP, 2008, *Nuclear Decay Data for Dosimetric Calculations,* Annals of the ICRP, ICRP Publication 107, Vol. 38, No. 3, Elsevier.

ISCORS (International Steering Committee on Radiation Standards), 2002, *A Method for Estimating Radiation Risk from TEDE*, ISCORS Technical Report No. 1, July.

Kamboj, S., E. Gnanapragasam, D. LePoire, B.M. Biwer, J. Cheng, J. Arnish, C. Yu, S.Y. Chen, T. Mo, R. Abu-Eid, and M. Thaggard, 2002, "Probabilistic Approach to Identify Sensitive Parameter Distributions in Multimedia Pathway Analysis," *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, Jan.

Kamboj, S., J.-J. Cheng, and C. Yu, 2005, "Deterministic vs. Probabilistic Analyses to Identify Sensitive Parameters in Dose Assessment Using RESRAD," *Operational Radiation Safety, Supplement to Health Physics*, pp. S104-S109, May.

NAS (National Academy of Sciences), 1999, *Health Effects of Exposure to Radon*, National Research Council, Committee on the Health Effects of Exposure to Radon (BEIR VI).

National Academy Press, Washington. D.C. Available at http://books.nap.edu/openbook.php?isbn=0309056454.

Vandenhove, H., C. Gil-Garcia, A. Rigol, and M. Vidal, 2009, "New Best Estimates for Radionuclide Solid–Liquid Distribution Coefficients in Soils, Part 2: Naturally Occurring Radionuclides," *Journal of Environmental Radioactivity* 100:697–703.

Walker, S.A., 2013, "Revisions to US EPA Superfund Risk and Dose Assessment Models and Guidance," Paper presented at the Waste Management 2013 Symposium, Phoenix, Ariz., Feb. 28. Paper available at http://www.wmsym.org/archives/2013/papers/13403.pdf. Slides available at http://www.wmsym.org/archives/2013/panels/103-625.pdf.

Walker, S.A., undated, *Dose Compliance Concentration (DCC) Calculator*. Available at http://www.epa.gov/superfund/health/contaminants/radiation/pdfs/Dose%20Compliance%20Concentration%20(DCC)%20Calculator%20Fact%20Sheet%20final.pdf.

Yu, C., 1999, "RESRAD Family of Codes and Comparison with Other Codes for Decontamination and Restoration of Nuclear Facilities," in *Decommissioning and Restoration of Nuclear Facilities*, M.J. Slobodien (ed.), Chapter 11, pp. 207–231. Health Physics Society 1999 Summer School Textbook.

Yu, C., 2006, "Modeling Radionuclide Transport in the Environment and Assessing Risks to Humans, Flora, and Fauna: The RESRAD Family of Codes," Chapter 5, 14 pp., *Applied Modeling and Computations in Nuclear Science*, ACS Symposium Series 945, American Chemical Society, Washington, D.C., 2006.

Yu, C., 2007, "Tools for Assessing Radiological Doses to Human and Biota," in *Radiological Assessment: Detection, Identification, and Evaluation*, Health Physics Society Professional Development School Textbook.

Yu, C., A.J. Zielen, J-J. Cheng, D.J. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo III, W.A. Williams, and H. Peterson, 2001, *User's Manual for RESRAD Version 6*, ANL/EAD-4, July, Argonne National Laboratory, Argonne, Ill.

This page intentionally left blank.

APPENDIX A:

DESCRIPTIONS OF THE RESRAD FAMILY OF CODES AND THE EPA PRG AND DCC CALCULATORS

This page intentionally left blank.

APPENDIX A:

DESCRIPTIONS OF THE RESRAD FAMILY OF CODES AND THE EPA PRG AND DCC CALCULATORS

A.1 RESRAD FAMILY OF CODES

The RESRAD (RESidual RADioactivity) family of codes has been used by health physicists and radiological engineers as a tool for deriving cleanup criteria and radiological risk assessment for releasing contaminated sites since its first release in 1989. The RESRAD family of codes has been widely used in more than 100 countries and includes nine codes, as shown in Figure A.1:

1. RESRAD (onsite) for assessing soil contaminated with radionuclides,

2. RESRAD-BUILD for assessing buildings contaminated with radionuclides,

3. RESRAD-CHEM for assessing soil contaminated with hazardous chemicals,

4. RESRAD-BASELINE for conducting baseline risk assessments with measured concentrations of both radionuclides and chemicals,

5. RESRAD-ECORISK for assessing ecological risks from exposure to hazardous chemicals,

6. RESRAD-BIOTA for assessing doses to non-human biota from exposure to radionuclides,

7. RESRAD-RECYCLE for assessing the recycling and reuse of radiologically contaminated metals and equipment,

8. RESRAD-OFFSITE for assessing radiological doses to off-site human receptors, and

9. RESRAD-RDD for responding to nuclear emergencies such as radiological dispersal device incidents.

Four of the codes—RESRAD (onsite), RESRAD-BUILD, RESRAD-BIOTA, and RESRAD-OFFSITE—also have probabilistic analysis capabilities that allow the user to input distributions of parameters. Six codes—RESRAD (onsite), RESRAD-BUILD, RESRAD-RECYCLE, RESRAD-OFFSITE, RESRAD-BIOTA, and RESRAD-RDD—are regularly maintained and updated. The other three codes—RESRAD-CHEM, RESRAD-BASELINE, and RESRAD-ECORISK—are beta versions for testing and evaluation and receive less maintenance.

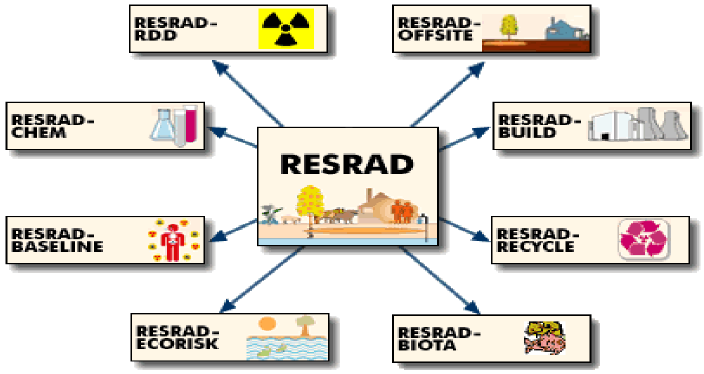

FIGURE A.1 RESRAD Family of Codes

All RESRAD codes have user-friendly interfaces and provide online help. The RESRAD family of codes is the industry standard in evaluating contaminated sites. Applications of RESRAD codes include derivation of cleanup criteria, evaluation of remediation alternatives, radiological dose and risk assessment, waste disposal facility performance assessment, and emergency response to nuclear incidents. The RESRAD family of codes has been applied to numerous sites, and more than 2,000 journal and other papers (including Ph.D. dissertations) have been published either based on or citing RESRAD codes.

Many new features have recently been added to the RESRAD family of codes. They include the incorporation of the International Commission on Radiological Protection (ICRP) Publication 107 radionuclide database of more than 1,200 radionuclides (ICRP 2008[2]), an enhanced probabilistic analysis feature [in RESRAD (onsite), RESRAD-BUILD, RESRAD-OFFSITE, and RESRAD-BIOTA], and a significantly improved user interface (in RESRAD-OFFSITE, RESRAD-BIOTA, and RESRAD-RDD). Most of the RESRAD codes (except RESRAD-CHEM, -BASELINE, and -ECORISK) are regularly updated, and many supporting documents have been prepared to facilitate their application. More than 140 training courses have been conducted and 2000+ individuals have been formally trained to use RESRAD codes. All RESRAD codes and supporting documents can be downloaded from the RESRAD website at http://www.evs.anl.gov/resrad.

The RESRAD (onsite) code employs a pathway analysis method to estimate radiation exposures and characterize the resulting radiological dose and cancer risk. A total of nine exposure pathways are considered, which can be activated or suppressed to consider various receptors and exposure scenarios. The nine pathways are external radiation; inhalation (of dust particles, and vapor for tritium [H-3] and carbon-14 [C-14]); ingestion of plants (produce consumption), meat, milk, aquatic foods, drinking water, and soil; and inhalation of radon. Among them, the external radiation, inhalation, and ingestion of soil pathways have only water-independent components, meaning the exposures are not related to the use of water. The

---

2 ICRP, 2008, *Nuclear Decay Data for Dosimetric Calculations*, Annals of the ICRP, ICRP Publication 107, Vol. 38, No. 3, Elsevier.

ingestion of water and aquatic foods pathways have only water-dependent components, because the exposures are associated with water contamination, which results from the migration of radionuclides from soil to an underlying groundwater aquifer and may take a long period of time to occur depending on the radionuclides, soil properties, site-specific hydraulic and hydrogeologic conditions, etc. The ingestion of plants, meat, and milk, as well as the inhalation of radon pathways, have both water-independent and water-dependent components; that is, a part of the exposures is not the result of the use of contaminated water, while the other part is associated with the use of contaminated water.

The radiation doses and cancer risks for water-dependent components and water-independent components are calculated by the RESRAD (onsite) code in the same run; they are reported separately and then combined at each future time period evaluated. The combined results are summed over all applicable pathways to obtain the total radiation doses or cancer risks. The maximum of the totals within the time frame considered can then be used to derive the initial concentration limits in soil; that is, Soil Concentration Guidelines (SCGs) or Derived Concentration Guideline Levels (DCGLs) for individual radionuclides corresponding to a specified dose or cancer risk level.

Figure A.2 depicts the relations among the radiation source, the environment, the exposure pathways, and the resulting human health impacts as modeled in the RESRAD (onsite) code.

A.2 EPA PRG AND DCC CALCULATORS

The U.S. Environmental Protection Agency (EPA) has developed two calculation tools for evaluating Superfund sites with radiological contamination. One tool, the Preliminary Remediation Goal (PRG) Calculator, expresses impacts in terms of excess lifetime cancer risk;

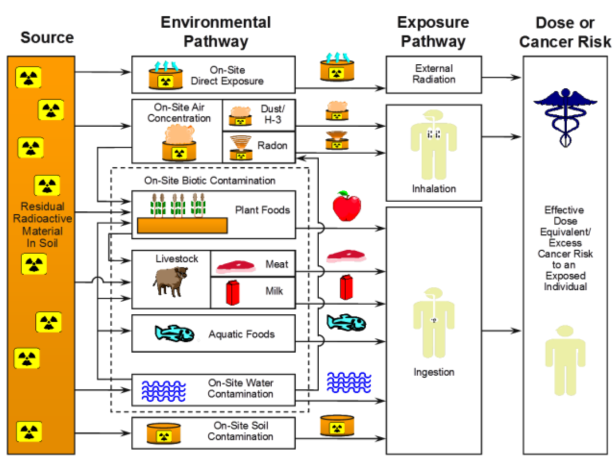

FIGURE A.2 RESRAD (onsite) Code Pathways the other, the Dose Compliance Concentration (DCC) Calculator, expresses impacts in terms of radiological dose. These two Calculators—PRG and DCC—are described in Sections A.2.1 and A.2.2, respectively.

A.2.1 PRG Calculator

The EPA developed the PRG Calculator as a screening tool for use by Superfund sites to evaluate potential cancer risks to eight groups of human receptors associated with radiological contamination in different media—soil, air, tap/surface water, or biota/biota product (fish, game, poultry, eggs, beef, milk, or swine), and to derive medium-specific remediation goals based on a target cancer risk level. The eight groups of receptors are (1) resident, (2) composite worker, (3) outdoor worker, (4) indoor worker, (5) construction worker for unpaved road vehicle traffic, (6) construction worker for wind erosion and other construction activities, (7) recreator, and (8) farmer. The contaminated media (available for selection) and exposure pathways considered for each receptor group are pre-determined as shown in Figure A.3 (source: the PRG Calculator website, http://epa-prgs.ornl.gov/radionuclides/).

To derive PRGs for each contaminated medium, the PRG Calculator evaluates potential cancer risks associated with each exposure pathway separately over an exposure period starting at the current time to derive pathway-specific concentration limits. The pathway-specific concentration limits are then combined to obtain the total PRGs of individual radionuclides in the medium based on the principle that the total risk to a receptor is the sum of risks over the exposure pathways. If the Farmer Scenario is selected, the potential cancer risk associated with the ingestion of contaminated biota/biota product can be attributed to either soil contamination (due to animals ingesting soils and plants growing in contaminated soils) or water contamination (due to animals ingesting contaminated water) and included in the derivation of total soil PRGs or total water PRGs.

For soil contamination, the PRG Calculator evaluates potential cancer risk associated with four water-independent pathways—external radiation, inhalation (of dust particles, and vapor for H-3), ingestion of soil, and ingestion of produce—to derive total soil PRGs. If there is a potential at Superfund sites for radionuclides in soil leaching out and contaminating the underlying groundwater aquifer, resulting in exposure through the use of groundwater, the PRG Calculator can also derive soil concentration limits called Soil Screening Levels (SSLs) to meet the target cancer risk level or target groundwater concentration levels, for example, the Maximum Concentration Limits (MCLs) for water. To derive SSLs based on a target risk level, the PRG Calculator first calculates the total water PRGs by considering four exposure pathways associated with the use of water by residents—ingestion of water, inhalation of volatiles (for H-3, C-14, radon-220 [Rn-220], and Rn-222 that could escape from water as gas), water immersion, and ingestion of produce (contaminated due to irrigation). To derive SSLs based on MCLs, the total water PRGs are simply set to the values of the MCLs. The PRG Calculator then multiplies the total water PRGs with a groundwater dilution factor to obtain the target leachate concentrations, that is, the target concentrations of radionuclides in the soil water that leave the contaminated zone. The target leachate concentrations are then used to derive soil concentration limits (i.e., SSLs) for the contaminated zone by considering radionuclides dissolving in water

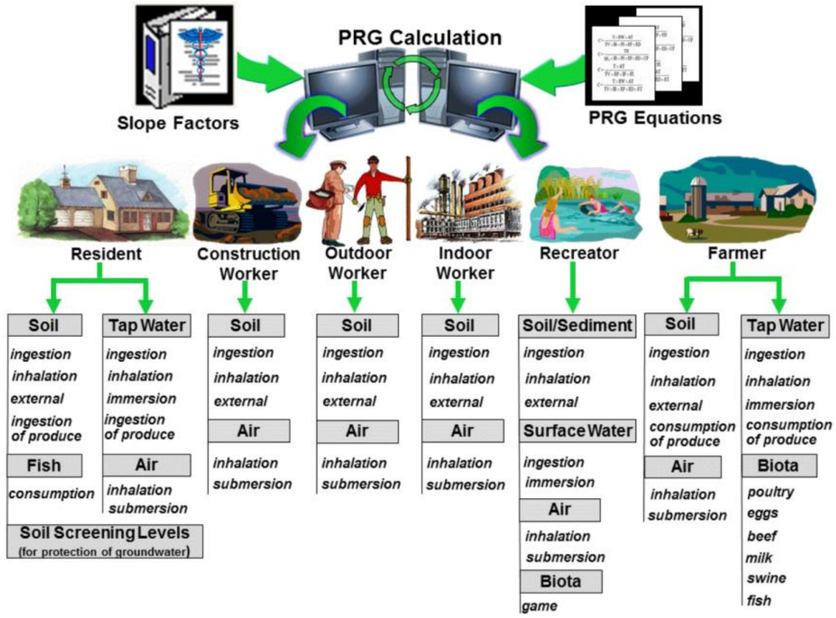

FIGURE A.3 Contaminated Medium and Exposure Pathways Considered in the PRG Calculator

uniformly for a period of time, or radionuclides partitioning between the soil particles and soil water in equilibrium. The SSLs and soil PRGs are derived independently of each other and require separate runs with the PRG Calculator to obtain their values.

