EPRI

Use of Probabilistic Methods in Nuclear Power Plant Decommissioning Dose Analysis

Technical Report

Use of Probabilistic Methods in Nuclear Power Plant Decommissioning Dose Analysis

1006949

Final Report, May 2002

EPRI Project Manager
C. Wood

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

North Carolina State University

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

CITATIONS

This report was prepared by

North Carolina State University
1110 Burlington Engineering Labs
Raleigh, NC 27695

Principal Investigator
M. Yim

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Use of Probabilistic Methods in Nuclear Power Plant Decommissioning Dose Analysis, EPRI, Palo Alto, CA: 2002. 1006949

REPORT SUMMARY

This report provides guidance on the use of probabilistic dose analysis in the demonstration of regulatory compliance for final release of decommissioned nuclear plant sites. It also addresses probabilistic dose analysis and the interpretation of its results in general terms. Finally, the report examines the use of the RESRAD 6.0 as a tool for screening dose analysis and for site specific probabilistic dose analysis.

Background
Issues related to license termination and site release are central to the decommissioning of nuclear power plants. This process must demonstrate that any remaining radioactivity does not pose an unacceptable risk to members of the public following release of the site. Present site release regulations state that a site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a Total Effective Dose Equivalent (TEDE) to an average member of the critical group of less than 25 mrem (0.25 mSv) per year. Utilities use computer dose modeling codes to establish an acceptable level of contamination, the derived concentration guideline level (DCLG) that will meet this regulatory limit. Since the DCLG value is the principal measure of residual radioactivity, it is critical to understand the technical basis of these dose-modeling codes.

Objective
To provide guidance on the use of the RESRAD 6.0 probabilistic dose analysis related to decommissioned nuclear plant site release.

Approach
For nuclear plant decommissioning, the project team analyzed the residential farmer scenario dose using the RESRAD codes. They identified, examined and compared important exposure pathways, capabilities and conservatism, key parameters, and default parameter values. The project team examined both the screening and site-specific probabilistic dose analysis methodologies. The report presents an example of site-specific analysis using the probabilistic approach.

Results
The objective of this research was to provide guidance on nuclear power plant decommissioning dose analysis in a probabilistic analysis framework. The focus was on the demonstration of regulatory compliance for surface soil contamination using the RESRAD 6.0 code. In both screening and site-specific analysis, the analysis results indicated the benefits of using probabilistic approach. Example analyses performed with the screening probabilistic dose analysis confirmed the conservatism of the NRC screening values and indicated the effectiveness

of probabilistic dose analysis in reducing the conservatism in DCGL derivation. For a site-specific probabilistic dose analysis, this study found the nuclides' soil-to-plant transfer factor the most important parameter. Example analyses using the site-specific soil-to-plant transfer factor for ^{137}Cs and ^{90}Sr showed a significant benefit of site-specific approach. Examination of the probabilistic dose analysis for regulatory compliance demonstration also showed that distinguishing the difference between the mean of the peak dose from the peak of the mean dose is not important with RESRAD 6.0. Finally, discussions on the use of distribution types to represent input variables indicated the importance of understanding the nature and amount of relevant data available for a given problem.

EPRI Perspective

The RESRAD codes are considered basic dose modeling tools for assessing the acceptable level of residual contamination for site release following decommissioning. This EPRI report is one of a series dealing with the central issue of nuclear plant license termination and site release. EPRI utilized the results of this work in the *Guide to Assessing Radiological Elements for License Termination of Nuclear Power Plants* (TR-1003196). Other reports include *License Termination Plans – Summary and Lessons Learned from Submittals from 3 Nuclear Utilities* (TR-1003426) and *Trojan Nuclear Plant License Termination Plan Development Project* (TR-1003423).

Key Words

Decommissioning
License termination plan
Nuclear plant site release
Dose modeling codes

ABSTRACT

The objective of this research is to provide guidance on the use of probabilistic RESRAD 6.0 code for nuclear power plant decommissioning dose analysis. Only the surface soil contamination was addressed in this report. Based upon a typical source term expected in a nuclear power plant, the report discusses the use of screening and site-specific probabilistic dose analysis. General understanding of probabilistic dose analysis and the interpretation of probabilistic results are also described along with the discussion on how to select probability distribution models for input parameters. In both screening and site-specific analysis, the analysis results indicated the benefits of using probabilistic approach. An example of site-specific analysis using the probabilistic approach is also presented.

EXECUTIVE SUMMARY

Discussion

Dose analysis is required in nuclear power plant decommissioning to determine if radionuclide-specific residual contamination levels would result in a dose that comply with the regulatory limit of 25 mrem per year. EPRI published a report in 1999 [TR-112874], entitled "Comparisons of Decommissioning Dose Modeling Codes for Nuclear Power Plant Use: RESRAD and DandD", to assist the utilities in performing deterministic dose analysis. The report compared the two major dose analysis computer code, DandD and RESRAD, by identifying and comparing important exposure pathways and capabilities and conservatism of models, key parameters, and default input values of the two codes.

The focus of current report is to provide guidance on dose analysis in a probabilistic analysis framework. The focus is on the demonstration of regulatory compliance for surface soil contamination using the RESRAD 6.0 code. The RESRAD 6.0 code incorporates the capability of Monte Carlo parameter uncertainty analysis into the existing deterministic version of the RESRAD code. The following three tasks are covered in this report:

- • Use of screening probabilistic dose analysis.
- • Use of site-specific probabilistic dose analysis.
- • General understanding of probabilistic dose analysis and its interpretation.

To provide guidance on the use of screening probabilistic analysis, example computer analyses using a typical source term(s) for a nuclear power station was performed. Screening analysis here means that the existing default inputs of the RESRAD 6.0 code are used except for the user-provided site-specific source term information. The source term nuclides in the example analyses were determined according to the sampling efforts at decommissioning power plant sites as following: ^{3}H, ^{14}C, ^{55}Fe, ^{60}Co, ^{63}Ni, ^{99}Tc, ^{129}I, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{238}Pu, ^{239}Pu, ^{241}Pu, ^{241}Am, ^{242}Cm, and ^{243}Cm/^{244}Cm. Unfortunately, ^{242}Cm was not included in the RESRAD6.0 data library thus was dropped in the subsequent analyses.

In the example analysis, the distribution of peak annual dose to a member of a critical group was calculated for a unit soil contamination level (1 pCi/g) for each respective nuclide. Summary of these results as the calculated DCGLs (derived concentration guideline levels) are presented in Table S-1. The table also compares with the deterministically calculated DCGL and the NRC screening values. The DCGL is the concentration of residual activity distinguishable from background which, if distributed uniformly throughout a survey unit, would result in a total effective dose equivalent of 25 mrem per year to an average member of the critical group. The DCGL values derived from the deterministic analysis were higher than the NRC screening

values except for ^{60}Co, ^{134}Cs, and ^{137}Cs. The DCGL values derived based on the mean of the peak dose from the probabilistic analysis were always higher than the NRC screening values. For ^{60}Co, ^{63}Ni, ^{90}Sr, ^{99}Tc, ^{134}Cs, ^{137}Cs, and ^{241}Am, the DCGL values from the probabilistic analyses matched well with the NRC screening values. For ^{3}H, ^{14}C, ^{55}Fe, ^{129}I, ^{238}Pu, ^{239}Pu, ^{241}Pu, and ^{243}Cm, the screening DCGL from NRC was much more conservative than the results from probabilistic analysis. Overall the results confirm the conservatism of the NRC screening values and indicate that probabilistic dose analysis can be very effective in reducing the conservatism in DCGL derivation.

Table S-1.
Comparisons of DCGL (NRC Screening Approach versus the Values Using RESRAD Probabilistic Dose Analysis)

Nuclide	NRC's surface soil screening values (pCi/g)	DCGL - Concentration (pCi/g) equivalent to 25 mrem/y for a specific value of Pcrit (Using Probabilistic RESRAD 6.0)				DCGL from deterministic analysis (RESRAD 6.0)
	From NRC	Based on the mean of peak	Pcrit=0.5	Pcrit=0.10	Pcrit=0.05	Deterministic
H-3	1.1e+2	1.55E+03	1.68E+3	1.05E+3	9.48E+2	1.75e+3
C-14	1.2e+1	3.64E+01	4.01E+01	2.40e+1	2.10e+1	2.19e+1
Fe-55	1.0e+4	5.73E+04	6.60e+4	3.60e+4	3.10e+4	9.73e+4
Co-60	3.8e+0	4.40E-00	5.20e+0	2.80e+0	2.50e+0	2.82e+0
Ni-63	2.1e+3	2.83E+03	4.58E+3	1.51E+3	9.92E+2	5.45e+3
Sr-90	1.7e+0	2.11E-00	4.79e+0	1.40e+0	8.42e-1	5.01e+0
Tc-99	1.9e+1	2.12E+01	3.76e+1	1.18e+1	7.51e+0	5.36e+1
I-129	5.0e-1	8.93E-00	1.91e+1	5.94e+0	3.90e+0	3.85e+1
Cs-134	5.7e+0	6.63E-00	7.53E+0	4.55E+0	3.85E+0	5.01e+0
Cs-137	1.1e+1	1.24E+01	1.59E+1	8.28E+0	6.85E+0	1.10e+1
Ce-144	N/A*	3.19E+02	3.77E+2	2.21E+2	1.85E+2	2.03e+2
Pu-238	2.5e+0	4.73E+01	7.49E+1	2.51E+1	1.71E+1	6.31e+1
Pu-239	2.3e+0	3.68E+01	6.70e+1	2.08e+1	1.47e+1	5.69e+1
Pu-241	7.2e+1	2.19E+03	3.38e+3	1.19e+3	8.04e+2	3.01e+3
Am-241	2.1e+0	3.82E+01	6.10E+01	1.76E+01	1.45E+01	5.30e+1
Cm-243	3.2e+0	3.91E+01	5.39e+1	2.53e+1	1.98e+1	3.95e+1
Cm-244	-	7.02E+01	1.22e+2	3.94e+1	3.11e+1	1.03e+2

* Since Ce-144 was not included in the NRC's list for screening DCGL, the comparison was not given

To provide guidance on the use of site-specific probabilistic dose analysis, the following was performed: 1) Key parameters of importance were identified; 2) Sources of information to provide site-specific data for key parameters were examined, and; 3) Example computer analyses using key site-specific parameters were conducted. In the present study, site-specific dose analysis is narrowly defined as "changes to the default inputs of the RESRAD 6.0 code are made for at least one input parameter in addition to the user-provided site-specific source term information".

Key parameters were identified from the probabilistic sensitivity analysis. Probabilistic sensitivity analysis involves running simulations in which different subsets of variable and/or uncertain inputs are assigned distributions, while all other inputs are set to their default central value. The results of these analyses showed that truly site-specific key parameters are the soil-to-plant transfer factor, thickness of unsaturated zone; K_d in the contaminated zone; density of the unsaturated zone, and; contaminated zone total porosity. Among these, the soil-to-plant transfer factor was most significant for site-specific investigations.

Example site-specific probabilistic dose analyses were performed with two key nuclides of concern in nuclear power plant decommissioning, i.e., ^{137}Cs and ^{90}Sr. The input distributions for site-specific soil-to-plant transfer factors of ^{137}Cs and ^{90}Sr were derived based on the soil conditions for a site selected as the test case and the default input distributions using the Bayesian technique. The resulting difference in DCGL between the screening probabilistic analysis and site-specific analysis are summarized in Table S-2. The DCGL values for several critical points, e.g., 50%, 90%, and 95% confidence levels (corresponding to Pcri=0.5, 0.1, and 0.05), are listed in this Table. The results showed that use of site-specific data led to a higher DCGL for a given site in comparison to the DCGL from the screening methodology. Based on the use of the mean of the peak dose, the DCGL changed from 12.5 and 2.62 pCi/g to 16.3 and 8.7 pCi/g, for ^{137}Cs and ^{90}Sr, respectively, for the given site. This indicates a significant benefit of using site-specific soil-to-plant transfer factors especially for ^{90}Sr.

Table S-2
Comparison of the DCGL (pCi/g) calculated between the Screening and Site-Specific Probabilistic Dose Analysis

	Cs-137		Sr-90	
	Screening	Site-specific	Screening	Site-specific
Pcrit = 0.5	15.2	18.0	4.83	10.7
Pcrit = 0.1	8.36	11.6	1.35	5.21
Pcrit = 0.05	6.36	10.3	0.95	4.28
Based on the peak of the mean	12.5	16.3	2.62	8.71
Based on the mean of the peak	12.5	16.3	2.62	8.71
NRC screening value	11		1.7	

This report also provides the details on the background of probabilistic dose analysis. The needs for probabilistic analysis are discussed along with its pros and cons in comparison to deterministic dose analysis. Key terms in probabilistic analysis and how results should be interpreted were discussed along with the description of the differences between the peak of the mean and the mean of the peak, and pros and cons of their use for regulatory compliance demonstration. The study finds that distinguishing the difference between the mean of the peak dose from the peak of the mean dose is not necessary in probabilistic dose analysis with RESRAD 6.0 unless the nuclide shows the time of peak to be different from time zero (^{129}I, in this study). Even for the case of the peak dose occurring at time other than zero, the difference between the peak of the mean and the mean of the peak was very small. Finally, suggestions on the type of distribution to be used for input variables are described. The descriptions were based on the nature and amount of relevant data available for a given problem.

Conclusions

The objective of this research was to provide guidance on nuclear power plant decommissioning dose analysis in a probabilistic analysis framework. The focus was on the demonstration of regulatory compliance for surface soil contamination using the RESRAD 6.0 code. Both the screening and site-specific probabilistic dose analysis methodologies were examined. Example analyses performed with the screening probabilistic dose analysis confirmed the conservatism of the NRC screening values and indicated the effectiveness of probabilistic dose analysis in reducing the conservatism in DCGL derivation. For a site-specific probabilistic dose analysis, this study found the nuclides' soil-to-plant transfer factor as the most important parameter. Example analyses using the site-specific soil-to-plant transfer factor for ^{137}Cs and ^{90}Sr showed a significant benefit of site-specific approach. Examination of the probabilistic dose analysis for regulatory compliance demonstration also showed that distinguishing the difference between the mean of the peak dose from the peak of the mean dose is not important with RESRAD 6.0. Finally, discussions on the use of distribution types to represent input variables indicted the importance of understanding the nature and amount of relevant data available for a given problem.

CONTENTS

1 INTRODUCTION 1-1

2 SCREENING PROBABILISTIC ANALYSIS 2-1

2.1 Basis for Screening Analysis 2-1

2.2 An Example Computer Analysis for Surface Contaminated Soil Using a Typical Source Term(s) for a Nuclear Power Station 2-2

2.3 Comparison of the Probabilistic Results with Deterministic and Default Results for Soil 2-13

3 SITE-SPECIFIC PROBABILISTIC ANALYSIS 3-1

3.1 Key parameters to be considered in a site-specific analysis 3-1

3.2 Sources of information for key parameters 3-11

3.2.1 Porosity, density, saturated hydraulic conductivity 3-11

3.2.2 Soil to plant transfer factor 3-12

3.2.3 Partition coefficient (K_d) 3-14

3.2.3.1 Cesium partition coefficient [US EPA, 1999] 3-15

3.2.3.2 Strontium partition coefficient 3-16

3.2.3.3 Plutonium partition coefficient 3-17

3.3 Example computer analyses using site-specific parameters 3-18

3.3.1 Basic principles 3-18

3.3.2 Example Analysis 3-19

3.3.2.1 Dose Analysis Results 3-25

3.3.2.2 DCGL Analysis Results 3-25

4 DESCRIPTION OF THE PROBABILISTIC ANALYSIS AND ITS INTERPRETATION 4-1

4.1 Probabilistic Dose Analysis 4-1

4.2 Key Terms in Probabilistic Analysis 4-3

4.2.1 Random variable 4-3

4.2.2 Probability 4-3

4.2.3 Probability distribution 4-4
4.2.4 Correlations 4-5
4.3 Interpretation of the Results from Probabilistic Dose Analysis 4-6
4.4 Differences Between the Peak of the Mean and the Mean of the Peak, and Pros and Cons of their Use for Regulatory Compliance Demonstration 4-7
4.5 Explanation of the Type of Distribution to be Used for Input Variables 4-9
4.5.1 General guidelines in assigning probability distributions 4-9
4.5.2 Specific guidelines [Haimes, et al., 1994; Cullen and Frey, 1999] 4-9
4.5.2.1 When large amount of relevant data is available 4-9
4.5.2.2 When sufficient amount of relevant data is available 4-10
4.5.2.3 When only a limited amount of data or data partly relevant are available 4-11
4.5.2.4 When very limited data are available 4-12
4.5.2.5 When essentially no relevant data are available 4-13
4.5.3 Characteristics of distributions 4-13
4.5.3.1 The normal distribution 4-13
4.5.3.2 The lognormal distribution 4-14
4.5.3.3 The binomial distribution 4-14
4.5.3.4 The Poisson distribution 4-14
4.5.3.5 The exponential distribution 4-15
4.5.3.6 The gamma distribution 4-15
4.5.3.7 The beta distribution 4-16
4.5.3.8 The uniform distribution 4-16
4.5.3.9 The loguniform distribution 4-16
4.5.3.10 Triangular distribution 4-16
4.5.3.11 The Weibull distribution 4-16

5 REFERENCES 5-1

A IDENTIFICATION OF KEY PARAMETERS IN PROBABILISTIC DOSE ANALYSIS USING RESRAD 6.0 ..... A-1

LIST OF FIGURES

Figure 2-1 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (H-3) 2-7
Figure 2-2 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (C-14)..... 2-7
Figure 2-3 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Fe-55) 2-8
Figure 2-4 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Co-60)..... 2-8
Figure 2-5 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Ni-63)..... 2-9
Figure 2-6 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Sr-90)..... 2-9
Figure 2-7 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Tc-99) 2-10
Figure 2-8 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (I-129) 2-10
Figure 2-9 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Cs-137).....2-11
Figure 2-10 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Ce-144).....2-11
Figure 2-11 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Pu-239).....2-12
Figure 2-12 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Am-241).....2-12
Figure 2-13 Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Cm-244).....2-13
Figure 2-14 Predicted Peak Dose for the NRC Screening DCGL (H-3) 2-15
Figure 2-15 Predicted Peak Dose for the NRC Screening DCGL (C-14) 2-15
Figure 2-16 Predicted Peak Dose for the NRC Screening DCGL (Fe-55).....2-16
Figure 2-17 Predicted Peak Dose for the NRC Screening DCGL (Co-60) 2-16
Figure 2-18 Predicted Peak Dose for the NRC Screening DCGL (Ni-63) 2-17
Figure 2-19 Predicted Peak Dose for the NRC Screening DCGL (Sr-90) 2-17
Figure 2-20 Predicted Peak Dose for the NRC Screening DCGL (Tc-99).....2-18
Figure 2-21 Predicted Peak Dose for the NRC Screening DCGL (I-129).....2-18
Figure 2-22 Predicted Peak Dose for the NRC Screening DCGL (Cs-134) 2-19

Figure 2-23 Predicted Peak Dose for the NRC Screening DCGL (Cs-137) 2-19
Figure 2-24 Predicted Peak Dose for the NRC Screening DCGL (Pu-238) 2-20
Figure 2-25 Predicted Peak Dose for the NRC Screening DCGL (Pu-239) 2-20
Figure 2-26 Predicted Peak Dose for the NRC Screening DCGL (Pu-241) 2-21
Figure 2-27 Predicted Peak Dose for the NRC Screening DCGL (Am-241) 2-21
Figure 2-28 Predicted Peak Dose for the NRC Screening DCGL (Cm-244) 2-22
Figure 3-1 Key Parameters in Probabilistic Dose Analysis (H-3) 3-5
Figure 3-2 Key Parameters in Probabilistic Dose Analysis (C-14) 3-5
Figure 3-3 Key Parameters in Probabilistic Dose Analysis (Fe-55)..... 3-6
Figure 3-4 Key Parameters in Probabilistic Dose Analysis (Co-60) 3-6
Figure 3-5 Key Parameters in Probabilistic Dose Analysis (Ni-63) 3-7
Figure 3-6 Key Parameters in Probabilistic Dose Analysis (Sr-90) 3-7
Figure 3-7 Key Parameters in Probabilistic Dose Analysis (Tc-99)..... 3-8
Figure 3-8 Key Parameters in Probabilistic Dose Analysis (I-129)..... 3-8
Figure 3-9 Key Parameters in Probabilistic Dose Analysis (Cs-137) 3-9
Figure 3-10 Key Parameters in Probabilistic Dose Analysis (Ce-144) 3-9
Figure 3-11 Key Parameters in Probabilistic Dose Analysis (Pu-239) 3-10
Figure 3-12 Key Parameters in Probabilistic Dose Analysis (Am-241) 3-10
Figure 3-13 Key Parameters in Probabilistic Dose Analysis (Cm-244) 3-11
Figure 3-14 The pdfs of the prior, likelihood, and posterior distribution – Cs-137 3-23
Figure 3-15 The cumulative distribution functions (cdfs) of the prior, likelihood, and posterior distribution – Cs-137.....3-23
Figure 3-16 The pdfs of the prior, likelihood, and posterior distribution – Sr-90 3-24
Figure 3-17 The cdfs of the prior, likelihood, and posterior distribution – Sr-90 3-24
Figure 4-1 Comparison of the Peak of the Mean and the Mean of the Peak Dose for Cs-137 4-8
Figure 4-2 Comparison of the Peak of the Mean and the Mean of the Peak Dose for I-129 4-9
Figure 4-3 β_1-β_2 plane depicting several common parametric probability distributions [Hahn and Shapiro, 1967].....4-11