The PRG Calculator does not simulate the transport of radionuclides in soils between the contaminated zone and groundwater table. Instead, it assumes that the soil contamination extends to the groundwater table; therefore, radionuclides leaching out from the contaminated zone are discharged to the groundwater aquifer without any delay. Two methods—the partition method and the mass-limit (uniform dissolution) method—are incorporated in the PRG Calculator to relate the total water PRGs to soil concentration limits; either method can be used to derive SSLs. The soil PRGs should be limited by SSLs, that is, replaced by SSLs if the SSLs are smaller, when determining the soil remediation goals for a Superfund site.

A.2.2 DCC Calculator

The EPA developed the DCC Calculator as a calculation tool for use by Superfund sites to develop DCCs to demonstrate compliance with dose-based Applicable or Relevant and Appropriate Requirements (ARARs). The DCC Calculator evaluates potential radiation dose to six groups of human receptors associated with radiological contamination in different media—soil, air, tap/surface water, or biota/biota product (fish, game, poultry, eggs, beef, milk, or swine)—and derives medium-specific concentrations based on a target radiation dose level. The six groups of receptors are (1) resident, (2) indoor worker, (3) outdoor worker, (4) composite worker, (5) farmer, and (6) recreator. The contaminated media (available for selection) and exposure pathways considered for each receptor group are pre-determined as shown in Figure A.4 (source: the DCC Calculator website, http://epa-dccs.ornl.gov/). To derive DCCs for each contaminated medium, the DCC Calculator evaluates the potential dose associated with each exposure pathway separately over an exposure period starting at the current time to derive pathway-specific concentration limits. The pathway-specific concentration limits are then combined to obtain the total DCCs of individual radionuclides in the medium based on the principle that the total dose to a receptor is the sum of doses over the exposure pathways. The differences in the PRG and DCC Calculators and the equations used in calculating dose from each exposure pathways for the Farmer Scenario are presented in Section 4 of this report. The other scenarios include a subset of the exposure pathways considered in the Farmer Scenario.

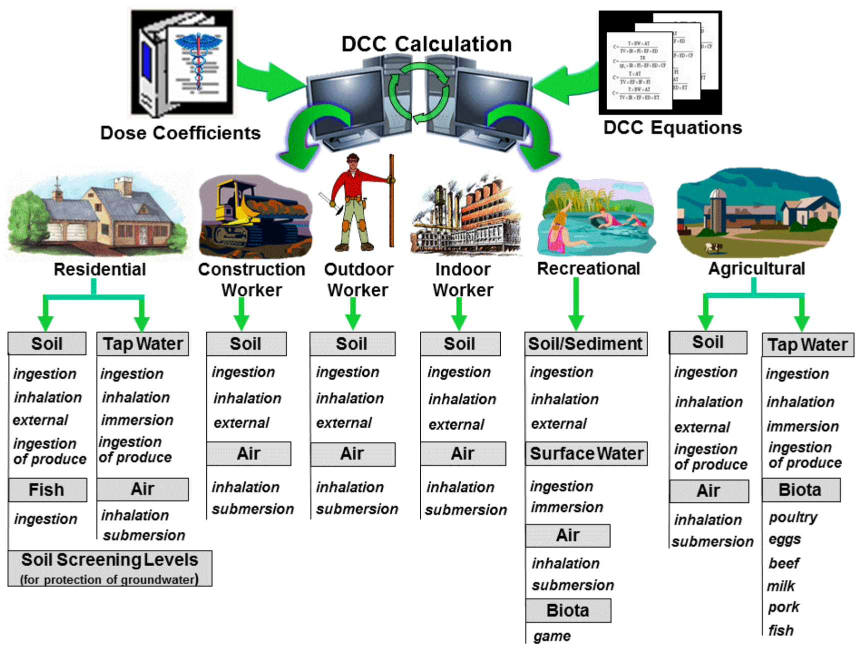

FIGURE A.4 Contaminated Medium and Exposure Pathways Considered in the DCC Calculator

APPENDIX B:

SELECTED RADIONUCLIDE PROPERTIES AND COMPARISON RESULTS

This page intentionally left blank.

APPENDIX B:

SELECTED RADIONUCLIDE PROPERTIES AND COMPARISON RESULTS

Some of the detailed properties of selected radionuclides are included in this appendix. Figures B.1 through B.4 show the decay schemes of the selected radionuclides. Table B.1 lists the properties of radionuclides selected for comparison analyses. Radionuclide- and element-specific input parameters are compared in Tables B.2 and B.3. Some other radionuclide properties and comparison results are presented in Tables B.4 through B.16.