LIST OF TABLES

Table 2-1 Comparison of Peak Dose between Deterministic and Probabilistic RESRAD Dose Analysis 2-6

Table 2-2 Comparisons of DCGL (NRC Screening Approach versus the Values Using RESRAD Probabilistic Dose Analysis) 2-14

Table 3-1 Key Parameters of RESRAD6.0 Identified from Multivariate Linear Regression 3-3

Table 3-2 Key Parameters Identified from Probabilistic Sensitivity Analysis (with RESRAD 6.0 based upon the default probabilistic input distributions, in the order of importance) 3-4

Table 3-3 Estimated Values of Porosity and Saturated Hydraulic Conductivity for Different Soil Textures [Carsel and Parrish, 1988] 3-12

Table 3-4 Geometric Mean and 95% Confidence Intervals for Soil-to-Plant Transfer Factor of Cesium for edible crop parts (Bq/kg dry mass plant per Bq/kg dry mass soil) 3-13

Table 3-5 Geometric Mean and 95% Confidence Intervals for Soil-to-Plant Transfer Factor of Strontium for edible crop parts (Bq/kg dry mass plant per Bq/kg dry mass soil) 3-14

Table 3-6 Estimated Values of Soil-Specific K_d Values [Sheppard and Thibault, 1990] 3-15

Table 3-7 Estimated range of Kd values (ml/g) for cesium based on clay content for system containing <5% mica-like minerals in clay-size fraction and $<10^{-9}$ M aqueous cesium. 3-16

Table 3-8 Estimated Kd Values (ml/g) for cesium based on Clay content for systems containing >5% mica-like minerals in clay-size fraction and $<10^{-9}$ M aqueous cesium. 3-16

Table 3-9 Estimated Range of K_d values for Strontium 3-17

Table 3-10 Estimated Range of K_d Values for Plutonium 3-17

Table 3-11 Soil-to-plant transfer factor for Cs in loam - pCi/kg(dry)/pCi/kg(dry) 3-20

Table 3-12 Soil-to-plant transfer factor for Sr in loam - pCi/kg(dry)/pCi/kg(dry) 3-20

Table 3-13 Comparison of Peak Dose (mrem/yr) Distributions between Screening and Site-Specific Probabilistic Dose Analysis (per 1 pCi/g) 3-25

Table 3-14 Comparison of the DCGL (pCi/g) calculated between the Screening and Site-Specific Probabilistic Dose Analysis 3-26

Table 4-1 Suggestions on the selection of probability distribution model with very limited data 4-12

Table A-1 Identification of Key Parameters in Probabilistic Dose Analysis (H-3) A-2

Table A-2 Identification of Key Parameters in Probabilistic Dose Analysis (C-14) A-3

Table A-3 Identification of Key Parameters in Probabilistic Dose Analysis (Fe-55)..... A-4
Table A-4 Identification of Key Parameters in Probabilistic Dose Analysis (Co-60) A-5
Table A-5 Identification of Key Parameters in Probabilistic Dose Analysis (Ni-63) A-6
Table A-6 Identification of Key Parameters in Probabilistic Dose Analysis (Sr-90) A-7
Table A-7 Identification of Key Parameters in Probabilistic Dose Analysis (Tc-99)..... A-8
Table A-8 Identification of Key Parameters in Probabilistic Dose Analysis (I-129)..... A-9
Table A-9 Identification of Key Parameters in Probabilistic Dose Analysis (Cs-137) A-10
Table A-10 Identification of Key Parameters in Probabilistic Dose Analysis (Ce-144) A-11
Table A-11 Identification of Key Parameters in Probabilistic Dose Analysis (Pu-239)..... A-12
Table A-12 Identification of Key Parameters in Probabilistic Dose Analysis (Am-241)..... A-13
Table A-13 Identification of Key Parameters in Probabilistic Dose Analysis (Cm-244) A-14

1
INTRODUCTION

One of the essential issues in nuclear power plant decommissioning is to ensure that any remaining radioactivity at a decommissioned site should not pose unacceptable risk to any member of the public after the release of the site. Based on the consideration of acceptable risk, the levels of allowable residual contamination should be determined and the site must be cleaned accordingly. The safety and cost of a decommissioning project will be controlled predominately by this allowable residual contamination level.

In 1997, the U.S. Nuclear Regulatory Commission (NRC) published in the Federal Register a final rule incorporating a new Subpart E into 10 CFR Part 20 that includes radiological criteria for license termination [NRC, 1997]. The regulation, as given in Subpart E, 10 CFR 20.1402, "Radiological Criteria for Unrestricted Use", states that a site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a Total Effective Dose Equivalent (TEDE) to an average member of the critical group does not exceed 25 mrem (0.25 mSv) per year, including that from groundwater sources of drinking water, and the residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA).

For this demonstration, dose modeling is performed using exposure pathway/dose assessment computer models to determine if radionuclide-specific residual contamination levels would result in a dose that complies with the regulatory limit.

To assist these utilities in performing dose modeling, EPRI initiated a research in 1998. The first report [Yim, 1999], published in November 1999, was entitled "Comparisons of Decommissioning Dose Modeling Codes for Nuclear Power Plant Use: RESRAD and DandD". This report focused on comparing the two major dose analysis computer code, DandD and RESRAD, for plant decommissioning. The report identified and compared important exposure pathways and capabilities and conservatism of models, key parameters, and default input values of the two codes, in deterministic analysis framework.

The focus of current report is to provide guidance on the use of probabilistic dose analysis in the demonstration of regulatory compliance for surface soil contamination. The computer code selected was RESRAD 6.0 [Yu, et al., 2000]. Due to the code's unavailability, the DandD probabilistic code was not used in the present study. The RESRAD code was first developed by Argonne National Laboratory in the late 80s for deterministic dose analysis, and has been widely used by the Department of Energy (DOE), Environmental Protection Agency (EPA), and the nuclear power industry. The RESRAD version 6.0, was released in August 2000 for probabilistic dose analysis by incorporating the capability for Monte Carlo parameter uncertainty analysis. This report covers the following subjects:

- Use of screening probabilistic dose analysis.
- Use of site-specific probabilistic dose analysis.
- General understanding of probabilistic dose analysis and its interpretation.

2
SCREENING PROBABILISTIC ANALYSIS

2.1 Basis for Screening Analysis

Due to the practical difficulties in experimenting the field situations, determination of allowable residual contamination is possible only through predictive analysis (hereafter called "dose analysis"). Dose analysis uses mathematical/computational models as the conceptualization of the actual field situations and estimates the dose from the remaining source of radiation to any potentially exposed individual through various pathways after the release of the site. The principal components of dose analysis are: (a) models for transport of radionuclides through the environment to a receptor, and (b) the parameters used in those models. As in the case of most predictive analyses, uncertainty is present in almost every aspect of dose analysis including the conceptualization of the site, assumptions on human exposure pathways, implementation of mathematical models, and development of data for model parameters. This uncertainty can be very large depending upon the amount of effort given to the characterization of site and related parameters. Decisions on the regulatory compliance (acceptance/rejection of the residual risk) or the required cleanup efforts at the site must be made in the light of the uncertainties in the predictive analysis.

To facilitate the preparation and evaluation of the analysis, a phased approach to decision-making for license termination was adopted by the NRC because of the very wide range of levels of contamination and complexity of analysis and potential remediations necessary at NRC-licensed sites. The phased approach consists of generic screening analysis and of making use of site-specific information as appropriate.

Whether screening or site-specific, dose analysis requires a site conceptual model. The site conceptual model includes [NRC, 2000] appropriate source term (concentrations of residual surface radioactivity), assumptions used in characterizing the source term (assumptions of homogeneity), and the understanding of potential exposures to this source term in the plant environment. The scenarios of human exposure to the residual radioactivity are related to (1) the type and location of contamination, (2) the characteristics of its movement in the environment, and (3) the exposed humans' behavioral habit and pattern. The site conceptual model must be compatible with the conceptual model built into the computer model used for the analysis.

There could be numerous possible scenarios of how future human exposure groups could interact with residual radioactivity. However, the exposure pathways for many of the exposure groups can be bounded by a small number of bounding scenarios for an adult in a critical group. A critical group is defined as a "maximally exposed" group of individuals whose activities and location would make them likely to receive the largest exposures. Although the regulations require the calculation of human dose for the 1000 years after the site release, current land

patterns or the habits of the people living or working in the vicinity can be used to identify the critical group. The NRC accepts a residential farmer scenario as a bounding exposure scenario for surface soil contamination, with the exceptions of special site-specific features for a critical group.

Screening dose analyses are performed with little site-specific information. The screening would comply with more restrictive criteria, but would do so based on a decision to not expend resources for a more realistic dose estimate, and would have high assurance that the criteria would be met. If the site has very simple situations, exhibits only surface contamination (not greater than 6 inches below the ground surfaces) and does not have contamination in the underlying aquifer or in surface water sediments, a screening analysis can be useful for dose modeling. For more complex situations or more realistic analyses, the methodology ensures that as more site-specific information is incorporated, the uncertainty is reduced and the estimate of the resulting dose generally decreases. This provides assurance that obtaining additional site-specific information is worthwhile because it ensures that a more "realistic" dose analysis will not generally result in a dose higher than that estimated using screening.

Presently there are three ways of screening analysis: (1) Using the NRC lookup table to compare with the site-specific source term concentrations, or (2) Deterministic screening dose analysis using DandD with the site-specific source term without modifying any default input parameters, and; (3) Probabilistic screening dose analysis using RESRAD 6.0 with the site-specific source term without modifying any default input parameters.

If the planned residual contamination levels are equal to or less than those values specified in the lookup table or the dose values (in the case of probabilistic analysis, the peak of the mean dose) calculated by the code with the site-specific source term is less than 25 mrem/yr limit, compliance with the regulatory criteria is successful.

In the screening probabilistic dose analysis, model parameters representing the physical characteristics of a site were assigned conservative default values resulting in conservatively high doses. Thus, sites with estimated dose below regulatory limits have a high probability of meeting the limits if a site-specific analysis were to be performed.

2.2 An Example Computer Analysis for Surface Contaminated Soil Using a Typical Source Term(s) for a Nuclear Power Station

An example screening probabilistic dose analysis for surface contaminated soil was performed with the RESRAD6.0 code for major nuclides expected from a decommissioning nuclear power plant. The screening analysis in the study meant that the existing default inputs of the RESRAD 6.0 code are used except for the user-provided site-specific source term information. The source term nuclides were determined according to the sampling efforts at decommissioning power plant sites. The major nuclides in the source term include: ^{3}H, ^{14}C, ^{55}Fe, ^{60}Co, ^{63}Ni, ^{99}Tc, ^{129}I, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{238}Pu, ^{239}Pu, ^{241}Pu, ^{241}Am, ^{242}Cm, ^{243}Cm/^{244}Cm. Unfortunately, ^{242}Cm was not included in the RESRAD6.0 data library thus was dropped in the subsequent analyses.

In the subsequent analysis, the distribution of peak annual dose to a member of a critical group was calculated for a unit soil contamination level (1 pCi/g) for each respective nuclide. The

results are shown in Figures 2-1 through 2-13. Summary of these results are also presented in Table 2-1. For all of the nuclides analyzed, the peak dose occurred at time zero except ^{129}I. For ^{129}I, the peak occurred at year 3. These results are explained in the following.

1) H-3

For ^{3}H, the predicted peak dose ranged from 0.008 mrem/yr to 0.03 mrem/yr with the mean of 0.0161 mrem/yr and the median of 0.0149 mrem/yr (Fig.2-1). The distribution is quite narrowly peaked indicating that the uncertainty distributions of input parameters play a minor role. The 90th and 95th percentile peak dose was 0.0239 mrem/yr and 0.0264 mrem/yr, respectively. The peak dose from the deterministic analysis was close to the 50th percentile of the probabilistic dose results.

2) C-14

The predicted peak dose distribution for ^{14}C ranged between 0.3 mrem/yr and 1.75 mrem/yr with the mean of 0.687 mrem/yr and the median of 0.624 mrem/yr (Fig. 2-2). The 90th and 95th percentile peak dose was 1.04 mrem/yr and 1.19 mrem/yr, respectively. The deterministic dose result was 1.14 mrem/yr which corresponds to about the 95th percentile value of the probabilistic results.

3) Fe-55

The peak dose from the probabilistic analysis for ^{55}Fe ranged from 0.00018 mrem/yr to 0.0022 mrem/yr with the median of about 0.0004 mrem/yr (Fig. 2-3). The 90th and 95th percentile peak dose was 0.00067 and 0.00079. The results indicated a narrowly peaked distribution. The peak dose result from deterministic analysis was 0.00026 mrem/yr which corresponds to about 20th percentile value of the probabilistic results. The results were not very sensitive to the uncertainty of the input parameters.

4) Co-60

The predicted peak dose distribution for ^{60}Co soil contamination ranged from 3.7 mrem/yr to 12.8 mrem/yr with the median of 4.83 mrem/yr (Fig. 2-4). The 90th and 95th percentile peak dose was 9 and 10.2 mrem/yr, respectively. The peak dose from deterministic analysis was 8.85 mrem/yr which corresponds to roughly the 90th percentile of the probabilistic dose results.

5) Ni-63

The predicted dose distribution for ^{63}Ni in surface soil ranged from 0.0012 mrem/yr to 0.03 mrem/yr with the mean of 0.0088 mrem/yr and the median of about 0.00546 mrem/yr (Fig. 2-5). The 90th and 95th percentile dose was about 0.0166 and 0.0252 mrem/yr, respectively. The peak dose from deterministic analysis was 0.046 mrem/yr which corresponds to about 45th percentile of the probabilistic dose.

6) Sr-90

For ^{90}Sr in the surface soils, the predicted peak dose from probabilistic analysis ranged from 0.7 mrem/yr to 165 mrem/yr with the mean of 11.8 mrem/yr and the median of 5.22 mrem/yr (Fig. 2-6). The 90th and 95th percentile dose was 17.9 and 29.7 mrem/yr. The peak dose predicted from deterministic analysis was about 5 mrem/yr which corresponds to 47.5^{h} percentile of the probabilistic results. The results indicate that the uncertainties of the input parameters are very important.

7) Tc-99

For a unit activity contamination of surface soil, the predicted peak dose from probabilistic analysis ranged from 0.1 mrem/yr to 11.9 mrem/yr with the mean of 1.18 mrem/yr and the median of 0.665 mrem/yr (Fig. 2-7). The 90th and 95th percentile dose was 2.11 and 3.33 mrem/yr, respectively. The peak dose predicted from deterministic analysis was about 0.466 mrem/yr which corresponds to 40th percentile of the probabilistic results. The range covered by the probabilistic results is the widest among all the nuclides examined in this study. This indicates that the uncertainties of the input parameters are very important.

8) I-129

The predicted peak dose distribution from probabilistic analysis for ^{129}I contamination ranged from 0.4 mrem/yr to 38 mrem/yr with the mean of 2.8 mrem/yr and the median peak dose of 1.31 mrem/yr (Fig. 2-8). The 90th and 95th percentile peak dose was 4.21 and 6.41 mrem/yr, respectively. The peak dose from deterministic analysis was 0.65 mrem/yr which corresponds to the 15th percentile of the probabilistic results.

9) Cs-134

The predicted peak dose distribution behaves similarly to that of ^{60}Co. The peak dose for a unit Cs-134 soil contamination ranged from 12 mrem/yr to 60 mrem/yr with the mean of 3.77 mrem/yr and the median of 3.32 mrem/yr. The 90th and 95th percentile value was 5.5 and 6.5 mrem/yr, respectively. The peak dose from the deterministic analysis corresponds to the 87th percentile of the probabilistic results.

10) Cs-137

For ^{137}Cs, the predicted peak dose from probabilistic analysis ranged from 0.9 mrem/yr to 9.49 mrem/yr with the mean of 2.02 mrem/yr and the median of 1.61 mrem/yr (Fig. 2-9). The 90th and 95th percentile dose was 3.02 and 3.65 mrem/yr, respectively. The peak dose from the deterministic analysis was about 2.3 mrem/yr which corresponds to 80th percentile of the probabilistic results. The results indicate that the uncertainties of the input parameters are important. The distribution of peak dose behaved similarly to that of ^{134}Cs.

11) Ce-144

For ^{144}Ce in the surface soils, the predicted peak dose from probabilistic analysis ranged from 0.05 mrem/yr to 0.2 mrem/yr with the mean of 0.078 mrem/yr and the median of 0.065 mrem/yr (Fig. 2-10). The 90th and 95th percentile dose was 0.11 and 0.13 mrem/yr, respectively. The peak

dose predicted from deterministic analysis was about 0.125 mrem/yr which corresponds to 92th percentile of the probabilistic results.

12) Pu-238

For a unit activity contamination of surface soil by ^{238}Pu, the predicted peak dose ranged between 0.5 mrem/yr to 10 mrem/yr with the mean of 0.53 mrem/yr and the median of about 1 mrem/yr. The 90th and 95th percentile dose is 2.8 and 3.5 mrem/yr, respectively. The results indicated a narrowly peaked distribution of dose. Thus input parameter uncertainty was not very important. The peak dose from the deterministic analysis corresponded to about 60th percentile of the probabilistic results.

13) Pu-239

For ^{239}Pu, the predicted peak dose from probabilistic analysis ranged from 0.1 mrem/yr to 6.48 mrem/yr with the mean of 0.68 mrem/yr and the median of 0.384 mrem/yr (Fig. 2-11). The 90th and 95th percentile dose was 1.09 and 1.57 mrem/yr, respectively. The peak dose predicted from deterministic analysis was about 0.44 mrem/yr which corresponds to 60th percentile of the probabilistic results.

14) Pu-241

For ^{241}Pu, the predicted peak dose from probabilistic analysis ranged from 0.002 mrem/yr to 0.04 mrem/yr with the mean of 0.0114 mrem/yr and the median of 0.0074 mrem/yr. The 90th and 95th percentile dose was 0.02 and 0.03 mrem/yr, respectively. The peak dose predicted from deterministic analysis was about 0.008 mrem/yr which corresponds to 55th percentile of the probabilistic results.

15) Am-241

The peak dose distribution from the probabilistic analysis ranges from 0.13 mrem/yr to 4.04 mrem/yr with the mean of 0.66 mrem/yr and the median peak dose of 0.41 mrem/yr (Fig. 2-12). The 90th and 95th percentile dose was 1.31 and 1.84 mrem/yr, respectively. The peak dose has a rather narrow peak. This tells that the uncertainty of the parameters do not have significant impact on the dose. The predicted peak dose from the deterministic approach was 0.47 mrem/yr which corresponds to about the 60th percentile value of the probabilistic dose results.

16) Cm-243

The predicted peak dose distribution was very similar to that of ^{241}Am. It is narrowly peaked. The peak dose ranges from 0.2 mrem/yr to 2 mrem/yr with the mean of 0.64 mrem/yr and the median peak dose of 0.46 mrem/yr. The 90th and 95th percentile dose was 0.99 and 1.26 mrem/yr, respectively.

17) Cm-244

The peak dose ranged from 0.1 mrem/yr to 5 mrem/yr with the mean of 0.45 mrem/yr and the median peak dose of 0.2 mrem/yr (Fig. 2-13). The 90th and 95th percentile dose was 0.64 and 0.8 mrem/yr, respectively. The peak dose from the deterministic approach was 0.24 mrem/yr which corresponds to about the 60th percentile value of the probabilistic dose results.

Table 2-1
Comparison of Peak Dose between Deterministic and Probabilistic RESRAD Dose Analysis

Nuclide	Peak Dose per 1 pCi/g	Peak Dose per 1 pCi/g (Probabilistic Dose Analysis								
	Deterministic analysis	Peak dose time (yr)	5%	10%	25%	50%	75%	90%	95%	Mean
H-3	1.43e-2	0	8.11e-3	8.97e-3	1.19e-2	1.49e-2	1.86e-2	2.39e-2	2.64e-2	1.61E-02
C-14	1.14e+0	0	3.13e-1	3.81e-1	4.81e-1	6.24e-1	7.92e-1	1.04e+0	1.19e+0	6.87E-01
Fe-55	2.57e-4	0	1.89e-4	2.14e-4	2.70e-4	3.71e-4	5.03e-4	6.70e-4	7.88e-4	4.36E-04
Co-60	8.85e+0	0	3.77e+0	3.83e+0	4.05e+0	4.83e+0	6.38e+0	9.0e+0	1.02e+1	5.68E-00
Ni-63	4.59e-3	0	1.27e-3	1.66e-3	2.76e-3	5.46e-3	1.01e-2	1.66e-2	2.52e-2	8.83E-03
Sr-90	4.99e+0	0	9.61e-1	1.25e+0	2.71e+0	5.22e+0	1.00+1	1.79e+1	2.97e+1	1.18E+1
Tc-99	4.66e-1	0	1.27e-1	1.81e-1	3.17e-1	6.65e-1	1.13e+0	2.11e+0	3.33e+0	1.18E-00
I-129	6.50e-1	3	4.70e-1	5.63e-1	8.51e-1	1.31e+0	2.37e+0	4.21e+0	6.41e+0	2.80E-00
Cs-134	4.99e+0	0	2.15e+0	2.24e+0	2.57e+0	3.32e+0	4.32e+0	5.50e+0	6.50e+0	3.77E-00
Cs-137	2.27e+0	0	9.81e-1	1.07e+0	1.24e+0	1.57e+0	2.07e+0	3.02e+0	3.65e+0	2.02E-00
Ce-144	1.23e-1	0	5.18e-2	5.27e-2	5.59e-2	6.63e-2	9.18e-2	1.13e-1	1.35e-1	7.83E-02
Pu-238	3.96e-1	0	9.53e-2	1.24e-1	1.92e-1	3.34e-1	6.29e-1	9.88e-1	1.46e+0	5.28E-01
Pu-239	4.39e-1	0	1.18e-1	1.51e-1	2.41e-1	3.84e-1	7.13e-1	1.09e+0	1.57e+0	6.79E-01
Pu-241	8.30e-3	0	2.24e-3	2.88e-3	4.29e-3	7.39e-3	1.35e-2	2.11e-2	3.11e-2	1.14E-02
Am-241	4.72e-1	0	1.47e-1	1.86e-1	2.51e-1	4.14e-1	6.99e-1	1.31e+0	1.84e+0	6.55E-01
Cm-243	6.32e-1	0	2.27e-1	2.45e-1	3.44e-1	4.64e-1	6.69e-1	9.87e-1	1.26e+0	6.40E-01
Cm-244	2.43e-1	0	1.11e-1	1.21e-1	1.66e-1	2.53e-1	4.02e-1	6.94e-1	8.93e-1	4.47E-01