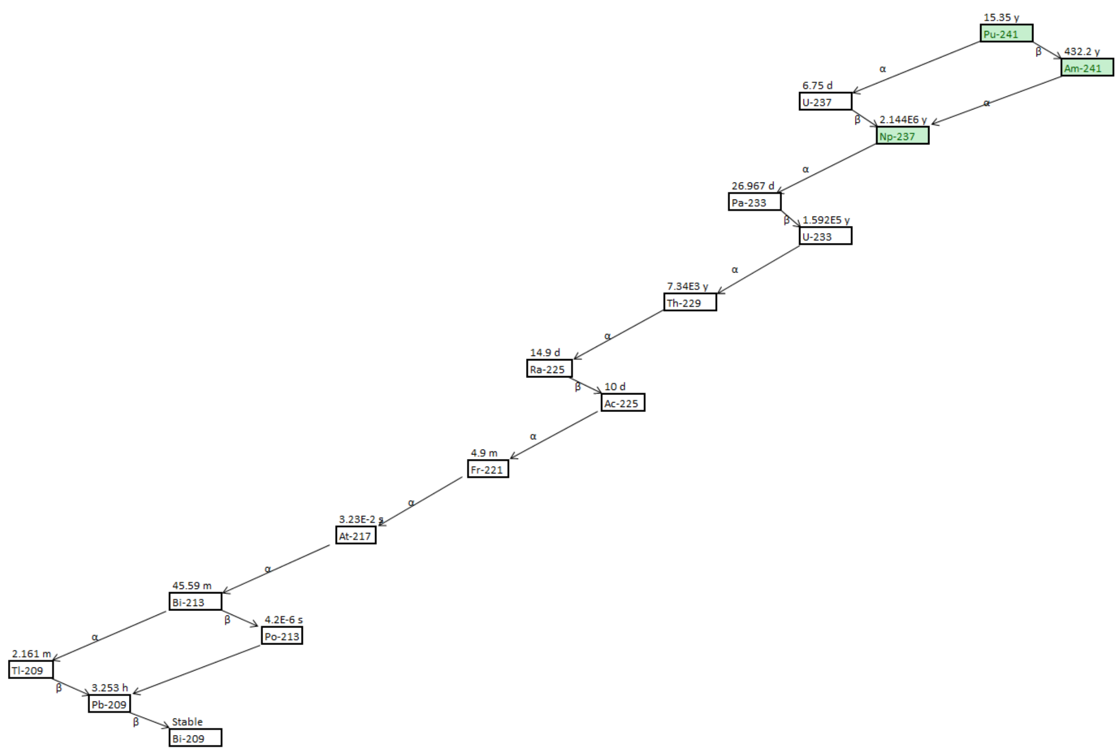

FIGURE B.1 Decay Schemes of Pu-241, Am-241, and Np-237

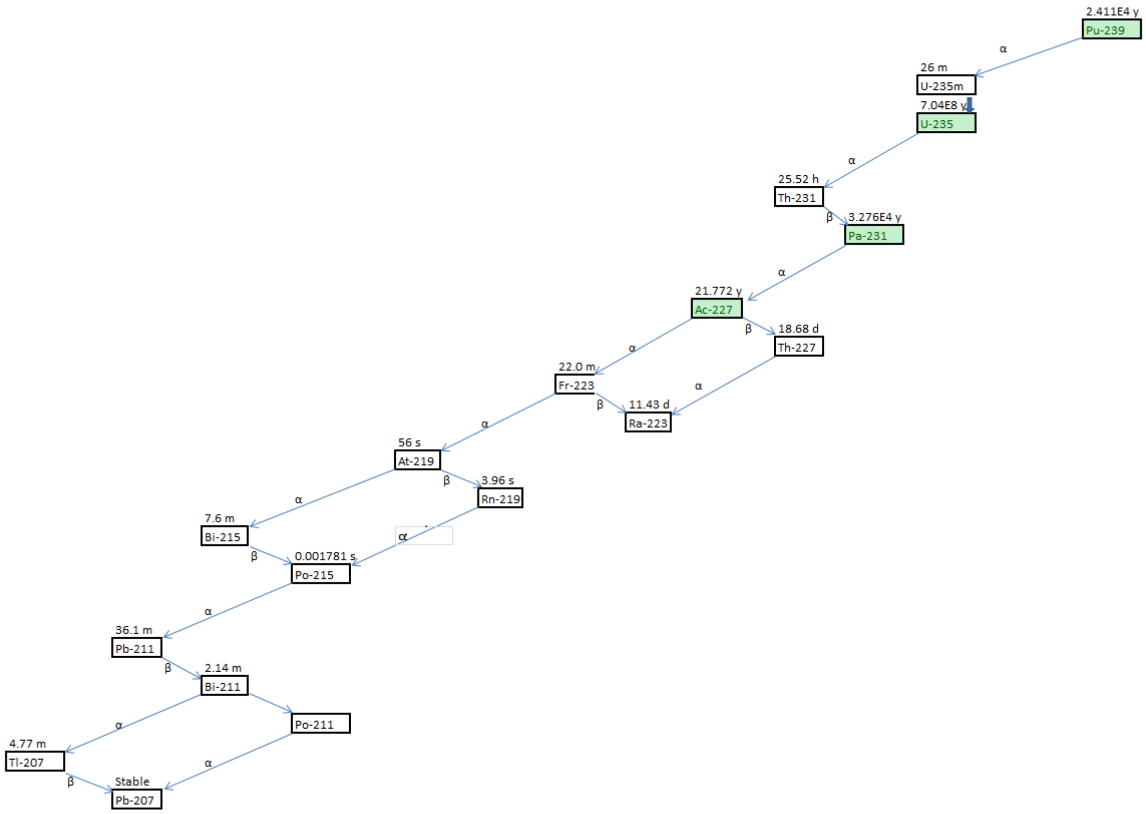

FIGURE B.2 Decay Schemes of Pu-239, U-235, Pa-231, and Ac-227

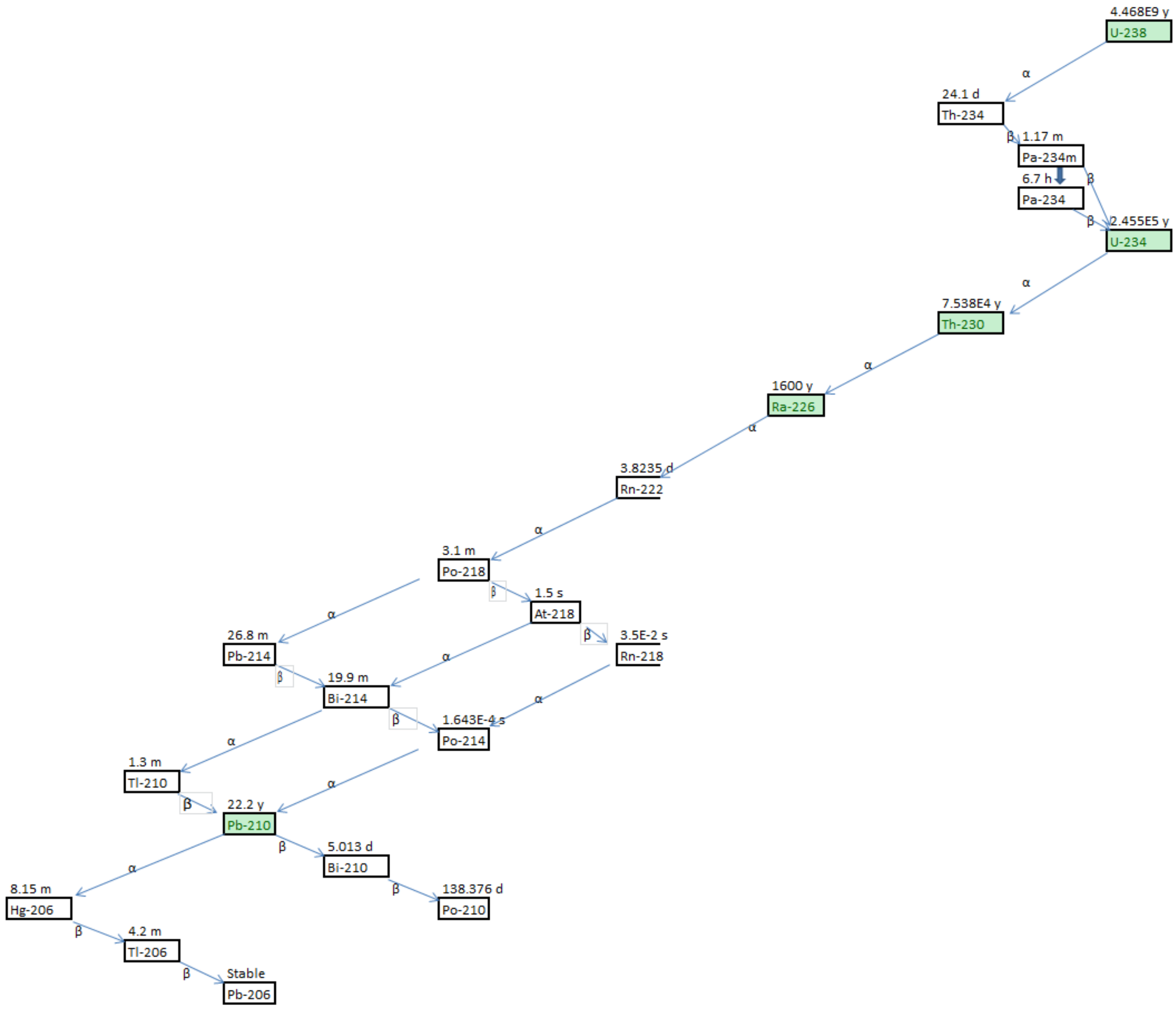

FIGURE B.3 Decay Schemes of U-238, U-234, Th-230, Ra-226, and Pb-210

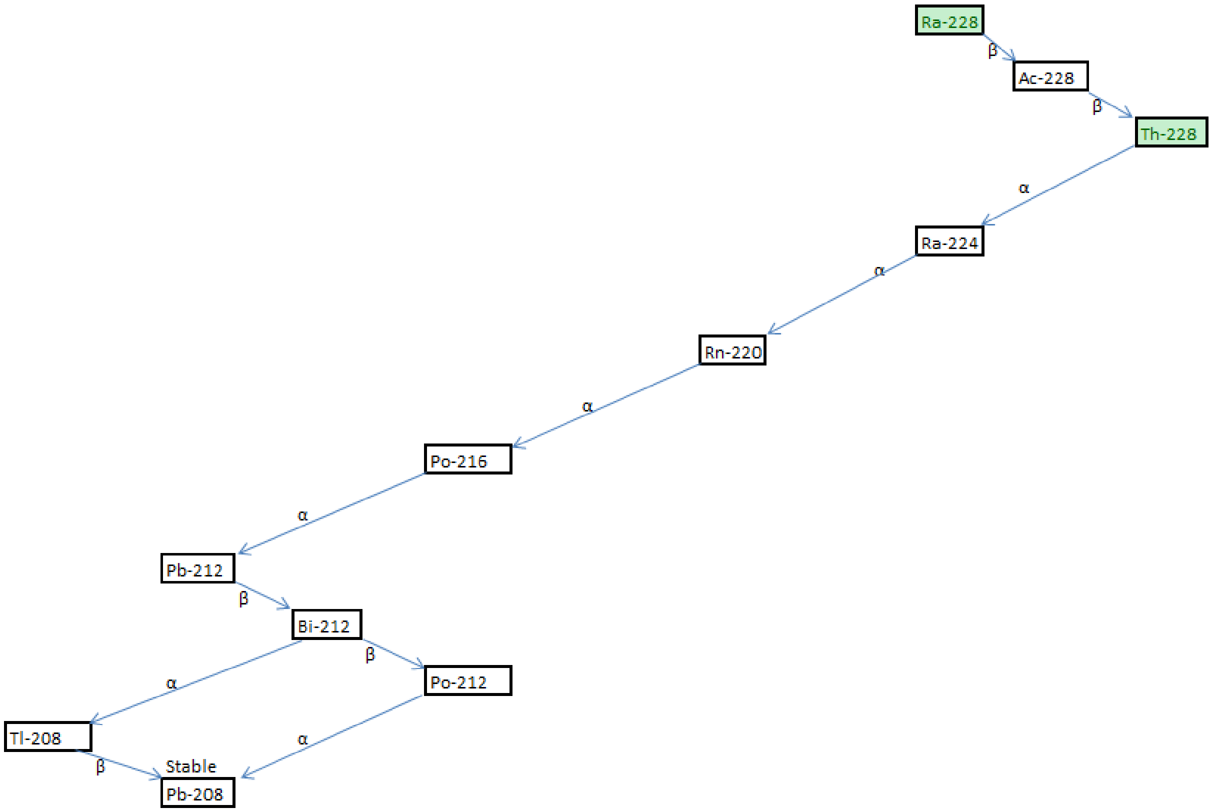

FIGURE B.4 Decay Schemes of Ra-228 and Th-228

TABLE B.1 Properties of Radionuclides Selected for Comparison

Radionuclide	Half-life (yr)	Cutoff Half-Life in the Analysis		
		6 months	100 Years	1,000 Years
		Associated Radionuclide	Associated Radionuclide	Associated Radionuclide
Ac-227	21.772	Th-227 (0.9862, 18.68 d), Fr-223 (0.0138, 22 m), At-219 (6E-5, 56 s), Ra-223 (11.43 d), Rn-219 (3.96 s), Po-215 (1.781E-3 s), Pb-211 (36.1 m), Bi-211 (2.14 m), Tl-207 (0.9972, 4.77 m), Po-211 (0.00276, 0.516 s)	Same as for 6 months	Same as for 6 months
Am-241	432.2	None	None	None
C-14	5,700	None	None	None
Co-60	5.2713	None	None	None
Cs-137	30.1671	Ba-137 m (0.944, 2.552 m)	Same as for 6 months	Same as for 6 months
H-3	12.32	None	None	None
I-129	1.57E+07	None	None	None
Np-237	2.14E+06	Pa-233 (26.967 d)	Same as for 6 months	Same as for 6 months
Pa-231	3.28E+04	None	6 months + Ac-227	6 months + Ac-227
Pb-210	22.2	Bi-210 (5.013 d), Po-210 (138.376 d), Hg-206 (1.9E-8, 8.15 m), Tl-206 (1.9E-8, 4.2 m)	Same as for 6 months	Same as for 6 months
Pu-239	2.41E+04	U-235 m (0.999, 26 m)	Same as for 6 months	Same as for 6 months
Pu-241	14.35	U-237 (0.0000245, 6.75 d)	Same as for 6 months	Same as for 6 months
Ra-226	1,600	Rn-222 (3.8235 d), Po-218 (3.1 m), Pb-214 (0.9998, 26.8 m), At-218 (0.0002, 1.5 s), Bi-214 (19.9 m), Po-214 (0.9998, 1.643E-4 s), Tl-210 (0.0002, 1.3 m)	6 months +Pb-210	6 months +Pb-210
Ra-228	5.75	Ac-228 (6.15 h)	6 months + Th-228	6 months + Th-228
Sr-90	28.79	Y-90 (64.1 h)	Same as for 6 months	Same as for 6 months
Tc-99	2.11E+05	None	None	None
Th-228	1.9116	Ra-224 (3.66 d), Rn-220 (55.6 s), Po-216 (0.145 s), Pb-212 (10.64 h), Bi-212 (60.55 m), Po-212 (0.6406, 2.99E-7 s), Tl-208 (0.3594, 3.053 m)	Same as for 6 months	Same as for 6 months
Th-230	7.54E+04	None	None	None
U-234	2.46E+05	None	None	None
U-235	7.04E+08	Th-231 (25.52 h)	Same as for 6 months	Same as for 6 months
U-238	4.47E+09	Th-234 (24.1 d), Pa-234m (1.17 m), Pa-234 (0.0016, 6.7 h)	Same as for 6 months	Same as for 6 months

TABLE B.2 Comparison of Area Correction Factors in RESRAD, DCC, and PRG Calculator for the Selected Radionuclides and Their Daughter Products

	RESRAD ACF			Bellamy et al. (2014)[a] ACF			DCC	Ratio	ACF from the PRG Calculator			Ratio of RESRAD/PRG		
Nuclide	10,000 m^2	2,000 m^2	1,000 m^2	10,000 m^2	2,000 m^2	1,000 m^2	Area Unspecified	RESRAD 10,000/ DCC	10,000 m^2	2,000 m^2	1,000 m^2	10,000 m^2	2,000 m^2	1,000 m^2
Ac-227	9.66E-01	9.44E-01	9.37E-01	1.10E+00[b]	9.80E-01	9.60E-01	1.00E+00	9.66E-01	1.00E+00	9.80E-01	9.60E-01	9.66E-01	9.63E-01	9.76E-01
Ac-228	9.36E-01	8.99E-01	8.87E-01	9.20E-01	8.60E-01	8.20E-01	9.69E-01	9.66E-01	9.25E-01	8.63E-01	8.18E-01	1.01E+00	1.04E+00	1.08E+00
Am-241	9.93E-01	9.56E-01	9.43E-01	1.10E+00	8.70E-01	8.20E-01	9.65E-01	1.03E+00	1.00E+00	8.72E-01	8.21E-01	9.93E-01	1.10E+00	1.15E+00
At-218	9.41E-01	9.06E-01	8.95E-01	1.00E+00	1.00E+00	1.00E+00	9.95E-01	9.46E-01	9.00E-01	9.00E-01	9.00E-01	1.05E+00	1.01E+00	9.94E-01
At-219	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	NA[c]	–[d]	9.00E-01	9.00E-01	9.00E-01	1.11E+00	1.11E+00	1.11E+00
Ba-137m	9.36E-01	8.98E-01	8.87E-01	9.00E-01	8.40E-01	7.60E-01	8.77E-01	1.07E+00	9.05E-01	8.41E-01	7.63E-01	1.03E+00	1.07E+00	1.16E+00
Bi-210	9.45E-01	9.11E-01	9.01E-01	8.50E-01	8.00E-01	7.30E-01	9.27E-01	1.02E+00	8.54E-01	8.04E-01	7.28E-01	1.11E+00	1.13E+00	1.24E+00
Bi-211	9.45E-01	9.11E-01	9.01E-01	9.30E-01	8.50E-01	7.90E-01	9.03E-01	1.05E+00	9.30E-01	8.50E-01	7.90E-01	1.02E+00	1.07E+00	1.14E+00
Bi-212	9.39E-01	9.04E-01	8.93E-01	9.10E-01	8.50E-01	8.10E-01	9.91E-01	9.48E-01	9.16E-01	8.48E-01	8.05E-01	1.03E+00	1.07E+00	1.11E+00
Bi-214	9.41E-01	9.06E-01	8.95E-01	9.30E-01	8.50E-01	8.30E-01	9.25E-01	1.02E+00	9.25E-01	8.49E-01	8.27E-01	1.02E+00	1.07E+00	1.08E+00
C-14	9.81E-01	9.39E-01	9.25E-01	1.00E+00	1.00E+00	1.00E+00	9.27E-01	1.06E+00	9.00E-01	9.00E-01	9.00E-01	1.09E+00	1.04E+00	1.03E+00
Co-60	9.41E-01	9.06E-01	8.95E-01	9.20E-01	8.50E-01	8.30E-01	8.34E-01	1.13E+00	9.23E-01	8.52E-01	8.37E-01	1.02E+00	1.06E+00	1.07E+00
Cs-137	9.50E-01	9.20E-01	9.11E-01	8.40E-01	8.00E-01	7.20E-01	9.27E-01	1.02E+00	8.36E-01	7.98E-01	7.22E-01	1.14E+00	1.15E+00	1.26E+00
Fr-223	9.50E-01	9.15E-01	9.05E-01	9.50E-01	8.10E-01	7.60E-01	9.61E-01	9.89E-01	9.48E-01	8.13E-01	7.64E-01	1.00E+00	1.13E+00	1.18E+00
H-3	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00E+00	–	9.00E-01	9.00E-01	9.00E-01	1.11E+00	1.11E+00	1.11E+00
I-129	9.93E-01	9.57E-01	9.43E-01	7.90E-01	8.60E-01	8.40E-01	9.80E-01	1.01E+00	7.89E-01	8.58E-01	8.32E-01	1.26E+00	1.12E+00	1.13E+00
Np-237	9.93E-01	9.57E-01	9.43E-01	9.90E-01	8.20E-01	8.40E-01	9.73E-01	1.02E+00	9.85E-01	8.18E-01	7.88E-01	1.01E+00	1.17E+00	1.20E+00
Pa-231	9.50E-01	9.20E-01	9.11E-01	9.00E-01	8.40E-01	7.80E-01	9.94E-01	9.56E-01	9.03E-01	8.46E-01	7.85E-01	1.05E+00	1.09E+00	1.16E+00
Pa-233	9.50E-01	9.20E-01	9.11E-01	9.10E-01	8.20E-01	7.60E-01	9.51E-01	9.99E-01	9.03E-01	8.13E-01	7.53E-01	1.05E+00	1.13E+00	1.21E+00
Pa-234	9.37E-01	8.99E-01	8.88E-01	9.20E-01	8.60E-01	8.00E-01	9.57E-01	9.79E-01	9.22E-01	8.55E-01	8.02E-01	1.02E+00	1.05E+00	1.11E+00
Pa-234m	9.39E-01	9.04E-01	8.93E-01	9.30E-01	8.70E-01	8.20E-01	9.99E-01	9.40E-01	9.32E-01	8.71E-01	8.23E-01	1.01E+00	1.04E+00	1.09E+00
Pb-210	1.00E+00	9.99E-01	9.99E-01	9.80E-01	9.00E-01	8.80E-01	9.96E-01	1.00E+00	9.76E-01	9.05E-01	8.75E-01	1.02E+00	1.10E+00	1.14E+00
Pb-211	9.37E-01	9.00E-01	8.88E-01	9.40E-01	8.70E-01	8.10E-01	8.94E-01	1.05E+00	9.42E-01	8.73E-01	8.11E-01	9.95E-01	1.03E+00	1.09E+00
Pb-212	9.52E-01	9.23E-01	9.15E-01	8.50E-01	7.70E-01	7.00E-01	9.19E-01	1.04E+00	8.48E-01	7.68E-01	6.98E-01	1.12E+00	1.20E+00	1.31E+00
Pb-214	9.50E-01	9.20E-01	9.11E-01	9.10E-01	8.30E-01	7.70E-01	9.29E-01	1.02E+00	9.08E-01	8.34E-01	7.68E-01	1.05E+00	1.10E+00	1.19E+00
Po-210	9.39E-01	9.04E-01	8.93E-01	9.20E-01	8.70E-01	8.00E-01	8.60E-01	1.09E+00	9.23E-01	8.70E-01	8.02E-01	1.02E+00	1.04E+00	1.11E+00
Po-211	9.36E-01	8.98E-01	8.87E-01	9.20E-01	8.70E-01	8.00E-01	8.65E-01	1.08E+00	9.26E-01	8.68E-01	8.02E-01	1.01E+00	1.03E+00	1.11E+00
Po-212	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00E+00	–	9.00E-01	9.00E-01	9.00E-01	1.11E+00	1.11E+00	1.11E+00
Po-214	9.36E-01	8.98E-01	8.87E-01	9.20E-01	8.70E-01	8.00E-01	8.61E-01	1.09E+00	9.20E-01	8.69E-01	8.02E-01	1.02E+00	1.03E+00	1.11E+00
Po-215	9.41E-01	9.04E-01	8.93E-01	9.60E-01	8.80E-01	8.10E-01	8.90E-01	1.06E+00	9.58E-01	8.76E-01	8.12E-01	9.82E-01	1.03E+00	1.10E+00
Po-216	9.39E-01	9.04E-01	8.93E-01	9.20E-01	8.70E-01	8.00E-01	8.60E-01	1.09E+00	9.23E-01	8.70E-01	8.03E-01	1.02E+00	1.04E+00	1.11E+00
Po-218	9.65E-01	9.30E-01	9.19E-01	1.00E+00	1.00E+00	1.00E+00	8.58E-01	1.12E+00	9.00E-01	9.00E-01	9.00E-01	1.07E+00	1.03E+00	1.02E+00
Pu-239	9.59E-01	9.35E-01	9.27E-01	1.10E+00	1.00E+00	9.80E-01	9.99E-01	9.60E-01	1.00E+00	1.00E+00	9.82E-01	9.59E-01	9.35E-01	9.44E-01
Pu-241	9.57E-01	9.29E-01	9.20E-01	9.80E-01	7.50E-01	7.30E-01	9.74E-01	9.83E-01	9.80E-01	7.46E-01	7.27E-01	9.77E-01	1.25E+00	1.27E+00
Ra-223	9.52E-01	9.23E-01	9.15E-01	9.20E-01	7.80E-01	7.30E-01	9.58E-01	9.94E-01	9.22E-01	7.84E-01	7.31E-01	1.03E+00	1.18E+00	1.25E+00
Ra-224	9.50E-01	9.20E-01	9.11E-01	8.00E-01	7.60E-01	6.90E-01	9.16E-01	1.04E+00	8.03E-01	7.61E-01	6.86E-01	1.18E+00	1.21E+00	1.33E+00
Ra-226	9.52E-01	9.23E-01	9.15E-01	8.60E-01	7.20E-01	6.90E-01	9.28E-01	1.03E+00	8.66E-01	7.27E-01	6.85E-01	1.10E+00	1.27E+00	1.34E+00
Ra-228	1.00E+00	1.00E+00	9.99E-01	1.20E+00	1.10E+00	1.10E+00	0.00E+00	–	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01

TABLE B.2 (Cont.)

	RESRAD ACF			Bellamy et al. (2014)[a] ACF			DCC	Ratio	ACF from the PRG Calculator			Ratio of RESRAD/PRG		
Nuclide	10,000 m^2	2,000 m^2	1,000 m^2	10,000 m^2	2,000 m^2	1,000 m^2	Area Unspecified	RESRAD 10,000/ DCC	10,000 m^2	2,000 m^2	1,000 m^2	10,000 m^2	2,000 m^2	1,000 m^2
Rn-219	9.50E-01	9.20E-01	9.11E-01	8.90E-01	8.30E-01	7.60E-01	9.11E-01	1.04E+00	8.90E-01	8.29E-01	7.62E-01	1.07E+00	1.11E+00	1.20E+00
Rn-220	9.37E-01	8.99E-01	8.88E-01	9.20E-01	8.50E-01	7.70E-01	8.80E-01	1.06E+00	9.21E-01	8.48E-01	7.72E-01	1.02E+00	1.06E+00	1.15E+00
Rn-222	9.37E-01	8.99E-01	8.88E-01	9.30E-01	8.60E-01	7.80E-01	8.83E-01	1.06E+00	9.32E-01	8.58E-01	7.84E-01	1.01E+00	1.05E+00	1.13E+00
Sr-90	9.52E-01	9.23E-01	9.15E-01	1.00E+00	1.00E+00	1.00E+00	9.27E-01	1.03E+00	9.00E-01	9.00E-01	9.00E-01	1.06E+00	1.03E+00	1.02E+00
Tc-99	9.57E-01	9.28E-01	9.20E-01	1.00E+00	7.80E-01	7.50E-01	9.27E-01	1.03E+00	1.00E+00	7.82E-01	7.48E-01	9.57E-01	1.19E+00	1.23E+00
Th-227	9.52E-01	9.23E-01	9.15E-01	8.60E-01	7.90E-01	7.30E-01	9.71E-01	9.80E-01	8.60E-01	7.93E-01	7.25E-01	1.11E+00	1.16E+00	1.26E+00
Th-228	9.57E-01	9.29E-01	9.21E-01	1.00E+00	8.30E-01	8.00E-01	9.80E-01	9.77E-01	1.00E+00	8.33E-01	7.95E-01	9.57E-01	1.12E+00	1.16E+00
Th-230	9.62E-01	9.32E-01	9.24E-01	1.10E+00	9.60E-01	9.40E-01	9.97E-01	9.65E-01	1.00E+00	9.62E-01	9.34E-01	9.62E-01	9.69E-01	9.89E-01
Th-231	1.00E+00	9.90E-01	9.85E-01	1.00E+00	8.80E-01	8.50E-01	9.85E-01	1.02E+00	1.00E+00	8.78E-01	8.49E-01	1.00E+00	1.13E+00	1.16E+00
Th-234	9.65E-01	9.30E-01	9.19E-01	1.10E+00	8.00E-01	7.60E-01	9.57E-01	1.01E+00	1.00E+00	8.04E-01	7.64E-01	9.65E-01	1.16E+00	1.20E+00
Tl-207	9.37E-01	8.99E-01	8.88E-01	9.30E-01	8.80E-01	8.20E-01	8.55E-01	1.10E+00	9.27E-01	8.83E-01	8.21E-01	1.01E+00	1.02E+00	1.08E+00
Tl-208	9.41E-01	9.06E-01	8.95E-01	9.70E-01	8.90E-01	8.70E-01	8.79E-01	1.07E+00	9.74E-01	8.84E-01	8.71E-01	9.66E-01	1.02E+00	1.03E+00
Tl-210	9.39E-01	9.04E-01	8.93E-01	9.30E-01	8.60E-01	8.30E-01	NA	–	9.23E-01	8.54E-01	8.23E-01	1.02E+00	1.06E+00	1.09E+00
U-234	9.99E-01	9.98E-01	9.97E-01	1.10E+00	1.00E+00	1.00E+00	9.98E-01	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.98E-01	9.97E-01
U-235	9.52E-01	9.23E-01	9.15E-01	8.70E-01	7.20E-01	6.90E-01	9.60E-01	9.92E-01	8.70E-01	7.23E-01	6.88E-01	1.09E+00	1.28E+00	1.33E+00
U-235m	1.00E+00	1.00E+00	1.00E+00	9.50E-01	9.50E-01	9.30E-01	NA	–	9.52E-01	9.52E-01	9.37E-01	1.05E+00	1.05E+00	1.07E+00
U-237	9.57E-01	9.29E-01	9.20E-01	9.40E-01	7.70E-01	7.20E-01	9.53E-01	1.00E+00	9.42E-01	7.66E-01	7.23E-01	1.02E+00	1.21E+00	1.27E+00
U-238	9.69E-01	9.51E-01	9.45E-01	1.10E+00	1.00E+00	1.00E+00	1.00E+00	9.69E-01	1.00E+00	1.00E+00	1.00E+00	9.69E-01	9.51E-01	9.45E-01
Y-90	9.39E-01	9.04E-01	8.93E-01	1.20E+00	1.10E+00	1.10E+00	1.00E+00	9.39E-01	1.00E+00	1.00E+00	1.00E+00	9.39E-01	9.04E-01	8.93E-01

[a] Bellamy, M., et al., 2014, *Area Correction Factors for Contaminated Soil for Use in Risk and Dose Assessment Models*, ORNL/TM-2013/00, September, Oak Ridge National Laboratory, Oak Ridge, Tenn.

[b] Area Correction Factor greater than 1 is highlighted in red.

[c] NA = not available or not applicable.

[d] A dash indicates that either one of the values in the ratio is not available or the value is zero.

TABLE B.3 Default Parameters Used in the Farmer Scenario PRGs and DCCs for Soil and RESRAD Defaults

Element	Wet Soil to Plant Transfer Factor (pCi/g per pCi/g)			Distribution Coefficient (cm^3/g)			Fish Bioaccumulation Factor (pCi/kg per pCi/L)			Beef Transfer Factor (pCi/kg per pCi/d)[a]			Dairy Transfer Factor (pCi/kg per pCi/d)		
	PRG	DCC	RESRAD	PRG	DCC	RESRAD	PRG	DCC	RESRAD	PRG	DCC	RESRAD	PRG	DCC	RESRAD
Ac	1.00E-03	2.50E-03	2.50E-03	1.70E+03	NA[b]	2.00E+01	1.50E+01	1.50E+01	1.50E+01	2.00E-05	2.00E-05	2.00E-05	2.00E-06	2.00E-05	2.00E-05
Am	1.91E-05	1.00E-03	1.00E-03	4.00E+00	8.20E+00	2.00E+01	2.40E+02	3.00E+01	3.00E+01	5.00E-04	5.00E-05	5.00E-05	4.20E-07	2.00E-06	2.00E-06
C	5.50E+00	5.50E+00	5.50E+00	8.00E-01	8.00E-01	0.00E+00	4.00E+05	5.00E+04	5.00E+04	3.10E-02	3.10E-02	3.10E-02	1.20E-02	1.20E-02	1.20E-02
Co	7.40E-03	8.00E-02	8.00E-02	4.80E+02	1.00E-01	1.00E+03	7.60E+01	3.00E+02	3.00E+02	4.30E-04	2.00E-02	2.00E-02	1.10E-04	2.00E-03	2.00E-03
Cs	2.52E-02	4.00E-02	4.00E-02	1.00E+01	1.00E+01	4.60E+03	2.50E+03	2.00E+03	2.00E+03	2.20E-02	3.00E-02	3.00E-02	4.60E-03	8.00E-03	8.00E-03
H	4.80E+00	4.80E+00	4.80E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	1.00E+00	1.00E+00	1.20E-02	1.20E-02	1.20E-02	1.00E-02	1.00E-02	1.00E-02
I	5.48E-04	2.00E-02	2.00E-02	0.00E+00	3.00E-02	1.00E-01	3.00E+01	4.00E+01	4.00E+01	6.70E-03	7.00E-03	7.00E-03	5.40E-03	1.00E-02	1.00E-02
Np	2.52E-03	2.00E-02	2.00E-02	2.00E-01	1.00E-01	soil/plant	3.00E+01	3.00E+01	3.00E+01	1.00E-03	1.00E-03	1.00E-03	1.00E-05	5.00E-06	5.00E-06
Pa	1.00E-02	1.00E-02	1.00E-02	2.00E+03	NA	5.00E+01	1.00E+01	1.00E+01	1.00E+01	5.00E-06	5.00E-03	5.00E-03	5.00E-06	5.00E-06	5.00E-06
Pb	9.57E-03	1.00E-02	1.00E-02	1.50E+02	6.00E+00	1.00E+02	2.50E+01	3.00E+02	3.00E+02	7.00E-04	8.00E-04	8.00E-04	1.90E-04	3.00E-04	3.00E-04
Pu	8.27E-06	1.00E-03	1.00E-03	5.00E+00	5.00E+00	2.00E+03	2.10E+04	3.00E+01	3.00E+01	1.10E-06	1.00E-04	1.00E-04	1.00E-05	1.00E-06	1.00E-06
Ra	1.48E-02	4.00E-02	4.00E-02	1.00E+00	3.00E+00	7.00E+01	4.00E+00	5.00E+01	5.00E+01	1.70E-03	1.00E-03	1.00E-03	3.80E-04	1.00E-03	1.00E-03
Sr	9.57E-02	3.00E-01	3.00E-01	1.00E+00	1.00E+00	3.00E+01	2.90E+00	6.00E+01	6.00E+01	1.30E-03	8.00E-03	8.00E-03	1.30E-03	2.00E-03	2.00E-03
Tc	1.13E+00	5.00E+00	5.00E+00	0.00E+00	7.00E-03	0.00E+00	2.00E+01	2.00E+01	2.00E+01	1.00E-04	1.00E-04	1.00E-04	1.00E-03	1.00E-03	1.00E-03
Th	1.83E-03	1.00E-03	1.00E-03	2.00E+01	2.00E+01	6.00E+04	6.00E+00	1.00E+02	1.00E+02	2.30E-04	1.00E-04	1.00E-04	5.00E-06	5.00E-06	5.00E-06
U	5.39E-03	2.50E-03	2.50E-03	4.00E-01	4.00E-01	5.00E+01	9.60E-01	1.00E+01	1.00E+01	3.90E-04	3.40E-04	3.40E-04	1.80E-03	6.00E-04	6.00E-04

[a] In the PRG and DCC Calculators, the beef and dairy transfer factors are wrongly called plant to beef transfer factor and plant to milk transfer factor, respectively. The transfer of activity to beef and dairy is not just from plant ingestion but also from other ingestion routes such as soil ingestion.

[b] NA = not available or not applicable.

TABLE B.4 Dose Conversion Factors Used in the DCC Calculator and RESRAD

Radionuclide	Inhalation Type Listed in DCC[a]	Inhalation Type Used in DCC[b]	Dose Coefficient Used in the DCC Calculator[c]				Dose Coefficient Used in RESRAD[c]		
			Ingestion DCF (mrem/pCi)	Inhalation DCF (mrem/pCi)	External Exposure DCF (mrem/yr per pCi/g)		Ingestion DCF (mrem/pCi)	Inhalation DCF (mrem/pCi)	External Exposure DCF (mrem/yr per pCi/g)
Ac-227	S	M	4.07E-03	8.14E-01	4.46E-04		4.07E-03	8.14E-01	4.49E-04
Am-241	M	M	7.40E-04	1.55E-01	3.71E-02		7.40E-04	1.55E-01	3.72E-02
C-14	M	V CO2	2.15E-06	2.29E-08	1.10E-05		2.15E-06	2.29E-08	1.11E-05
Co-60	M	M	1.26E-05	3.70E-05	1.54E+01		1.26E-05	3.70E-05	1.54E+01
Cs-137	F	F	4.81E-05	1.70E-05	8.34E-04		4.81E-05	1.70E-05	8.37E-04
H-3	M	V OBT	1.55E-07	1.52E-07	0.00E+00		1.55E-07	1.52E-07	0.00E+00
I-129	F	V (I2)	4.07E-04	2.74E-04	9.53E-03		4.07E-04	2.74E-04	9.61E-03
Np-237	M	M	4.07E-04	8.51E-02	6.94E-02		4.07E-04	8.51E-02	6.97E-02
Pa-231	S	M	2.63E-03	5.18E-01	1.76E-01		2.63E-03	5.18E-01	1.76E-01
Pb-210	M	M	2.55E-03	4.07E-03	1.98E-03		2.55E-03	4.07E-03	1.98E-03
Pu-239	M	M	9.25E-04	1.85E-01	2.63E-04		9.25E-04	1.85E-01	2.64E-04
Pu-241	M	M	1.78E-05	3.33E-03	5.30E-06		1.78E-05	3.33E-03	5.33E-06
Ra-226	M	M	1.04E-03	1.30E-02	2.91E-02		1.04E-03	1.30E-02	2.92E-02
Ra-228	M	M	2.55E-03	9.62E-03	0.00E+00		2.55E-03	9.62E-03	0.00E+00
Sr-90	M	M	1.04E-04	1.33E-04	6.45E-04		1.04E-04	1.33E-04	6.47E-04
Tc-99	M	M	2.37E-06	1.48E-05	1.08E-04		2.37E-06	1.48E-05	1.09E-04
Th-228	S	S	2.66E-04	1.48E-01	7.16E-03		2.66E-04	1.48E-01	7.18E-03
Th-230	S	S	7.77E-04	5.18E-02	1.07E-03		7.77E-04	5.18E-02	1.07E-03
U-234	M	M	1.81E-04	1.30E-02	3.43E-04		1.81E-04	1.30E-02	3.44E-04
U-235	M	M	1.74E-04	1.15E-02	6.58E-01		1.74E-04	1.15E-02	6.60E-01
U-238	M	M	1.67E-04	1.07E-02	7.94E-05		1.67E-04	1.07E-02	7.96E-05

[a] Inhalation types: F = Fast, M = Medium, and S = Slow.

[b] In actual calculations, different inhalation class type DCFs are used in the DCC Calculator for Ac-227, C-14, H-3, I-129, and Pa-231 (compare inhalation type listed vs. inhalation type used).

[c] There is no difference in the inhalation and ingestion DCFs used in the DCC Calculator and RESRAD code. A slight difference (<0.5%) in external DCFs is due to rounding errors (compare DCF values in the table).