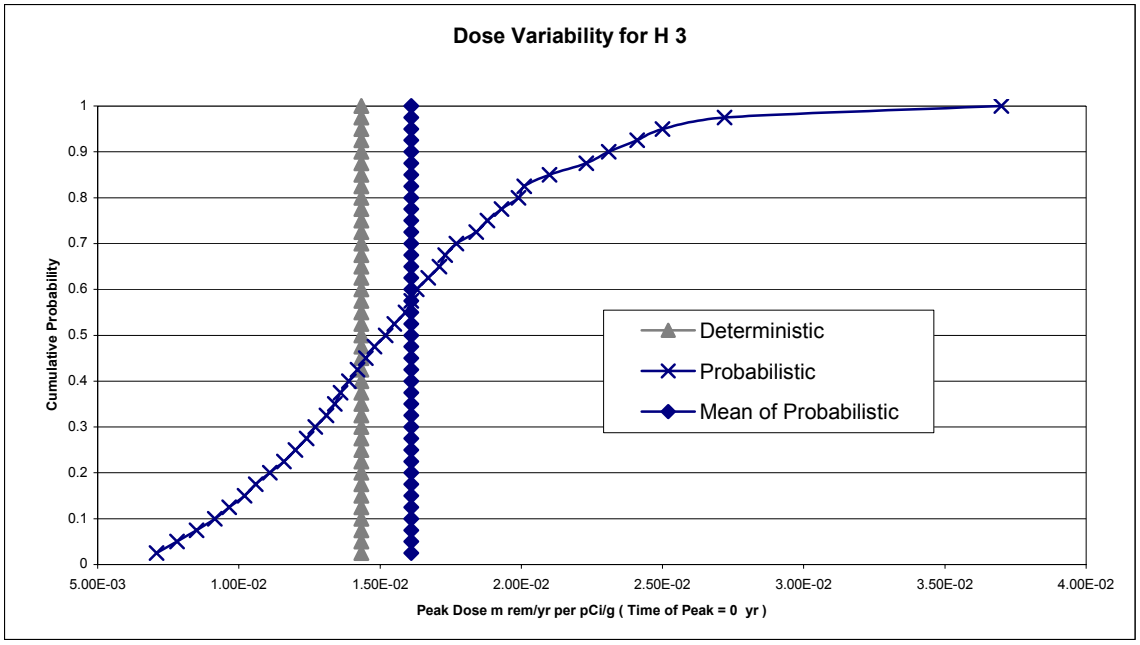

Figure 2-1
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (H-3)

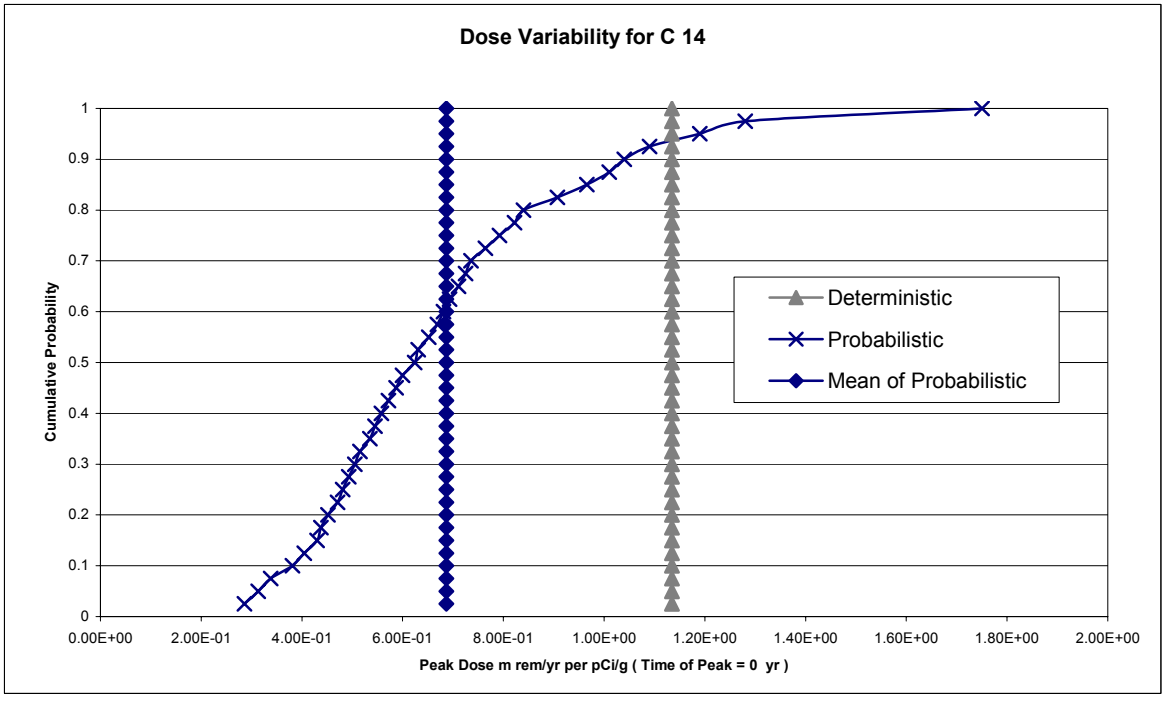

Figure 2-2
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (C-14)

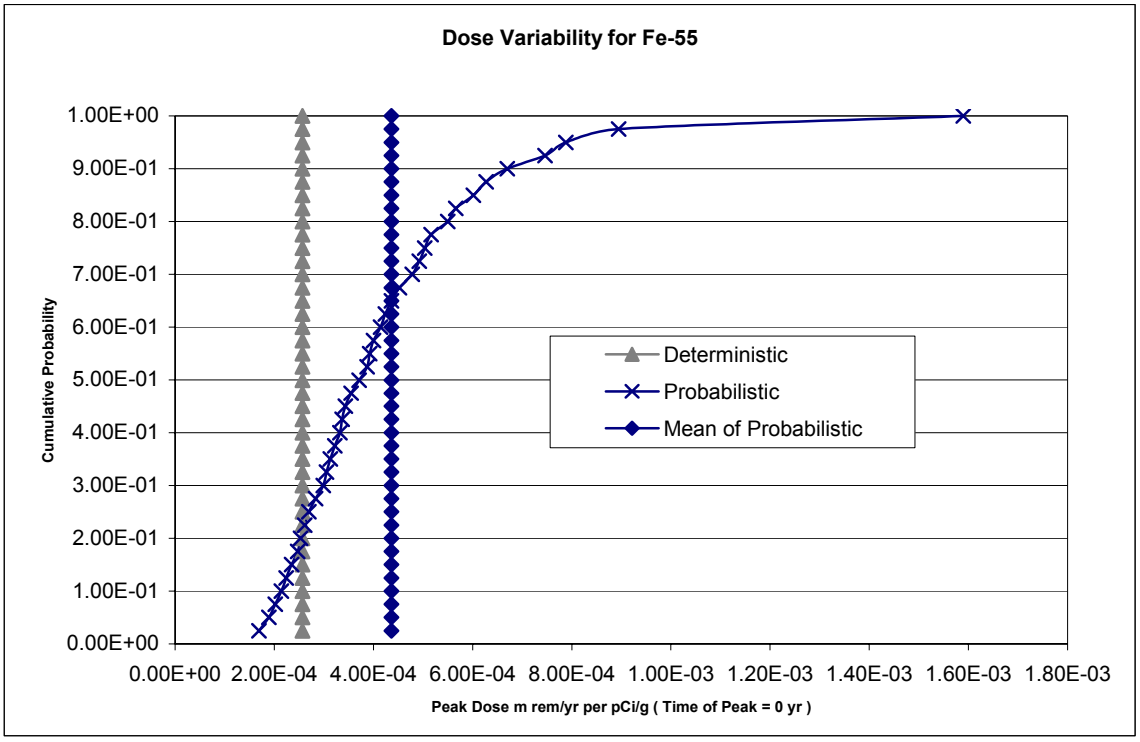

Figure 2-3
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Fe-55)

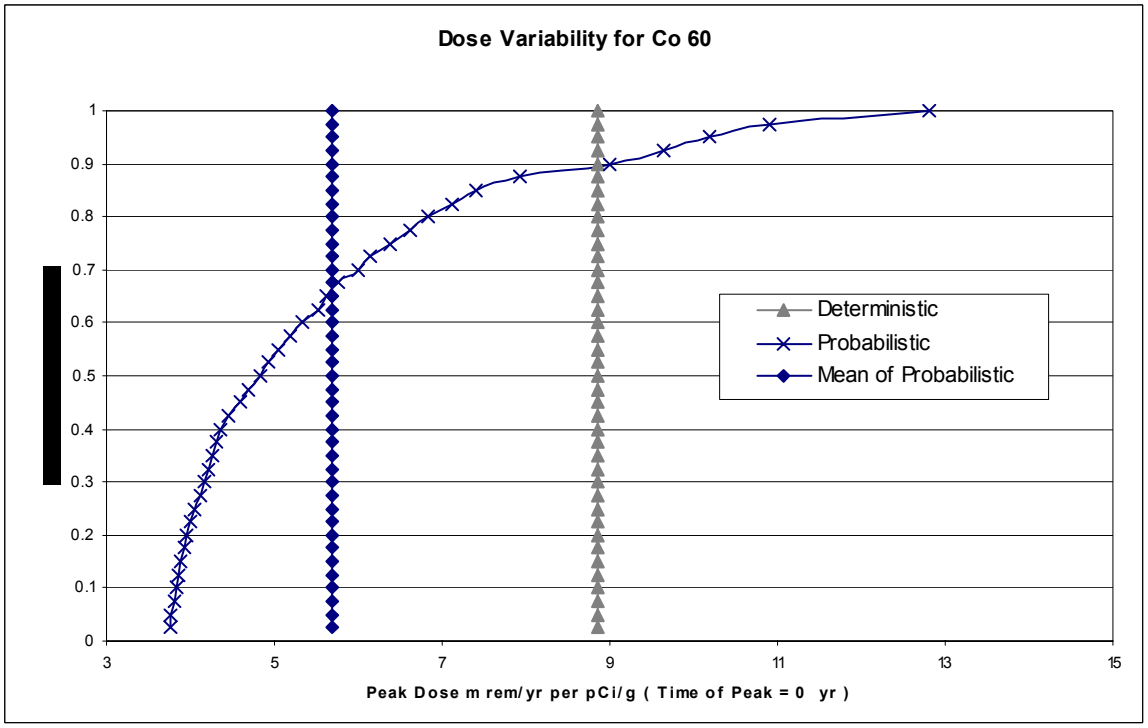

Figure 2-4
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Co-60)