TABLE B.5 Expected DCFs with Different Cutoff Half-Lives Compared with Actual Values Used by RESRAD and the DCC Calculator[a]

Radionuclide	Expected DCFs (Cutoff = 6 months)			Expected DCFs (Cutoff = 100 years)			DCFs Used in RESRAD (Cutoff = 6 months)			DCFs Used in DCC with +D			DCFs Used in DCC with +E		
	Ingestion DCF (mrem/pCi)	Inhalation DCF (mrem/pCi)	External Exposure DCF (mrem/yr per pCi/g)	Ingestion DCF (mrem/pCi)	Inhalation DCF (mrem/pCi)	External Exposure DCF (mrem/yr per pCi/g)	Ingestion DCF (mrem/pCi)	Inhalation DCF (mrem/pCi)	External Exposure DCF (mrem/yr per pCi/g)	Ingestion DCF (mrem/pCi)	Inhalation DCF (mrem/pCi)	External Exposure DCF (mrem/yr per pCi/g)	Ingestion DCF (mrem/pCi)	Inhalation DCF (mrem/pCi)	External Exposure DCF (mrem/yr per pCi/g)
Ac-227[b]	4.47E-03	8.78E-01	1.87E+00	4.47E-03	8.78E-01	1.87E+00	4.47E-03	8.78E-01	1.87E+00	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA
Am-241	7.40E-04	1.55E-01	3.72E-02	7.40E-04	1.55E-01	3.72E-02	7.40E-04	1.55E-01	3.72E-02	7.40E-04	1.55E-01	3.71E-02	7.40E-04	1.55E-01	3.71E-02
C-14	2.15E-06	2.29E-08	1.11E-05	2.15E-06	2.29E-08	1.11E-05	2.15E-06	2.29E-08	1.11E-05	2.15E-06	2.29E-08	1.10E-05	2.15E-06	2.29E-08	1.10E-05
Co-60	1.26E-05	3.70E-05	1.54E+01	1.26E-05	3.70E-05	1.54E+01	1.26E-05	3.70E-05	1.54E+01	1.26E-05	3.70E-05	1.54E+01	1.26E-05	3.70E-05	1.54E+01
Cs-137	4.81E-05	1.70E-05	3.19E+00	4.81E-05	1.70E-05	3.19E+00	4.81E-05	1.70E-05	3.19E+00	4.81E-05	1.70E-05	3.19E+00	4.81E-05	1.70E-05	3.19E+00
H-3	1.55E-07	1.52E-07	0.00E+00	1.55E-07	1.52E-07	0.00E+00	1.55E-07	1.52E-07	0.00E+00	1.55E-07	1.52E-07	0.00E+00	1.55E-07	1.52E-07	0.00E+00
I-129	4.07E-04	2.74E-04	9.61E-03	4.07E-04	2.74E-04	9.61E-03	4.07E-04	2.74E-04	9.61E-03	4.07E-04	2.74E-04	9.53E-03	4.07E-04	2.74E-04	9.53E-03
Np-237[c]	4.10E-04	8.51E-02	1.01E+00	4.10E-04	8.51E-02	1.01E+00	4.10E-04	8.51E-02	1.01E+00	DCF NA	DCF NA	DCF NA	4.07E-04	8.51E-02	1.01E+00
Pa-231[a, b]	2.63E-03	5.18E-01	1.76E-01	7.10E-03	1.40E+00	2.04E+00	2.63E-03	5.18E-01	1.76E-01	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA
Pb-210[a, b]	7.00E-03	1.66E-02	7.50E-03	7.00E-03	1.66E-02	7.50E-03	7.00E-03	1.66E-02	7.50E-03	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA
Pu-239[c]	9.25E-04	1.85E-01	2.64E-04	9.25E-04	1.85E-01	2.64E-04	9.25E-04	1.85E-01	2.64E-04	DCF NA	DCF NA	DCF NA	DCF NA	DCF NA	DCF NA
Pu-241[b]	1.78E-05	3.33E-03	1.71E-05	1.78E-05	3.33E-03	1.71E-05	1.78E-05	3.33E-03	1.71E-05	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA
Ra-226[a,d]	1.04E-03	1.30E-02	9.36E+00	8.03E-03	2.96E-02	9.37E+00	1.04E-03	1.30E-02	9.36E+00	1.04E-03	1.30E-02	1.06E+01	1.04E-03	1.30E-02	1.06E+01
Ra-228[a, e]	2.55E-03	9.68E-03	5.66E+00	3.08E-03	1.70E-01	1.53E+01	2.55E-03	9.68E-03	5.66E+00	3.07E-03	1.70E-01	5.65E+00	3.07E-03	1.70E-01	1.53E+01
Sr-90[d]	1.14E-04	1.38E-04	4.10E-02	1.14E-04	1.38E-04	4.10E-02	1.14E-04	1.38E-04	4.10E-02	1.04E-04	1.33E-04	4.07E-02	1.04E-04	1.33E-04	4.07E-02
Tc-99	2.37E-06	1.48E-05	1.09E-04	2.37E-06	1.48E-05	1.09E-04	2.37E-06	1.48E-05	1.09E-04	2.37E-06	1.48E-05	1.08E-04	2.37E-06	1.48E-05	1.08E-04
Th-228[b]	5.30E-04	1.60E-01	9.67E+00	5.30E-04	1.60E-01	9.67E+00	5.30E-04	1.60E-01	9.67E+00	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA	+D/+E NA
Th-230	7.77E-04	5.18E-02	1.07E-03	7.77E-04	5.18E-02	1.07E-03	7.77E-04	5.18E-02	1.07E-03	7.77E-04	5.18E-02	1.07E-03	7.77E-04	5.18E-02	1.07E-03
U-234	1.81E-04	1.30E-02	3.44E-04	1.81E-04	1.30E-02	3.44E-04	1.81E-04	1.30E-02	3.44E-04	1.81E-04	1.30E-02	3.43E-04	1.81E-04	1.30E-02	3.43E-04
U-235[f]	1.75E-04	1.15E-02	6.92E-01	1.75E-04	1.15E-02	6.92E-01	1.75E-04	1.15E-02	6.92E-01	DCF NA	DCF NA	6.90E-01	DCF NA	DCF NA	6.90E-01
U-238[d]	1.79E-04	1.08E-02	1.37E-01	1.79E-04	1.08E-02	1.37E-01	1.79E-04	1.08E-02	1.37E-01	1.67E-04	1.07E-02	1.56E-01	1.67E-04	1.07E-02	1.55E-01

[a] Note the difference in DCFs for Pa-231, Ra-226, and Ra-228 when a cutoff half-life of 100 years is used instead of 6 months.

[b] Ac-227, Pa-231, Pb-210, Pu-241, and Th-228 all include decay products with less than a 100-year half-life, but +D or +E are not included in the list of radionuclides for analysis.

[c] DCFs are not provided in the DCC Calculator for Pu-239+D, Pu-239+E, and Np-237+D.

[d] In the DCC Calculator, for Ra-226, Sr-90, and U-238 with +D and +E, progeny contributions in external DCFs are not added properly.

[e] In the DCC Calculator, for Ra-228 with +D for *ext* includes 6-month half-life decay products and for *inh* and *ing* includes longer-lived Th-228.

[f] Inhalation and ingestion DCFs are not provided in the DCC Calculator for U-235+D and U-235+E.

TABLE B.6 Input Parameters for the Outdoor Worker Scenario

Parameter in the DCC Calculator	Parameter Value Used in the DCC Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Notes
Area	Not defined	Area of contaminated zone (m^2)	10,000	RESRAD default used
		Thickness of contaminated zone (m)	2	RESRAD default used
		Cover depth (m)	0	RESRAD default used
		Cover erosion rate (m/yr)	0	Not required
		Contaminated zone erosion rate (m/yr)	0	
		Humidity in air (g/m^3)	6	The DCC Calculator assumes that the humidity in the air is 6 g/m^3 when considering the evaporation of H-3 in soil water to the air.
Soil intake rate (mg/d)	100	Soil ingestion (g/yr)	109.50	The DCC value is the amount of contaminated soil ingested in 1 day. The RESRAD input is the annual amount of soil ingested. Its value is obtained by multiplying the DCC value by exposure frequency (225 d/yr), dividing by 1,000 (mg/g), and the total time fraction on site [(8 × 225)/8,760 = 0.2055)].
Soil inhalation rate (m^3/d)	60	Inhalation rate (m^3/yr)	21,900	The DCC value is the amount of contaminated air inhaled in 1 day. The RESRAD input is the annual amount of air inhaled. Its value is obtained by multiplying the DCC value by exposure frequency and dividing by the total time fraction on site [(8 × 225)/8,760 = 0.2055].
Outdoor exposure time (h/d)	8	Outdoor time fraction	0.2055	In the DCC Calculator, the outdoor exposure time (h/d) is amount of time spent in 1 day, and it is used only for the external radiation pathway. The exposure time used for the inhalation pathway is 24 h/d. The RESRAD input is the time fraction spent outdoor in 1 year and is obtained by multiplying the DCC value by the exposure frequency and dividing by the total number of hours in 1 year
Exposure frequency (d/yr)	225			
Exposure duration—resident (yr)	1	Exposure duration (yr)	1	
		Indoor dust filtration factor	1	In the DCC Calculator, the indoor and outdoor dust levels are the same. Therefore, the input for RESRAD is set to 1.
PEF (particulate emission factor) (m^3/kg)	1.36E+09[a]	Mass loading for inhalation and foliar deposition (g/m^3)	1.07E-05	The PEF in the DCC Calculator is calculated; the inverse of which is equivalent to the multiplication product of the mass loading factor and area factor for inhalation in RESRAD.
Mean annual wind speed (m/s)	4.69	Wind speed (m/s)	4.69	

[a] The yellow background indicates that the PEF value is calculated with other input parameters. For some parameters, there is no default value.

TABLE B.7 Comparison of RESRAD and DCC Calculator Results for the Outdoor Worker Scenario[a]

Radionuclide	Time of Dose in RESRAD (yr)	RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) from Individual Pathway That Results in a 1-mrem/yr Dose				Soil DCC (pCi/g) from Individual Pathway That Results in a 1-mrem/yr dose				Ratio (DCC/SCG)				Remarks
		Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total	
Ac-227	0	1.01E+01	3.47E+02	2.81E+00	2.18E+00	1.11E+01	3.77E+02	1.11E+04	1.08E+01	1.10E+00	1.09E+00	3.96E+03	4.95E+00	Short-lived progeny (half-life < 180 d) not included in DCC.
Am-241	0	6.07E+01	1.94E+03	1.36E+02	4.11E+01	60.1	1.95E+03	136	40.8	9.90E-01	1.00E+00	9.98E-01	9.92E-01	
C-14	0	7.42E+04	2.07E+04	1.61E+06	1.60E+04	2.07E+04	1.32E+10	4.79E+05	1.99E+04	2.79E-01	6.38E+05	2.98E-01	1.24E+00	Special model in RESRAD.
Co-60	0	4.67E+03	1.07E+07	4.44E-01	4.44E-01	3.77E+03	8.71E+06	0.405	0.405	8.08E-01	8.17E-01	9.13E-01	9.13E-01	Low K_d value reduces average soil conc. in RESRAD.
Cs-137+D	0	9.43E+02	1.79E+07	1.66E+00	1.66E+00	9.35E+02	1.80E+07	1.76E+00	1.76E+00	9.92E-01	1.01E+00	1.06E+00	1.06E+00	
H-3	0	5.12E+05	5.53E+03	NA[b]	5.47E+03	2.94E+05	2.56E+01	0	25.6	5.74E-01	4.63E-03	NA	4.68E-03	Special model in RESRAD. DCC Calculator uses volatilization factor (17 m^3/kg) instead of PEF.[c]
I-129	0	1.43E+02	1.42E+06	6.67E+02	1.17E+02	1.09E+02	1.10E+06	5.21E+02	9.03E+01	7.64E-01	7.72E-01	7.82E-01	7.69E-01	Low K_d value reduces average soil conc. in RESRAD.
Np-237+D	0	1.35E+02	4.36E+03	6.32E+00	6.03E+00	1.09E+02	3.55E+03	4.96	4.74	8.09E-01	8.13E-01	7.85E-01	7.87E-01	Low K_d value reduces average soil conc. in RESRAD.
Pa-231	0	1.65E+01	5.62E+02	2.51E+01	9.78E+00	1.69E+01	5.83E+02	2.78E+01	1.03E+01	1.02E+00	1.04E+00	1.11E+00	1.05E+00	
Pb-210	0	6.54E+00	1.85E+04	6.99E+02	6.47E+00	1.77E+01	7.54E+04	2.51E+03	17.6	2.71E+00	4.08E+00	3.59E+00	2.72E+00	Short-lived progeny (half-life < 180 d) not included in DCC.
Pu-239	0	4.88E+01	1.64E+03	1.97E+04	4.73E+01	4.80E+01	1.63E+03	1.85E+04	4.66E+01	9.84E-01	9.94E-01	9.40E-01	9.86E-01	
Pu-241	0	2.52E+03	8.99E+04	1.11E+05	2.40E+03	2.56E+03	9.29E+04	9.66E+05	2.49E+03	1.02E+00	1.03E+00	8.68E+00	1.04E+00	
Ra-226+D	0	3.98E+01	2.30E+04	5.01E-01	4.94E-01	4.29E+01	2.33E+04	4.95E-01	4.90E-01	1.08E+00	1.01E+00	9.89E-01	9.91E-01	
Ra-228+D	0	1.83E+01	9.01E+03	7.75E-01	7.43E-01	15.4	1.88E+03	0.987	0.927	8.41E-01	2.09E-01	1.27E+00	1.25E+00	Buildup of long-lived progeny Th-228 in 1 yr not included.

TABLE B.7 (Cont.)

Radionuclide	Time of Dose in RESRAD (yr)	RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) from Individual Pathway That Results in a 1-mrem/yr Dose				Soil DCC (pCi/g) from Individual Pathway That Results in a 1-mrem/yr dose				Ratio (DCC/SCG)				Remarks
		Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total	
Sr-90+D	0	4.22E+02	2.33E+06	1.36E+02	1.03E+02	4.34E+02	2.30E+06	1.21E+02	9.47E+01	1.03E+00	9.87E-01	8.87E-01	9.18E-01	
Tc-99	0	2.50E+04	2.69E+07	6.25E+04	1.79E+04	1.88E+04	2.04E+07	4.85E+04	1.35E+04	7.51E-01	7.58E-01	7.76E-01	7.56E-01	Low K_d value reduces average soil conc. in RESRAD.
Th-228	0	1.00E+02	2.24E+03	6.39E-01	6.34E-01	1.99E+02	2.43E+03	8.27E+02	1.50E+02	1.98E+00	1.09E+00	1.30E+03	2.36E+02	Short-lived progeny (half-life < 180 d) not included in DCC.
Th-230	0	5.74E+01	5.79E+03	1.55E+03	5.48E+01	5.72E+01	5.83E+03	4.57E+03	5.60E+01	9.96E-01	1.01E+00	2.95E+00	1.02E+00	
U-234	0	2.77E+02	2.61E+04	1.66E+04	2.70E+02	2.45E+02	2.33E+04	1.42E+04	2.39E+02	8.84E-01	8.94E-01	8.56E-01	8.86E-01	Low K_d value reduces average soil conc. in RESRAD.
U-235+D	0	2.87E+02	2.94E+04	8.35E+00	8.11E+00	NA[c]	NA	7.35E+00	7.35E+00	0.00E+00	0.00E+00	8.81E-01	9.06E-01	
U-238+D	0	2.80E+02	3.14E+04	4.24E+01	3.68E+01	2.67E+02	2.82E+04	3.20E+01	2.85E+01	9.52E-01	8.99E-01	7.54E-01	7.74E-01	Difference in +D DCF calculation.
Pa-231	61	8.94E+00	3.06E+02	3.88E+00	2.68E+00	1.69E+01	5.83E+02	2.78E+01	1.03E+01	1.89E+00	1.91E+00	7.17E+00	3.84E+00	Buildup of long-lived progeny Ac-227 not included.
Pu-241	6	2.75E+03	9.47E+04	1.73E+04	2.32E+03	2.56E+03	9.29E+04	9.66E+05	2.49E+03	9.30E-01	9.81E-01	5.60E+01	1.08E+00	Buildup of long-lived progeny Am-241 not included.
Ra-228	2	2.33E+01	3.72E+03	6.33E-01	6.16E-01	15.4	1.88E+03	0.987	0.927	6.62E-01	5.05E-01	1.56E+00	1.51E+00	Buildup of long-lived progeny Th-228 not included.
Th-230	29	7.07E+01	7.33E+03	8.49E+01	3.84E+01	5.72E+01	5.83E+03	4.57E+03	5.60E+01	8.09E-01	7.95E-01	5.38E+01	1.46E+00	Buildup of long-lived progeny Ra-226 not included.

[a] The differences in total ratio (DCC/SCG) greater than 10% are shown in red.

[b] NA = not available.

[c] The Volatilization Factor is calculated from the soil moisture content and humidity.

TABLE B.8 Comparison of RESRAD and DCC Calculator Results for the Outdoor Worker Scenario with High K_d and Low Infiltration

Radionuclide	Time of Dose in RESRAD (yr)	RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) That Results in a 1-mrem/yr Dose				DCC (pCi/g) That Results in a 1-mrem/yr dose				Ratio (DCC/SCG)				Remarks
		Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total[a]	
Ac-227	0	1.01E+01	3.46E+02	2.79E+00	2.17E+00	1.11E+01	3.77E+02	1.11E+04	1.08E+01	1.10E+00	1.09E+00	3.97E+03	4.97E+00	Short-lived progeny (half-life < 180 d) not included in DCC.
Am-241	0	6.01E+01	1.92E+03	1.35E+02	4.07E+01	60.1	1.95E+03	136	40.8	1.00E+00	1.01E+00	1.01E+00	1.00E+00	
C-14	0	7.13E+04	1.99E+04	1.54E+06	1.54E+04	2.07E+04	1.32E+10	4.79E+05	1.99E+04	2.90E-01	6.64E+05	3.10E-01	1.29E+00	Special model in RESRAD.
Co-60	0	3.77E+03	8.61E+06	3.58E-01	3.58E-01	3.77E+03	8.71E+06	0.405	0.405	1.00E+00	1.01E+00	1.13E+00Ra	1.13E+00	Difference in ACF value.
Cs-137+D	0	9.35E+02	1.77E+07	1.65E+00	1.64E+00	9.35E+02	1.80E+07	1.76E+00	1.76E+00	1.00E+00	1.01E+00	1.07E+00	1.07E+00	
H-3	0	2.94E+05	1.11E+03	NA[b]	1.10E+03	2.94E+05	2.56E+01	0	25.6	1.00E+00	2.32E-02	NA	2.32E-02	Special model in RESRAD.
I-129	0	1.09E+02	1.09E+06	5.10E+02	8.99E+01	1.09E+02	1.10E+06	5.21E+02	9.03E+01	9.98E-01	1.01E+00	1.02E+00	1.00E+00	
Np-237+D	0	1.08E+02	3.51E+03	5.08E+00	4.84E+00	1.09E+02	3.55E+03	4.96	4.74	1.01E+00	1.01E+00	9.77E-01	9.79E-01	
Pa-231	0	1.65E+01	5.61E+02	2.50E+01	9.76E+00	1.69E+01	5.83E+02	2.78E+01	1.03E+01	1.03E+00	1.04E+00	1.11E+00	1.06E+00	
Pb-210	0	6.45E+00	1.82E+04	6.90E+02	6.39E+00	1.77E+01	7.54E+04	2.51E+03	17.6	2.74E+00	4.13E+00	3.64E+00	2.75E+00	Short-lived progeny (half-life < 180 d) not included in DCC.
Pu-239	0	4.81E+01	1.61E+03	1.94E+04	4.66E+01	4.80E+01	1.63E+03	1.85E+04	4.66E+01	9.99E-01	1.01E+00	9.55E-01	1.00E+00	
Pu-241	0	2.48E+03	8.85E+04	1.10E+05	2.36E+03	2.56E+03	9.29E+04	9.66E+05	2.49E+03	1.03E+00	1.05E+00	8.82E+00	1.05E+00	
Ra-226+D	0	3.88E+01	2.24E+04	4.88E-01	4.82E-01	4.29E+01	2.33E+04	4.95E-01	4.90E-01	1.11E+00	1.04E+00	1.01E+00	1.02E+00	
Ra-228+D	0	1.79E+01	8.82E+03	7.56E-01	7.26E-01	15.4	1.88E+03	0.987	0.927	8.62E-01	2.13E-01	1.30E+00	1.28E+00	Buildup of long-lived progeny Th-228 in 1 yr not included.
Sr-90+D	0	3.96E+02	2.18E+06	1.28E+02	9.67E+01	4.34E+02	2.30E+06	1.21E+02	9.47E+01	1.10E+00	1.05E+00	9.46E-01	9.80E-01	
Tc-99	0	1.88E+04	2.02E+07	4.68E+04	1.34E+04	1.88E+04	2.04E+07	4.85E+04	1.35E+04	1.00E+00	1.01E+00	1.04E+00	1.01E+00	
Th-228	0	1.00E+02	2.23E+03	6.36E-01	6.32E-01	1.99E+02	2.43E+03	8.27E+02	1.50E+02	1.99E+00	1.09E+00	1.30E+03	2.37E+02	Short-lived progeny (half-life < 180 d) not included in DCC.
Th-230	0	5.72E+01	5.76E+03	1.53E+03	5.46E+01	5.72E+01	5.83E+03	4.57E+03	5.60E+01	1.00E+00	1.01E+00	2.99E+00	1.03E+00	
U-234	0	2.45E+02	2.31E+04	1.47E+04	2.39E+02	2.45E+02	2.33E+04	1.42E+04	2.39E+02	9.99E-01	1.01E+00	9.68E-01	1.00E+00	
U-235+D	0	2.54E+02	2.60E+04	7.39E+00	7.17E+00			7.35E+00	7.35E+00	0.00E+00	0.00E+00	9.95E-01	1.02E+00	
U-238+D	0	2.48E+02	2.78E+04	3.76E+01	3.26E+01	2.67E+02	2.82E+04	3.20E+01	2.85E+01	1.08E+00	1.02E+00	8.52E-01	8.75E-01	Difference in +D DCF calculation.
Pa-231	223	6.29E+00	2.15E+02	2.53E+00	1.79E+00	1.69E+01	5.83E+02	2.78E+01	1.03E+01	2.69E+00	2.71E+00	1.10E+01	5.76E+00	Buildup of long-lived progeny Ac-227 not included.
Pu-241	58	1.96E+03	6.30E+04	4.61E+03	1.35E+03	2.56E+03	9.29E+04	9.66E+05	2.49E+03	1.31E+00	1.47E+00	2.10E+02	1.85E+00	Buildup of long-lived progeny Am-241 not included.
Ra-226+D	53	6.72E+00	1.15E+04	4.99E-01	4.64E-01	4.29E+01	2.33E+04	4.95E-01	4.90E-01	6.38E+00	2.03E+00	9.92E-01	1.05E+00	
Ra-228	3	2.25E+01	3.12E+03	5.66E-01	5.52E-01	15.4	1.88E+03	0.987	0.927	6.84E-01	6.03E-01	1.74E+00	1.68E+00	Buildup of long-lived progeny Th-228 not included.

TABLE B.8 (Cont.)

Radionuclide	Time of Dose in RESRAD (yr)	RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) That Results in a 1-mrem/yr Dose				DCC (pCi/g) That Results in a 1-mrem/yr dose				Ratio (DCC/SCG)				Remarks
		Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total	Ingestion	Inhalation	External	Total[a]	
Th-230	1,000	1.26E+01	4.85E+03	1.39E+00	1.25E+00	5.72E+01	5.83E+03	4.57E+03	5.60E+01	4.53E+00	1.20E+00	3.28E+03	4.46E+01	Buildup of long-lived progeny Ra-226 not included.
U-234	1,000	2.21E+02	2.22E+04	2.77E+02	1.22E+02	2.45E+02	2.33E+04	1.42E+04	2.39E+02	1.11E+00	1.05E+00	5.13E+01	1.95E+00	Buildup of long-lived progeny Th-230 not included.
U-235+D	1,000	1.39E+02	7.44E+03	6.97E+00	6.63E+00	NA	NA	7.35E+00	7.35E+00	0.00E+00	0.00E+00	1.05E+00	1.11E+00	Buildup of long-lived progeny Pa-231 not included.
U-238+D	1,000	2.48E+02	2.77E+04	3.76E+01	3.26E+01	2.67E+02	2.82E+04	3.20E+01	2.85E+01	1.08E+00	1.02E+00	8.52E-01	8.75E-01	Difference in +D DCF calculation.

[a] The differences in total ratio (DCC/SCG) greater than 10% are shown in red.

[b] NA = not available or not applicable.

TABLE B.9 Input Parameters for the Resident Scenario[a]

Parameter in the DCC Calculator	Parameter Value Used in the DCC Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Notes
Area	Not defined	Area of contaminated zone (m^2)	10,000	RESRAD default used.
		Thickness of contaminated zone (m)	2	
		Cover depth (m)	0	
		Cover erosion rate (m/yr)	0	
		Contaminated zone erosion rate (m/yr)	0	
		Humidity in air (g/m^3)	6	The DCC Calculator assumes that the humidity in the air is 6 g/m^3 when considering the evaporation of H-3 in soil water to the air.
Age-adjusted soil ingestion rate (mg/d)	120	Soil ingestion (g/yr)	57.86	The DCC age-adjusted value is the total amount of contaminated soil ingested in 1 day. The RESRAD input is the annual amount of soil ingested. Its value is obtained by multiplying the DCC value by the exposure frequency (350 d/yr), dividing by 1,000 (mg/g), and the total time fraction on site (0.726).
Age-adjusted soil inhalation rate (m^3/d)	18	Inhalation rate (m^3/yr)	8,679	The DCC age-adjusted value is the total amount of contaminated air inhaled in 1 year. The RESRAD input is the annual amount of air inhaled. Its value is obtained by multiplying the DCC value by the exposure frequency and dividing by the total time fraction on site (0.726).
Age-adjusted vegetable consumption rate (kg/yr)	9.08	Leafy vegetable consumption (kg/yr)	9.08	The DCC age-adjusted value is the total amount of produce ingested in 1 year. The RESRAD input is also the annual amount of produced ingested.
Age-adjusted fruit consumption rate (kg/yr)	17.48	Fruit, vegetable, and grain consumption (kg/yr)	17.48	
Contaminated produce fraction	0.25	Contamination fraction for plant food	0.25	
Outdoor exposure time fraction (h/h)	0.073	Outdoor time fraction	0.0700	In the DCC Calculator, the indoor and outdoor exposure time fraction is used only for the external radiation pathway. The sum can be less than 24 hours. However, the exposure time used for the inhalation pathway is 24 h/d. In the DCC Calculator, the outdoor exposure time fraction is the total time fraction spent in 1 day outdoors. The RESRAD input is the time fraction spent outdoors in 1 year, and the value is obtained by multiplying the DCC value by the exposure frequency and dividing by the total days in 1 year.
Indoor exposure time fraction (h/h)	0.684	Indoor time fraction	0.6559	In the DCC Calculator, the indoor exposure time fraction is the total time fraction spent in 1 day indoors. The RESRAD input is the time fraction spent indoors in 1 year, and the value is obtained by multiplying the DCC value by the exposure frequency and dividing by the total days in 1 year.

TABLE B.9 (Cont.)

Parameter in the DCC Calculator	Parameter Value Used in the DCC Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Notes
Exposure frequency for resident, resident child, resident adult (d/yr)	350			
Exposure duration - resident (yr)	1	Exposure duration (yr)	1	
Gamma shielding factor (indoor)	0.4	External gamma shielding factor	0.4	
		Indoor dust filtration factor	1	In the DCC Calculator, the indoor and outdoor dust levels are the same. Therefore, the input for RESRAD is set to 1.
PEF (m^3/kg)	1.36E+09[b]	Mass loading for inhalation and foliar deposition (g/m^3)	1.07E-05	The PEF in the DCC Calculator is calculated; the inverse of which is equivalent to the multiplication product of the mass loading factor and area factor for inhalation in RESRAD.
Mean annual wind speed (m/s)	4.69	Wind speed (m/s)	4.69	

[a] For some parameters, there is no default value.

[b] The yellow background indicates that the PEF value listed for the DCC Calculator was calculated with other input parameters.

TABLE B.10 Comparison of RESRAD and DCC Calculator Results for the Resident Scenario[a]

Radionuclide	RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) That Results in a 1-mrem/yr Dose					DCC (pCi/g) That Results in a 1-mrem/yr Dose					Ratio (DCC/SCG)					Remarks
	Soil Ingestion	Inhalation	External	Plant Ingestion	Total	Soil Ingestion	Inhalation	External	Plant Ingestion	Total	Soil Ingestion	Inhalation	External	Plant Ingestion	Total	
Ac-227	5.43E+00	2.48E+02	1.73E+00	1.37E+01	1.19E+00	5.94E+00	2.69E+02	6.86E+03	1.57E+01	4.24E+00	1.09E+00	1.09E+00	3.96E+03	1.14E+00	3.55E+00	Short-lived progeny (half-life < 180 d) not included in PRG.
Am-241	3.25E+01	1.39E+03	8.42E+01	2.06E+02	2.07E+01	3.22E+01	1.39E+03	8.41E+01	2.12E+02	2.07E+01	9.90E-01	1.00E+00	9.98E-01	1.03E+00	9.98E-01	
C-14	3.98E+04	1.48E+04	9.94E+05	4.51E+01	4.50E+01	1.11E+04	9.41E+09	2.96E+05	1.33E+01	1.33E+01	2.79E-01	6.37E+05	2.98E-01	2.95E-01	2.96E-01	Special model in RESRAD.
Co-60	2.50E+03	7.62E+06	2.74E-01	1.98E+02	2.74E-01	2.02E+03	6.22E+06	2.50E-01	1.67E+02	2.50E-01	8.08E-01	8.17E-01	9.12E-01	8.45E-01	9.13E-01	
Cs-137	5.05E+02	1.28E+07	1.03E+00	7.98E+01	1.01E+00	5.01E+02	1.28E+07	1.09E+00	8.26E+01	1.07E+00	9.92E-01	1.00E+00	1.06E+00	1.03E+00	1.06E+00	
H-3	2.74E+05	3.95E+03	NA[b]	5.80E+02	5.05E+02	1.58E+05	1.83E+01	-	2.17E+02	1.69E+01	5.76E-01	4.63E-03	NA	3.74E-01	3.35E-02	Special model in RESRAD.
I-129	7.64E+01	1.02E+06	4.12E+02	2.42E+01	1.76E+01	5.85E+01	7.88E+05	3.22E+02	1.93E+01	1.39E+01	7.66E-01	7.75E-01	7.81E-01	7.99E-01	7.91E-01	Low K_d value reduces average soil conc. in RESRAD.
Np-237	7.22E+01	3.12E+03	3.90E+00	2.28E+01	3.18E+00	5.85E+01	2.54E+03	3.06E+00	1.93E+01	2.53E+00	8.10E-01	8.15E-01	7.84E-01	8.45E-01	7.95E-01	Low K_d value reduces average soil conc. in RESRAD.
Pa-231	8.84E+00	4.02E+02	1.55E+01	5.70E+00	2.81E+00	9.06E+00	4.17E+02	1.72E+01	5.98E+00	2.96E+00	1.02E+00	1.04E+00	1.11E+00	1.05E+00	1.05E+00	
Pb-210	3.50E+00	1.32E+04	4.32E+02	2.21E+00	1.35E+00	9.47E+00	5.38E+04	1.55E+03	6.25E+00	3.76E+00	2.70E+00	4.07E+00	3.59E+00	2.82E+00	2.78E+00	Short-lived progeny (half-life < 180 d) not included in PRG.
Pu-239	2.61E+01	1.17E+03	1.22E+04	1.65E+02	2.21E+01	2.57E+01	1.17E+03	1.15E+04	1.70E+02	2.19E+01	9.83E-01	9.99E-01	9.46E-01	1.03E+00	9.91E-01	
Pu-241	1.35E+03	6.42E+04	6.88E+04	8.53E+03	1.13E+03	1.37E+03	6.64E+04	5.97E+05	9.06E+03	1.17E+03	1.02E+00	1.03E+00	8.67E+00	1.06E+00	1.04E+00	
Ra-226	2.13E+01	1.64E+04	3.09E-01	3.63E+00	2.81E-01	2.30E+01	1.67E+04	3.06E-01	3.79E+00	2.80E-01	1.08E+00	1.02E+00	9.89E-01	1.04E+00	9.95E-01	
Ra-228	9.80E+00	6.43E+03	4.79E-01	1.60E+00	3.55E-01	8.23E+00	1.35E+03	6.10E-01	1.36E+00	4.00E-01	8.39E-01	2.10E-01	1.27E+00	8.49E-01	1.13E+00	Issues with DCFs in DCC.
Sr-90	2.26E+02	1.66E+06	8.43E+01	4.77E+00	4.43E+00	2.33E+02	1.64E+06	7.49E+01	5.11E+00	4.69E+00	1.03E+00	9.85E-01	8.88E-01	1.07E+00	1.06E+00	
Tc-99	1.34E+04	1.92E+07	3.86E+04	1.70E+01	1.69E+01	1.01E+04	1.46E+07	3.00E+04	1.33E+01	1.32E+01	7.53E-01	7.59E-01	7.77E-01	7.84E-01	7.79E-01	Low K_d value reduces average soil conc. in RESRAD.
Th-228	5.38E+01	1.60E+03	3.95E-01	3.40E+02	3.91E-01	1.07E+02	1.74E+03	5.11E+02	7.03E+02	7.50E+01	1.99E+00	1.09E+00	1.29E+03	2.07E+00	1.92E+02	Short-lived progeny (half-life < 180 d) not included in PRG.
Th-230	3.08E+01	4.13E+03	9.58E+02	1.92E+02	2.56E+01	3.06E+01	4.17E+03	2.82E+03	2.02E+02	2.62E+01	9.95E-01	1.01E+00	2.94E+00	1.05E+00	1.02E+00	
U-234	1.48E+02	1.86E+04	1.03E+04	3.75E+02	1.05E+02	1.31E+02	1.67E+04	8.79E+03	3.47E+02	9.37E+01	8.83E-01	8.97E-01	8.57E-01	9.24E-01	8.95E-01	Low K_d value reduces average soil conc. in RESRAD.
U-235	1.54E+02	2.10E+04	5.16E+00	3.88E+02	4.93E+00	1.37E+02	1.88E+04	4.76E+00	3.61E+02	4.54E+00	8.92E-01	8.95E-01	9.22E-01	9.30E-01	9.21E-01	
U-238	1.50E+02	2.24E+04	2.62E+01	3.80E+02	2.11E+01	1.43E+02	2.01E+04	1.97E+01	3.77E+02	1.66E+01	9.52E-01	8.97E-01	7.51E-01	9.92E-01	7.88E-01	Difference in +D DCF calculation.