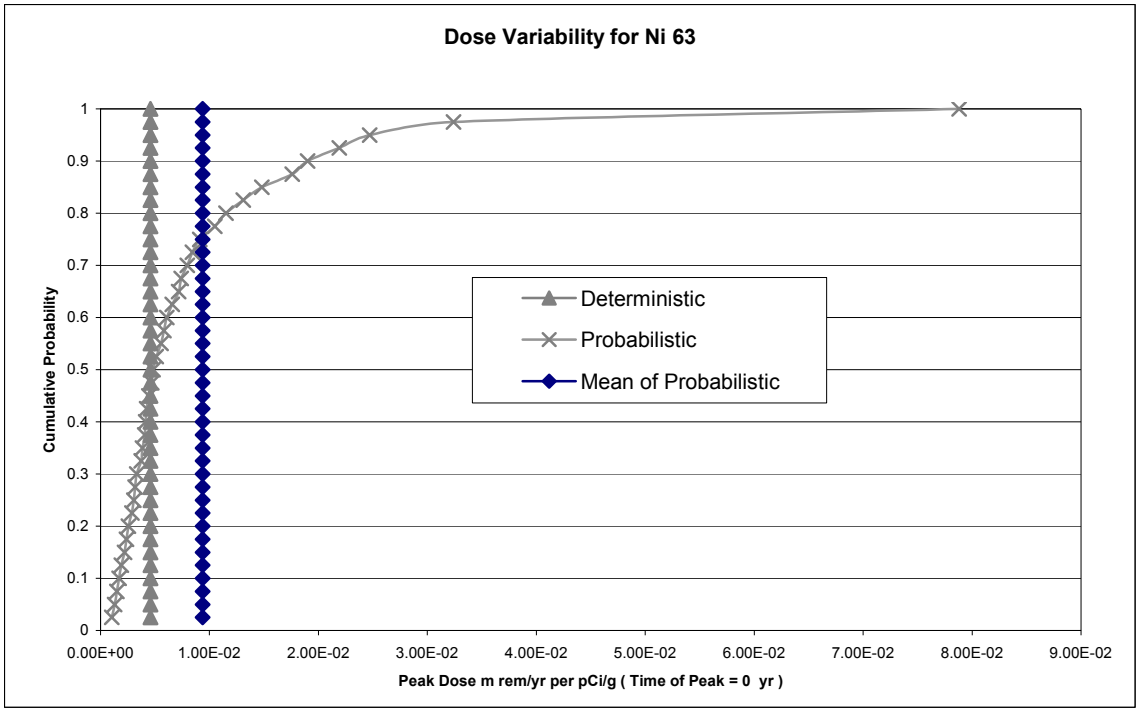

Figure 2-5
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Ni-63)

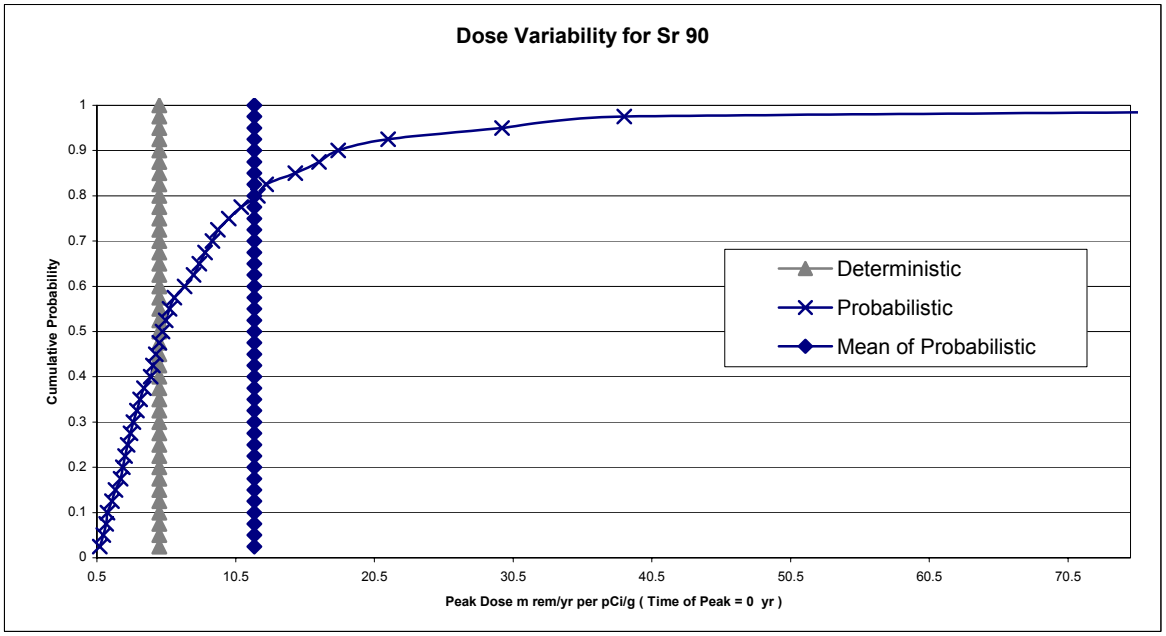

Figure 2-6
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Sr-90)

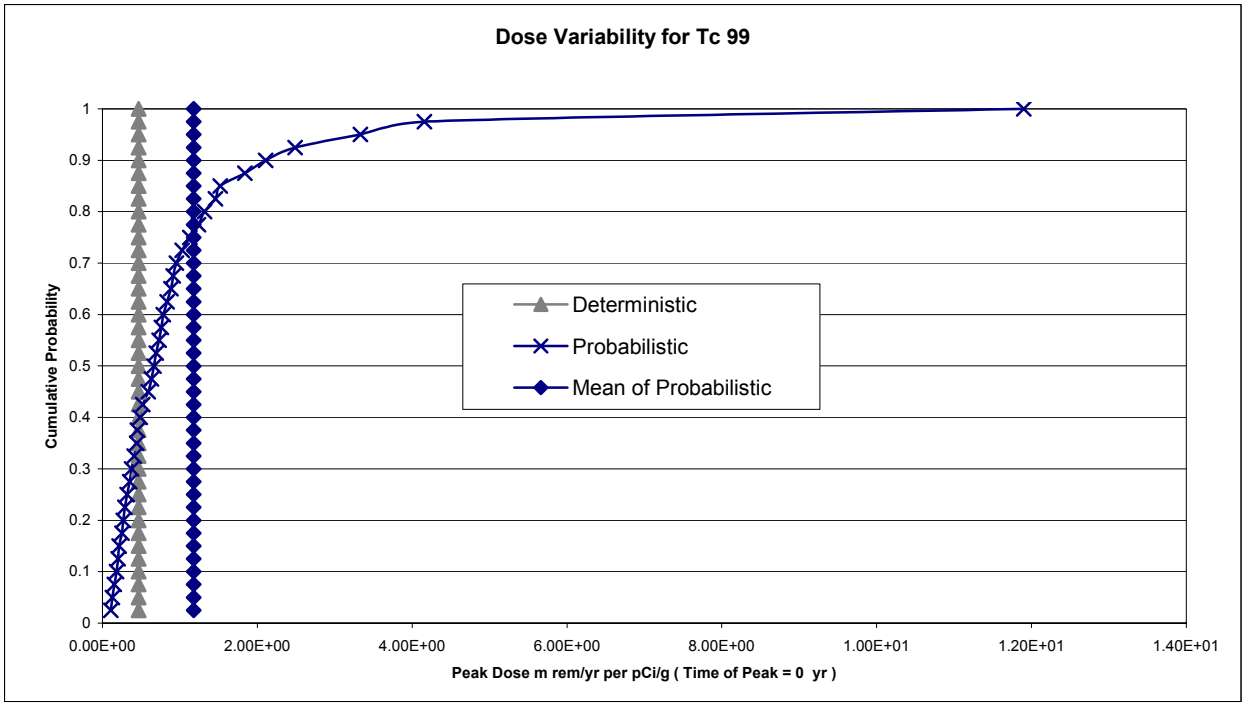

Figure 2-7
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Tc-99)

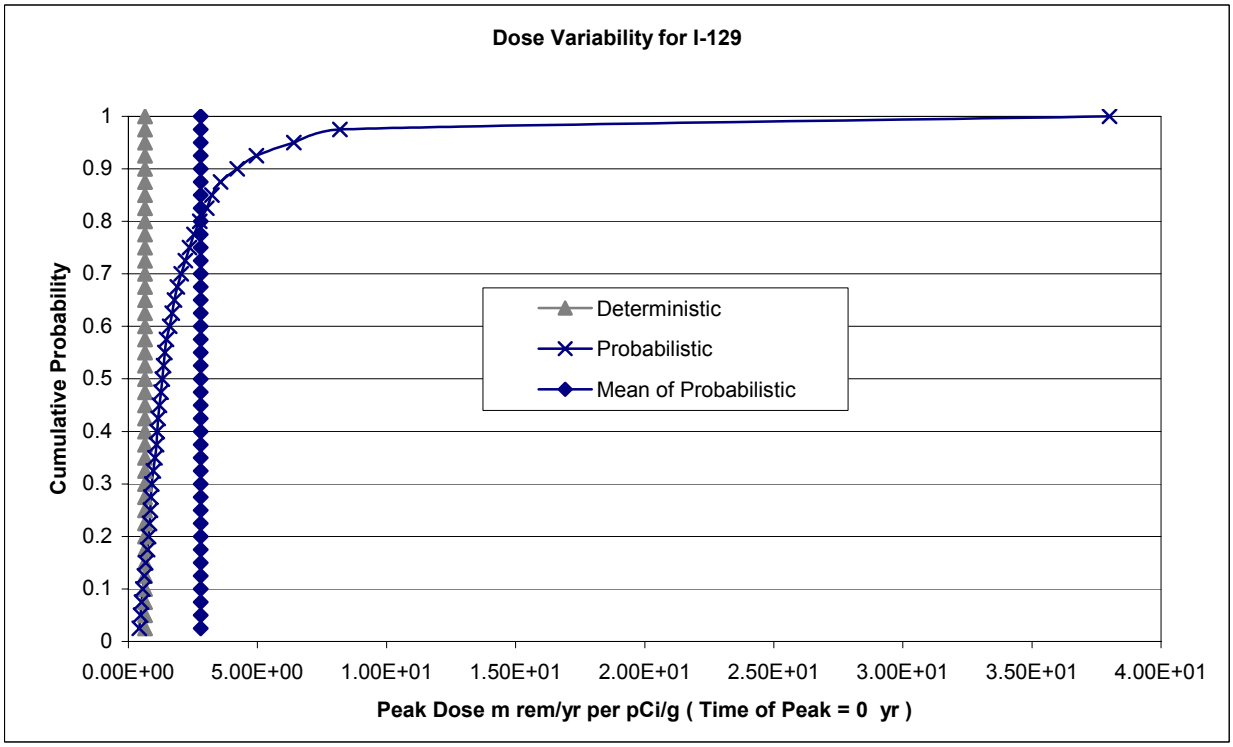

Figure 2-8
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (I-129)