TABLE B.10 (Cont.)

Radionuclide	RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) That Results in a 1-mrem/yr Dose: Soil Ingestion	Inhalation	External	Plant Ingestion	Total	DCC (pCi/g) That Results in a 1-mrem/yr Dose: Soil Ingestion	Inhalation	External	Plant Ingestion	Total	Ratio (DCC/SCG): Soil Ingestion	Inhalation	External	Plant Ingestion	Total	Remarks
Ra-228*	1.10E+01	3.29E+03	4.06E-01	1.90E+00	3.25E-01	8.23E+00	1.35E+03	6.10E-01	1.36E+00	4.00E-01	7.49E-01	4.11E-01	1.50E+00	7.16E-01	1.23E+00	Buildup of long-lived progeny Th-228 not included.
Pa-231*	4.78E+00	2.18E+02	2.41E+00	5.24E+00	1.22E+00	9.06E+00	4.17E+02	1.72E+01	5.98E+00	2.96E+00	1.90E+00	1.92E+00	7.15E+00	1.14E+00	2.43E+00	Buildup of long-lived progeny Ac-227 not included
Pu-241*	1.41E+03	6.56E+04	1.65E+04	8.90E+03	1.11E+03	1.37E+03	6.64E+04	5.97E+05	9.06E+03	1.17E+03	9.73E-01	1.01E+00	3.62E+01	1.02E+00	1.05E+00	Buildup of long-lived progeny Am-241 not included.
Th-230*	3.79E+01	5.24E+03	5.25E+01	1.53E+02	1.92E+01	3.06E+01	4.17E+03	2.82E+03	2.02E+02	2.62E+01	8.08E-01	7.96E-01	5.37E+01	1.32E+00	1.37E+00	Buildup of long-lived progeny Ra 226 not included.

[a] The differences in total ratio (DCC/SCG) greater than 10% are shown in red.

[B] NA = not available or not applicable.

TABLE B.11 Comparison of RESRAD and DCC Results for the Resident Scenario with High K_d and Low Infiltration

Radionuclide	Time of Dose in RESRAD (yr)	Ratio (DCC/SCG)[a] Soil Ingestion	Inhalation	External	Plant Ingestion	Total	Remarks
Ac-227	0	1.10E+00	1.09E+00	3.97E+03	1.15E+00	3.57E+00	Short-lived progeny (half-life < 180 d) not included in PRG.
Am-241	0	1.00E+00	1.01E+00	1.01E+00	1.04E+00	1.01E+00	
C-14	0	2.91E-01	6.63E+05	3.10E-01	3.07E-01	3.08E-01	Special model in RESRAD.
Co-60	0	1.00E+00	1.01E+00	1.13E+00	1.05E+00	1.13E+00	ACF difference.
Cs-137	0	1.00E+00	1.01E+00	1.07E+00	1.04E+00	1.07E+00	
H-3	0	1.00E+00	3.45E-10	NA[b]	3.48E-06	1.08E-04	Special model in RESRAD.
I-129	0	1.00E+00	1.01E+00	1.02E+00	1.04E+00	1.03E+00	
Np-237	0	1.01E+00	1.01E+00	9.75E-01	1.05E+00	9.88E-01	
Pa-231	0	1.03E+00	1.04E+00	1.11E+00	1.05E+00	1.05E+00	
Pb-210	0	2.74E+00	4.13E+00	3.63E+00	2.86E+00	2.82E+00	Short-lived progeny (half-life < 180 d) not included in PRG.
Pu-239	0	9.99E-01	1.01E+00	9.61E-01	1.04E+00	1.01E+00	
Pu-241	0	1.03E+00	1.05E+00	8.82E+00	1.08E+00	1.06E+00	Buildup of long-lived progeny.
Ra-226	0	1.11E+00	1.04E+00	1.01E+00	1.07E+00	1.02E+00	Issues with DCFs in DCC.
Ra-228	0	8.60E-01	2.14E-01	1.30E+00	8.70E-01	1.15E+00	Issues with DCFs in DCC.
Sr-90	0	1.10E+00	1.05E+00	9.47E-01	1.14E+00	1.13E+00	Issues with DCFs in DCC.
Tc-99	0	1.00E+00	1.01E+00	1.04E+00	1.05E+00	1.04E+00	
Th-228	0	2.00E+00	1.09E+00	1.30E+03	2.08E+00	1.92E+02	Short-lived progeny (half-life < 180 d) not included in PRG.
Th-230	0	9.99E-01	1.01E+00	2.99E+00	1.05E+00	1.03E+00	
U-234	0	9.98E-01	1.01E+00	9.69E-01	1.04E+00	1.01E+00	
U-235	0	1.01E+00	1.01E+00	1.04E+00	1.05E+00	1.04E+00	
U-238	0	1.08E+00	1.01E+00	8.49E-01	1.12E+00	8.90E-01	Difference in +D DCF calculation.
Np-237	1000	1.01E+00	1.02E+00	9.75E-01	1.05E+00	9.89E-01	
Pa-231	219	2.69E+00	2.72E+00	1.10E+01	1.48E+00	3.53E+00	Buildup of long-lived progeny.
Pu-241	56	1.31E+00	1.48E+00	2.09E+02	1.37E+00	1.73E+00	Buildup of long-lived progeny.
Ra-226	82	7.06E+00	2.16E+00	9.80E-01	2.59E+00	1.17E+00	Buildup of long-lived progeny.
Ra-228	2	7.45E-01	5.52E-01	1.73E+00	6.85E-01	1.37E+00	Issues with DCFs in the DCC Calculator.
Th-230	1000	4.52E+00	1.20E+00	3.27E+03	5.25E+01	4.11E+01	Buildup of long-lived progeny.
U-234	1000	1.11E+00	1.05E+00	5.14E+01	1.49E+00	1.75E+00	Buildup of long-lived progeny.
U-235	1000	1.85E+00	3.54E+00	1.10E+00	2.91E+00	1.15E+00	Buildup of long-lived progeny.
U-238	1000	1.08E+00	1.02E+00	8.49E-01	1.12E+00	8.91E-01	Issues with DCFs in DCC.

[a] The differences in ratios (DCC/SCG) greater than 10% are shown in red.

[b] NA = not available or not applicable.

TABLE B.12 Input Parameters for the Farmer Scenario[a,b]

Parameter in the DCC Calculator	Parameter Value Used in the DCC Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Notes
Surface area of contaminated site (m^2)	10,000.000	Area of contaminated zone (m^2)	10,000	RESRAD default
		Thickness of contaminated zone (m)	2	
		Cover depth (m)	0	
Soil bulk density (kg/L)	1.500	Density of contaminated zone (g/cm^3)	1.5	
Total porosity	0.500	Contaminated zone total porosity	0.5	
Fraction water content	0.300	Field capacity	0.3	
		Cover erosion rate (m/yr)	0	
		Contaminated zone erosion rate (m/yr)	0	
Dilution factor for drinking water	1.000			Not used in RESRAD
Age-adjusted soil ingestion factor (mg/d)	115.000	Soil ingestion (g/yr)	45.43	The DCC age-adjusted value is the total amount of contaminated soil ingested in 1 day. The RESRAD input is the annual amount of soil ingested. Its value is obtained by multiplying the DCC value by the exposure frequency (350 d), and dividing by 1,000 (mg/g) and the total time fraction on site (0.8860).
Age-adjusted soil inhalation factor (m^3/d)	18.500	Inhalation rate (m^3/yr)	7,308	The DCC age-adjusted value is the amount of contaminated air inhaled in 1 day. The RESRAD input is the annual amount of air inhaled. Its value is obtained by multiplying the DCC value by the exposure frequency (350 d) and dividing by the total time fraction on site (0.8860).
Age-adjusted vegetable consumption factor (kg/yr)	9.410	Leafy vegetable consumption (kg/yr)	9.02	The DCC age-adjusted value is the total amount of food ingested in 1 day or 1 year. The RESRAD input is the annual amount of food or water ingested. Its value is obtained by multiplying the DCC value by the exposure frequency and dividing by the exposure duration, if necessary. For the annual milk ingestion rate, the result in kg/yr is converted to L/yr.
Age-adjusted fruit consumption factor (kg/yr)	18.235	Fruit, vegetable, and grain consumption (kg/yr)	17.49	
Age-adjusted beef consumption factor (kg/yr)	43.375	Meat and poultry consumption (kg/yr)	41.59	
Age-adjusted dairy consumption factor (kg/yr)	205.275	Milk consumption (L/yr)	191.11	
Density of milk (kg/L)	1.030			
Age-adjusted fish consumption factor (kg/yr)	39.890	Fish consumption (kg/yr)	38.25	
Surface area of water shed (m^2)	100000.000	Watershed area (m^2)	100,000.00	
		Other seafood consumption (kg/yr)	0	

TABLE B.12 (Cont.)

Parameter in the DCC Calculator	Parameter Value Used in the DCC Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Notes
Beef-contaminated fraction	1.000	Contamination fraction for meat	1	
Milk-contaminated fraction	1.000	Contamination fraction for milk	1	
Fish-contaminated fraction	1.000	Contamination fraction for fish	1	
Outdoor exposure time fraction (h/h)	0.507	Outdoor time fraction	0.486164384	In the DCC Calculator, the indoor and outdoor exposure time fraction (h) is used only for the external radiation pathway. The sum can be less than 24 h. However, the exposure time used for the inhalation pathway is 24 h/d.
Indoor exposure time fraction (h/h)	0.417	Indoor time fraction	0.399863014	
Exposure time farmer, farmer adult, farmer child (h/d)	24.000			
Exposure frequency for farmer, farmer child, farmer adult (d/yr)	350.000			
Exposure duration - farmer (yr)	1.000	Exposure duration (yr)	30	Parameter not used in dose calculations.
Exposure duration - farmer child (yr)	0.150			
Exposure duration - farmer adult (yr)	0.850			
Beef fodder intake rate (kg/d)	11.770	Livestock fodder intake for meat (kg/d)	58.85	The input value for the DCC Calculator is dry-weight based, with the default water content in fodder as 20%. It is divided by 0.2 to get the input value for RESRAD, which is wet-weight based.
Beef soil intake rate (kg/d)	0.390	Livestock intake of soil (kg/d)	0.39	In RESRAD, 100% of the soil and fodder ingested by livestock is assumed to come from the contaminated area.
Animal on-site fraction -beef	1.000			
Dairy fodder intake rate (kg/d)	16.900	Livestock fodder intake for milk (kg/d)	84.5	The input value for the DCC Calculator is dry-weight based, with the default water content in fodder as 20%. It is divided by 0.2 to get the input value for RESRAD, which is wet-weight based.
Dairy soil intake rate (kg/d)	0.410			In RESRAD, the livestock intake of soil is used for both dairy and meat cows.
Animal onsite fraction - dairy	1.000			
Beef water intake rate (L/d)	53.000	Livestock water intake for meat (L/d)	53	
Dairy water intake rate (L/d)	92.000	Livestock water intake for milk (L/d)	92	
Gamma shielding factor (indoor)	0.400	External gamma shielding factor	0.4	
		Indoor dust filtration factor	1	In the DCC Calculator, the indoor and outdoor dust levels are the same. Therefore, the input for RESRAD is set to 1.

TABLE B.12 (Cont.)

Parameter in the DCC Calculator	Parameter Value Used in the DCC Calculator	Parameter in RESRAD	Parameter Value Used in RESRAD	Notes
PEF (m^3/kg)	1.36E+09[c]	Mass loading for inhalation and foliar deposition (g/m^3)	1.07E-05	The PEF in the DCC Calculator is calculated; the inverse of which is equivalent to the product of the mass loading factor and area factor for inhalation in RESRAD.
Mean annual wind speed (m/s)	4.690	Wind speed (m/s)	4.69	

[a] Ingestion of egg and swine are also considered in the DCC Calculator but not in RESRAD. Transfer factors for poultry are different from meat ingestion, therefore poultry ingestion is not included.

[b] For some parameters, there is no default value.

[c] The PEF value listed for the DCC Calculator has a yellow background, indicating it is calculated with other input parameters.