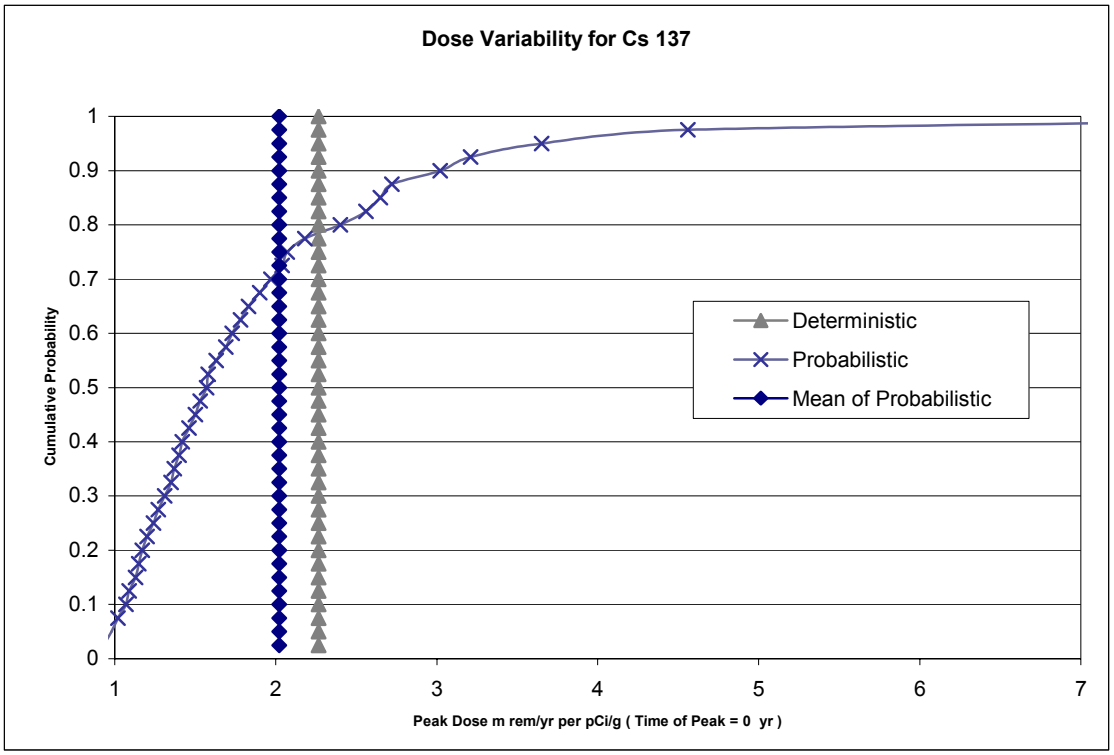

Figure 2-9
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Cs-137)

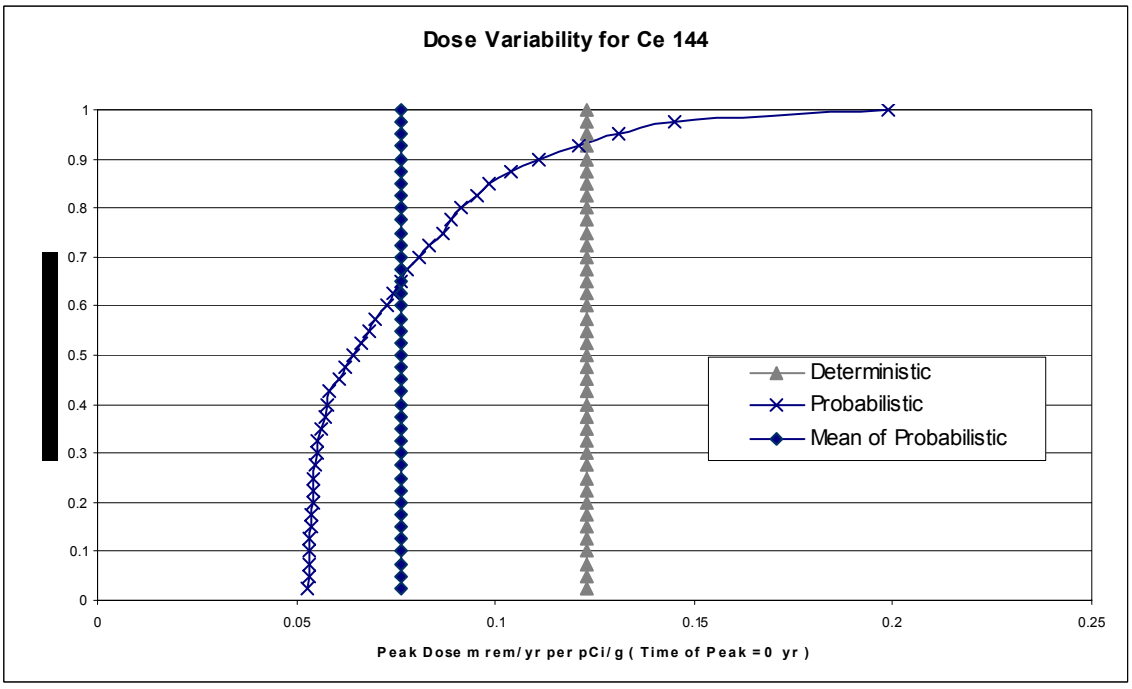

Figure 2-10
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Ce-144)

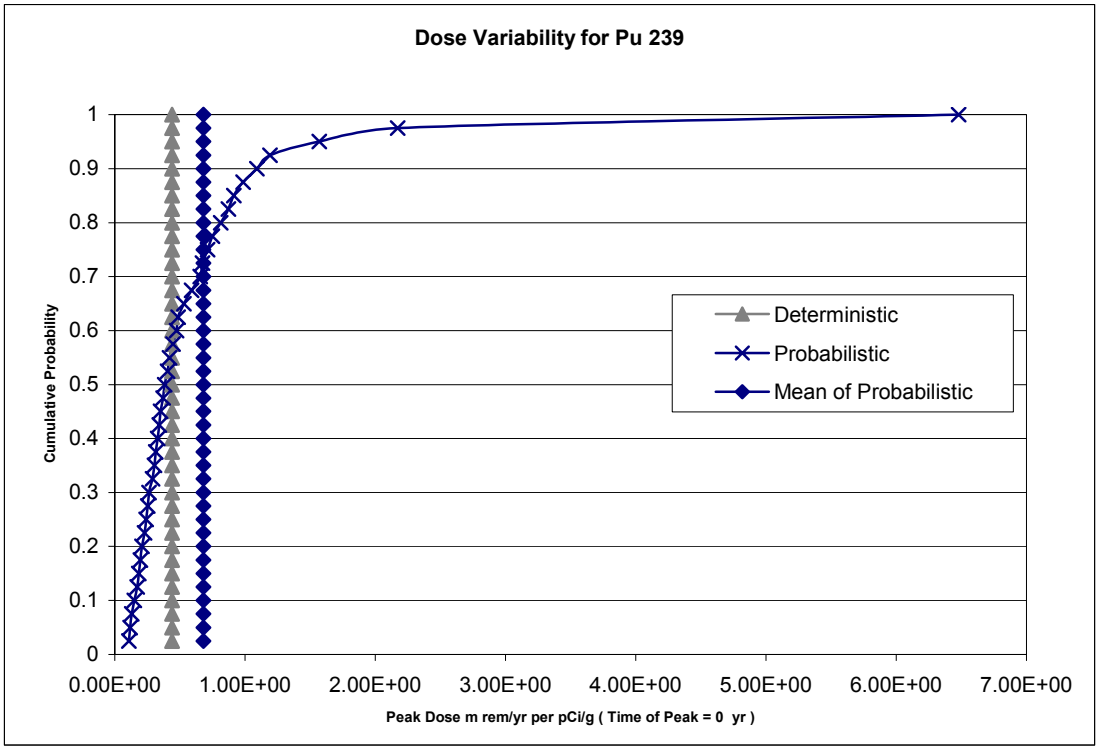

Figure 2-11
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Pu-239)

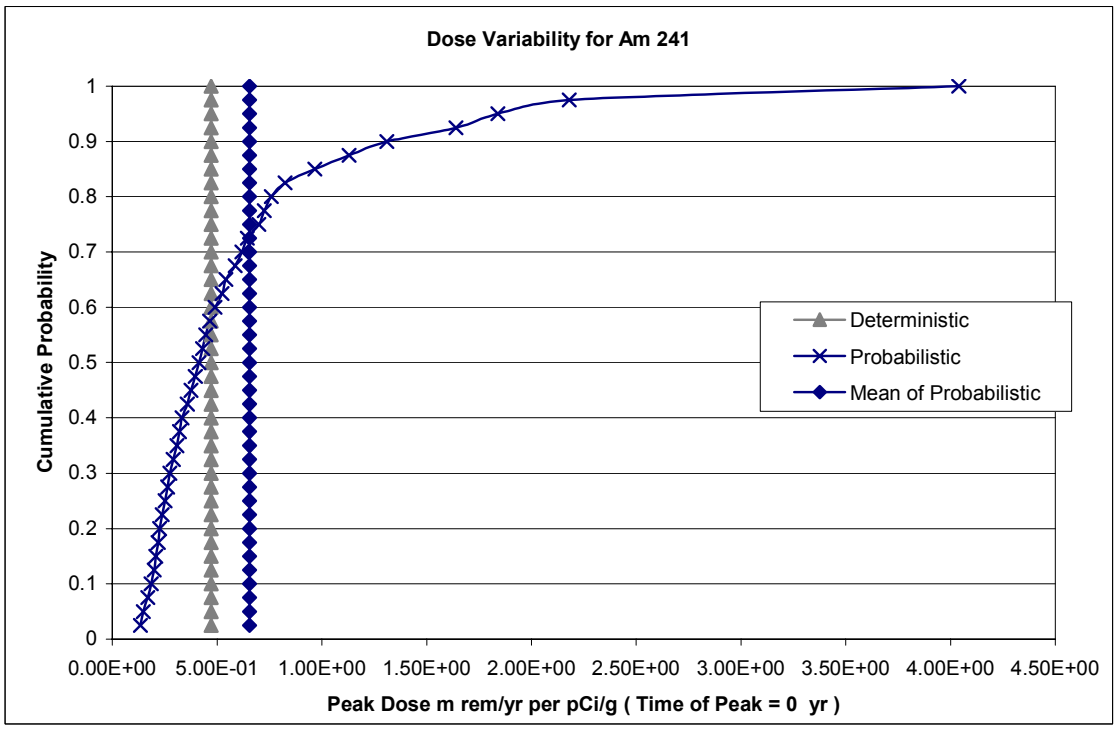

Figure 2-12
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Am-241)