TABLE B.13 Comparison of RESRAD Results and DCC Results for External Exposure, Inhalation, Dust Ingestion, and Plant Ingestion Pathways for the Farmer Scenario[a]

Radionuclide	RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) for Water-Independent Pathways at Time Zero That Results in a 1-mrem/yr Dose				Estimated DCC (pCi/g) for Water-Independent Pathways That Results in a 1-mrem/yr Dose				Ratio (DCC/SCG)				Remarks
	External	Inhalation	Plant	Soil	External	Inhalation	Plant	Soil	External	Inhalation	Plant	Soil	
Ac-227	8.92E-01	2.41E+02	3.44E+00	5.67E+00	3.53E+03	2.62E+02	3.77E+00	6.20E+00	3.96E+03	1.09E+00	1.10E+00	1.09E+00	Short-lived progeny (half-life < 180 d) not included in DCC.
Am-241	4.33E+01	1.35E+03	5.15E+01	3.39E+01	4.32E+01	1.35E+03	5.10E+01	3.36E+01	9.97E-01	1.00E+00	9.81E-01	9.90E-01	
C-14	5.12E+05	1.44E+04	1.13E+01	4.15E+04	1.52E+05	9.15E+09	3.20E+00	1.16E+04	2.97E-01	6.37E+05	2.83E-01	2.80E-01	Special model in RESRAD.
Co-60	1.41E-01	7.41E+06	4.95E+01	2.61E+03	1.29E-01	6.05E+06	4.00E+01	2.11E+03	9.14E-01	8.17E-01	8.08E-01	8.09E-01	Low K_d value reduces average soil conc. In RESRAD.
Cs-137+D	5.28E-01	1.24E+07	2.00E+01	5.27E+02	5.60E-01	1.25E+07	1.98E+01	5.22E+02	1.06E+00	1.01E+00	9.90E-01	9.91E-01	
H-3	NA[b]	3.84E+03	1.45E+02	2.86E+05	-	1.78E+01	5.20E+01	1.64E+05	NA	4.63E-03	3.58E-01	5.73E-01	Special model in RESRAD.
I-129	2.12E+02	9.90E+05	6.05E+00	7.97E+01	1.66E+02	7.67E+05	4.63E+00	6.10E+01	7.83E-01	7.75E-01	7.65E-01	7.65E-01	Low K_d value reduces average soil conc. In RESRAD.
Np-237+D	2.01E+00	3.03E+03	5.72E+00	7.53E+01	1.58E+00	2.47E+03	4.63E+00	6.10E+01	7.87E-01	8.14E-01	8.10E-01	8.10E-01	Low K_d value reduces average soil conc. in RESRAD.
Pa-231	7.97E+00	3.91E+02	1.43E+00	9.23E+00	8.84E+00	4.05E+02	1.44E+00	9.46E+00	1.11E+00	1.04E+00	1.01E+00	1.03E+00	
Pb-210	2.22E+02	1.28E+04	5.55E-01	3.65E+00	7.98E+02	5.24E+04	1.50E+00	9.88E+00	3.59E+00	4.08E+00	2.70E+00	2.70E+00	Short-lived progeny (half-life < 180 d) not included in DCC.
Pu-239	6.26E+03	1.14E+03	4.14E+01	2.73E+01	5.89E+03	1.13E+03	4.08E+01	2.69E+01	9.41E-01	9.92E-01	9.86E-01	9.86E-01	
Pu-241	3.54E+04	6.25E+04	2.14E+03	1.41E+03	3.07E+05	6.46E+04	2.18E+03	1.43E+03	8.67E+00	1.03E+00	1.02E+00	1.02E+00	Buildup of long-lived progeny.
Ra-226+D	1.59E-01	1.60E+04	9.09E-01	2.23E+01	1.58E-01	1.62E+04	9.11E-01	2.40E+01	9.93E-01	1.01E+00	1.00E+00	1.08E+00	
Ra-228+D	2.46E-01	6.26E+03	4.01E-01	1.02E+01	3.14E-01	1.31E+03	3.26E-01	8.59E+00	1.27E+00	2.09E-01	8.12E-01	8.40E-01	Issues with DCFs in DCC.
Sr-90+D	4.34E+01	1.62E+06	1.20E+00	2.36E+02	3.85E+01	1.60E+06	1.23E+00	2.43E+02	8.87E-01	9.88E-01	1.03E+00	1.03E+00	
Tc-99	1.99E+04	1.87E+07	4.25E+00	1.40E+04	1.54E+04	1.42E+07	3.19E+00	1.05E+04	7.75E-01	7.59E-01	7.51E-01	7.50E-01	Low K_d value reduces average soil conc. in RESRAD.
Th-228	2.03E-01	1.55E+03	8.51E+01	5.61E+01	2.63E+02	1.69E+03	1.69E+02	1.11E+02	1.29E+03	1.09E+00	1.99E+00	1.98E+00	Short-lived progeny (half-life < 180 d) not included in DCC.
Th-230	4.93E+02	4.02E+03	4.81E+01	3.21E+01	1.45E+03	4.05E+03	4.85E+01	3.20E+01	2.94E+00	1.01E+00	1.01E+00	9.97E-01	Contribution of long-lived progeny.
U-234	5.27E+03	1.81E+04	9.40E+01	1.55E+02	4.52E+03	1.62E+04	8.32E+01	1.37E+02	8.57E-01	8.95E-01	8.85E-01	8.85E-01	Low K_d value reduces average soil conc. in RESRAD.
U-235+D	2.65E+00	2.04E+04	9.73E+01	1.60E+02	2.45E+00	1.83E+04	8.68E+01	1.43E+02	9.23E-01	8.96E-01	8.92E-01	8.92E-01	Low K_d value reduces average soil conc. in RESRAD.
U-238+D	1.35E+01	2.18E+04	9.51E+01	1.57E+02	1.01E+01	1.96E+04	9.06E+01	1.49E+02	7.48E-01	8.99E-01	9.52E-01	9.50E-01	Difference in +D DCF calculation.

[a] The differences in ratios (DCC/SCG) greater than 10% are shown in red.

[b] NA = not available or not applicable.

TABLE B.14 Comparison of the Fish, Meat, and Milk Pathways' Most Conservative RESRAD Results with DCC Results for the Farmer Scenario

	Peak Dose Time in RESRAD (yr)			Maximum Dose-to-Source Ratio (mrem/yr per pCi/g)			RESRAD Estimated Soil Concentration Guideline (SCG) (pCi/g) That Results in a 1-mrem/yr Dose			Estimated DCC (pCi/g) That Results in a 1-mrem/yr Dose		
Radionuclide	Fish	Meat	Milk	Fish	Meat	Milk	Fish	Meat	Milk	Fish	Beef	Dairy
Ac-227	27.61	0	0	4.15E-01	2.00E-03	1.03E-02	2.41E+00	5.01E+02	9.76E+01	NA[a]	NA	NA
Am-241	127.60	124	124	3.00E+00	3.50E-03	1.08E-03	3.34E-01	2.85E+02	9.26E+02	9.78E-02	9.52E+01	2.97E+02
C-14	7.76	0	0	7.03E+00	1.77E-01	2.03E-01	1.42E-01	5.64E+00	4.92E+00	2.19E-03	9.44E-01	3.48E-01
Co-60	2.84	2.73	2.69	7.87E+00	3.69E-01	2.87E-01	1.27E-01	2.71E+00	3.49E+00	1.48E-02	3.78E-01	4.61E-01
Cs-137+D	32.49	0	0	2.75E+00	1.63E-01	2.75E-01	3.63E-01	6.12E+00	3.63E+00	2.78E-02	2.11E+00	1.04E+00
H-3	2.00	0	0	3.68E-04	5.13E-03	3.08E-01	2.72E+03	1.95E+02	3.24E+00	1.73E+02	1.63E+01	2.54E+00
I-129	3.67	3.73	3.67	7.49E+01	9.10E+00	1.01E+02	1.33E-02	1.10E-01	9.94E-03	2.09E-03	2.06E-02	1.76E-03
Np-237+D	4.62	4.67	4.6	4.61E+01	1.07E+00	4.13E-02	2.17E-02	9.38E-01	2.42E+01	4.28E-03	2.22E-01	5.40E+00
Pa-231	708.17	0	683.87	5.12E+00	3.47E-02	3.47E-02	1.95E-01	2.88E+01	2.88E+01	NA	NA	NA
Pb-210	22.80	12.23	15.1	1.14E+02	2.91E-01	7.72E-01	8.81E-03	3.44E+00	1.30E+00	2.11E-03	1.24E+00	4.12E-01
Pu-239	78.67	78.67	78.67	7.37E+00	1.72E-02	1.33E-03	1.36E-01	5.83E+01	7.55E+02	4.80E-02	2.40E+01	2.96E+02
Pu-241	91.14	78.5	93.02	1.02E-01	1.24E-04	3.67E-05	9.82E+00	8.06E+03	2.72E+04	2.56E+00	1.28E+03	1.58E+04
Ra-226+D	51.84	48.82	48.49	3.71E+02	9.69E-01	4.28E+00	2.69E-03	1.03E+00	2.34E-01	1.56E-02	1.17E+00	1.47E-01
Ra-228+D	6.69	0	0	8.13E+00	2.89E-01	1.85E+00	1.23E-01	3.47E+00	5.41E-01	5.60E-03	4.19E-01	5.25E-02
Sr-90+D	13.73	0	2.53	4.94E+00	6.78E-01	1.16E+00	2.02E-01	1.48E+00	8.65E-01	4.68E-02	4.43E-01	2.27E-01
Tc-99	3.11	0	0	2.35E-01	2.40E-03	1.54E-01	4.25E+00	4.18E+02	6.51E+00	5.91E-01	1.29E+02	1.67E+00
Th-228	2.27	0	0	3.16E-02	8.46E-04	2.05E-04	3.16E+01	1.18E+03	4.88E+03	2.35E-01	3.49E+02	8.97E+02
Th-230	115.57	115.57	100.9	1.27E+01	2.72E-02	1.08E-01	7.89E-02	3.68E+01	9.27E+00	6.76E-02	1.00E+02	2.58E+02
U-234	9.13	9.2	9.07	3.78E+00	8.90E-02	1.22E+00	2.65E-01	1.12E+01	8.22E-01	7.21E-02	3.66E+00	2.53E-01
U-235+D	9.13	9.2	9.07	3.65E+00	8.60E-02	1.17E+00	2.74E-01	1.16E+01	8.51E-01	7.52E-02	3.82E+00	2.64E-01
U-238+D	9.13	9.2	9.07	3.73E+00	8.79E-02	1.20E+00	2.68E-01	1.14E+01	8.33E-01	7.85E-02	3.99E+00	2.75E-01

[a] NA = not available or not applicable.

TABLE B.15 Comparison of Fish, Meat, and Milk Pathway Results for the Farmer Scenario

Radionuclide	Ratio (DCC/SCG)			Water Concentration Ratio	Remarks
	Fish	Meat	Milk	(RESRAD/DCC)	
Ac-227	NA[a]	NA	NA	NA	DCC does not provide values.
Am-241	2.93E-01	3.34E-01	3.21E-01	2.93E-01	Difference in water concentration.
C-14	1.54E-02	1.67E-01	7.08E-02	1.55E-02	Difference in water concentration.
Co-60	1.17E-01	1.40E-01	1.32E-01	1.10E-01	Difference in water concentration.
Cs-137+D	7.65E-02	3.45E-01	2.86E-01	7.55E-02	Difference in water concentration.
H-3	6.37E-02	8.36E-02	7.83E-01	6.22E-02	Difference in water concentration.
I-129	1.57E-01	1.87E-01	1.77E-01	1.61E-01	Difference in water concentration.
Np-237+D	1.97E-01	2.37E-01	2.23E-01	2.00E-01	Difference in water concentration.
Pa-231	NA	NA	NA	NA	DCC does not provide values.
Pb-210	2.40E-01	3.61E-01	3.18E-01	8.63E-02	Short-lived progeny (half-life < 180 d) not included in DCC.
Pu-239	3.54E-01	4.12E-01	3.92E-01	3.55E-01	Difference in water concentration.
Pu-241	2.61E-01	1.59E-01	5.80E-01	7.14E-02	Contribution of long-lived progeny.
Ra-226+D	5.79E+00	1.13E+00	6.29E-01	3.41E-01	Contribution of long-lived progeny.
Ra-228+D	4.55E-02	1.21E-01	9.70E-02	2.60E-01	Difference in water concentration and contribution of progeny.
Sr-90+D	2.31E-01	3.00E-01	2.62E-01	2.09E-01	Difference in water concentration.
Tc-99	1.39E-01	3.09E-01	2.57E-01	1.43E-01	Difference in water concentration.
Th-228	7.43E-03	2.95E-01	1.84E-01	3.18E-03	Difference in water concentration.
Th-230	8.57E-01	2.72E+00	2.78E+01	3.62E-01	Contribution of long-lived progeny.
U-234	2.72E-01	3.26E-01	3.08E-01	2.75E-01	Difference in water concentration.
U-235+D	2.74E-01	3.29E-01	3.10E-01	2.75E-01	Difference in water concentration.
U-238+D	2.93E-01	3.51E-01	3.30E-01	2.75E-01	Difference in water concentration.

[a] NA = not available or not applicable.

TABLE B.16 Comparison of the Meat and Milk Pathways for the Farmer Scenario with No Water Ingestion

Radionuclide	Dose-to-Source Ratio (mrem/yr per pCi/g)		Estimated Soil Concentration Guideline (SCG) (pCi/g) That Results in a 1-mrem/yr Dose		Beef DCC without Water Ingestion (pCi/g)	Dairy DCC without Water Ingestion (pCi/g)	Ratio (DCC/SCG)[a]		Remarks
	Meat	Milk	Meat	Milk			Meat	Milk	
Ac-227	2.00E-03	1.03E-02	5.01E+02	9.76E+01	558.6921	102.0669	1.115708	1.046186	Short-lived progeny not included in DCC.
Am-241	7.00E-04	1.36E-04	1.43E+03	7.37E+03	1448.871	6947.173	1.01363	0.942731	
C-14	1.70E-01	2.01E-01	5.87E+00	4.98E+00	1.113216	0.423344	0.189581	0.085007	Special model in RESRAD.
Co-60	4.33E-02	2.74E-02	2.31E+01	3.66E+01	19.96736	29.99887	0.865186	0.820469	Low K_d changes average soil concentration.
Cs-137+D	1.63E-01	2.73E-01	6.15E+00	3.66E+00	6.14214	3.523703	0.998098	0.962323	
H-3	4.53E-03	2.61E-02	2.21E+02	3.83E+01	46.9952	8.302108	0.213029	0.216851	Special model in RESRAD.
I-129	1.54E-01	1.31E+00	6.49E+00	7.62E-01	5.385474	0.594395	0.83044	0.779846	Low K_d changes average soil concentration.
Np-237+D	2.29E-02	6.85E-04	4.37E+01	1.46E+03	37.69832	1188.79	0.861784	0.813964	Low K_d changes average soil concentration.
Pa-231	5.41E-01	3.32E-03	1.85E+00	3.01E+02	1.868544	307.8392	1.010509	1.022334	
Pb-210	2.24E-01	4.86E-01	4.46E+00	2.06E+00	12.23353	5.374536	2.745204	2.614174	Short-lived progeny not included in DCC.
Pu-239	1.74E-03	8.44E-05	5.74E+02	1.18E+04	579.0934	11106.75	1.008202	0.937299	
Pu-241	3.32E-05	1.69E-06	3.01E+04	5.92E+05	30825.5	591219.1	1.02464	0.997978	
Ra-226+D	1.22E-01	7.45E-01	8.18E+00	1.34E+00	8.426785	1.28917	1.029753	0.960303	
Ra-228+D	2.72E-01	1.71E+00	3.68E+00	5.87E-01	3.03021	0.463576	0.824217	0.790397	Issues with DCFs in DCC.
Sr-90+D	6.45E-01	1.05E+00	1.55E+00	9.51E-01	1.620794	0.959627	1.045898	1.008568	
Tc-99	2.38E-03	1.53E-01	4.21E+02	6.55E+00	344.3071	5.06866	0.818418	0.773984	Low K_d changes average soil concentration.
Th-228	8.46E-04	2.05E-04	1.18E+03	4.88E+03	2401.293	9211.141	2.031013	1.889205	Short-lived progeny not included in DCC.
Th-230	2.36E-03	6.07E-03	4.24E+02	1.65E+02	689.3902	2644.438	1.625582	16.06232	Maximum dose at later times due to buildup of progeny.
U-234	1.27E-03	1.14E-02	7.91E+02	8.80E+01	727.3661	75.29968	0.920118	0.855404	Low K_d changes average soil concentration.
U-235+D	1.23E-03	1.10E-02	8.16E+02	9.12E+01	756.6269	78.32887	0.927625	0.859268	Low K_d changes average soil concentration.
U-238+D	1.25E-03	1.12E-02	8.01E+02	8.91E+01	788.3418	81.61211	0.984639	0.915688	

[a] The differences in ratios (DCC/SCG) greater than 10% are shown in red.

This page intentionally left blank.

Environmental Science Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 240
Argonne, IL 60439-4847

www.anl.gov