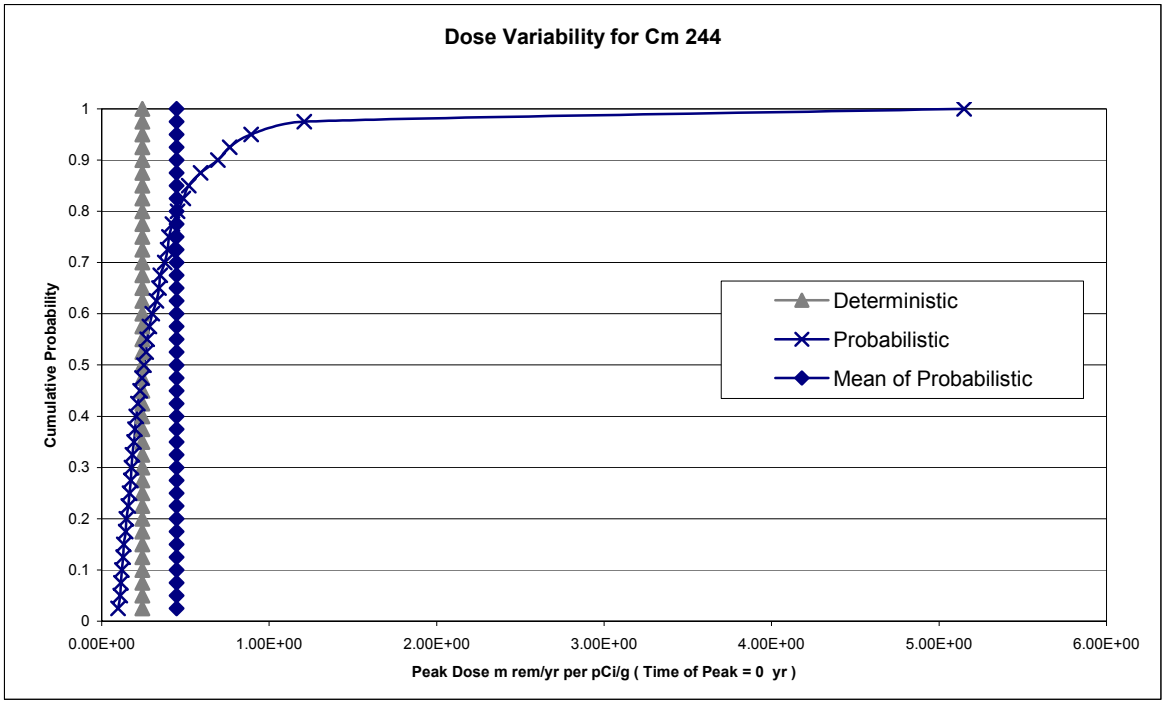

Figure 2-13
Comparison of Peak Dose between Deterministic and probabilistic RESRAD Dose Analysis (Cm-244)

2.3 Comparison of the Probabilistic Results with Deterministic and Default Results for Soil

The DCGL (derived concentration guideline level) values calculated from the probabilistic and deterministic approach were compared along with the NRC screening values. The DCGL is the concentration of residual activity distinguishable from background which, if distributed uniformly throughout a survey unit, would result in a total effective dose equivalent of 25 mrem per year to an average member of the critical group.

Table 2-2 shows the summary of the comparison. The DCGL values according to the deterministic RESRAD 6.0 analysis were also included. The DCGL values derived from the deterministic analysis were higher than the NRC screening values except for ^{60}Co, ^{134}Cs, and ^{137}Cs. The DCGL values derived based on the mean of the peak dose from the probabilistic analysis were always higher than the NRC screening values.

For ^{60}Co, ^{63}Ni, ^{90}Sr, ^{99}Tc, ^{134}Cs, ^{137}Cs, and ^{241}Am, the DCGL values from the probabilistic analyses matched well with the NRC screening values. For ^{3}H, ^{14}C, ^{55}Fe, ^{129}I, ^{238}Pu, ^{239}Pu, ^{241}Pu, and ^{243}Cm, the screening DCGL from NRC was much more conservative than the results from probabilistic analysis: The screening DCGL values were much lower than the DCGL values corresponding to the critical confidence level of 5% (the corresponding value to the 95th percentile of the peak dose distribution).

Table 2-2
Comparisons of DCGL (NRC Screening Approach versus the Values Using RESRAD Probabilistic Dose Analysis)

Nuclide	NRC's surface soil screening values (pCi/g)	DCGL - Concentration (pCi/g) equivalent to 25 mrem/y for a specific value of Pcrit (Using Probabilistic RESRAD 6.0)				DCGL from deterministic analysis (RESRAD 6.0)
	From NRC	Based on the mean of peak	Pcrit=0.5	Pcrit=0.10	Pcrit=0.05	Deterministic
H-3	1.1e+2	1.55E+03	1.68E+3	1.05E+3	9.48E+2	1.75e+3
C-14	1.2e+1	3.64E+01	4.01E+01	2.40e+1	2.10e+1	2.19e+1
Fe-55	1.0e+4	5.73E+04	6.60e+4	3.60e+4	3.10e+4	9.73e+4
Co-60	3.8e+0	4.40E-00	5.20e+0	2.80e+0	2.50e+0	2.82e+0
Ni-63	2.1e+3	2.83E+03	4.58E+3	1.51E+3	9.92E+2	5.45e+3
Sr-90	1.7e+0	2.11E-00	4.79e+0	1.40e+0	8.42e-1	5.01e+0
Tc-99	1.9e+1	2.12E+01	3.76e+1	1.18e+1	7.51e+0	5.36e+1
I-129	5.0e-1	8.93E-00	1.91e+1	5.94e+0	3.90e+0	3.85e+1
Cs-134	5.7e+0	6.63E-00	7.53E+0	4.55E+0	3.85E+0	5.01e+0
Cs-137	1.1e+1	1.24E+01	1.59E+1	8.28E+0	6.85E+0	1.10e+1
Ce-144	N/A*	3.19E+02	3.77E+2	2.21E+2	1.85E+2	2.03e+2
Pu-238	2.5e+0	4.73E+01	7.49E+1	2.51E+1	1.71E+1	6.31e+1
Pu-239	2.3e+0	3.68E+01	6.70e+1	2.08e+1	1.47e+1	5.69e+1
Pu-241	7.2e+1	2.19E+03	3.38e+3	1.19e+3	8.04e+2	3.01e+3
Am-241	2.1e+0	3.82E+01	6.10E+01	1.76E+01	1.45E+01	5.30e+1
Cm-243	3.2e+0	3.91E+01	5.39e+1	2.53e+1	1.98e+1	3.95e+1
Cm-244	-	7.02E+01	1.22e+2	3.94e+1	3.11e+1	1.03e+2

* Since Ce-144 was not included in the NRC's list for screening DCGL, the comparison was not given

Figures 2-14 through 2-28 provide a similar comparison of the screening DCGL values with the values derived from RESRAD dose analysis. The peak dose distributions predicted for the given NRC screening DCGL were also compared with the 25mrem/yr criterion.

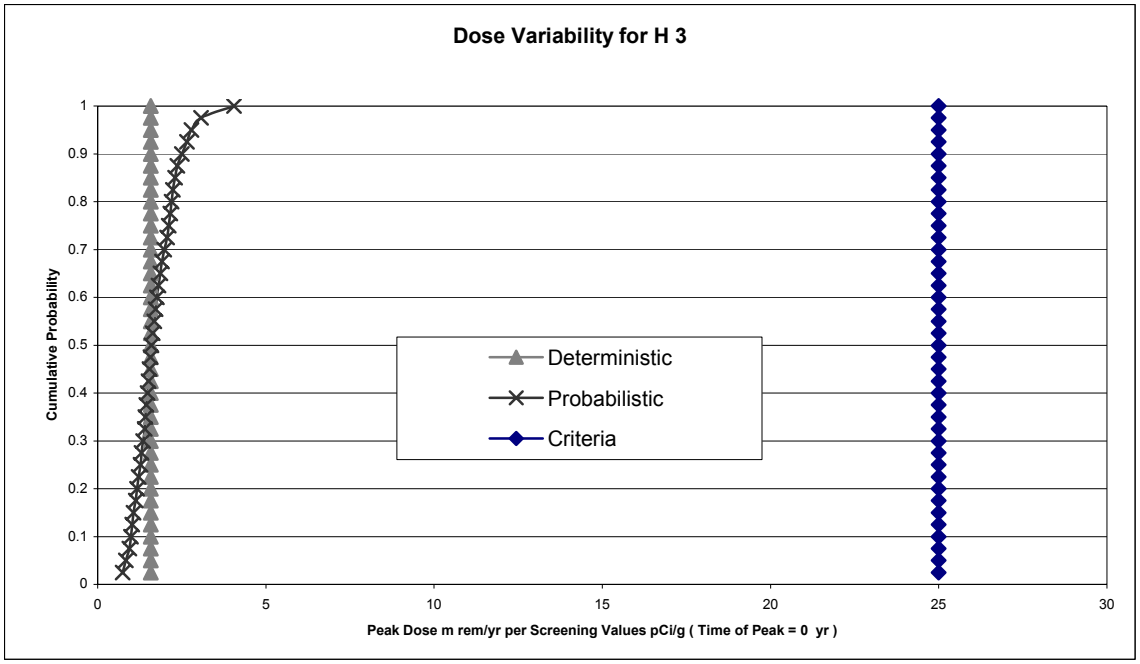

Figure 2-14
Predicted Peak Dose for the NRC Screening DCGL (H-3)

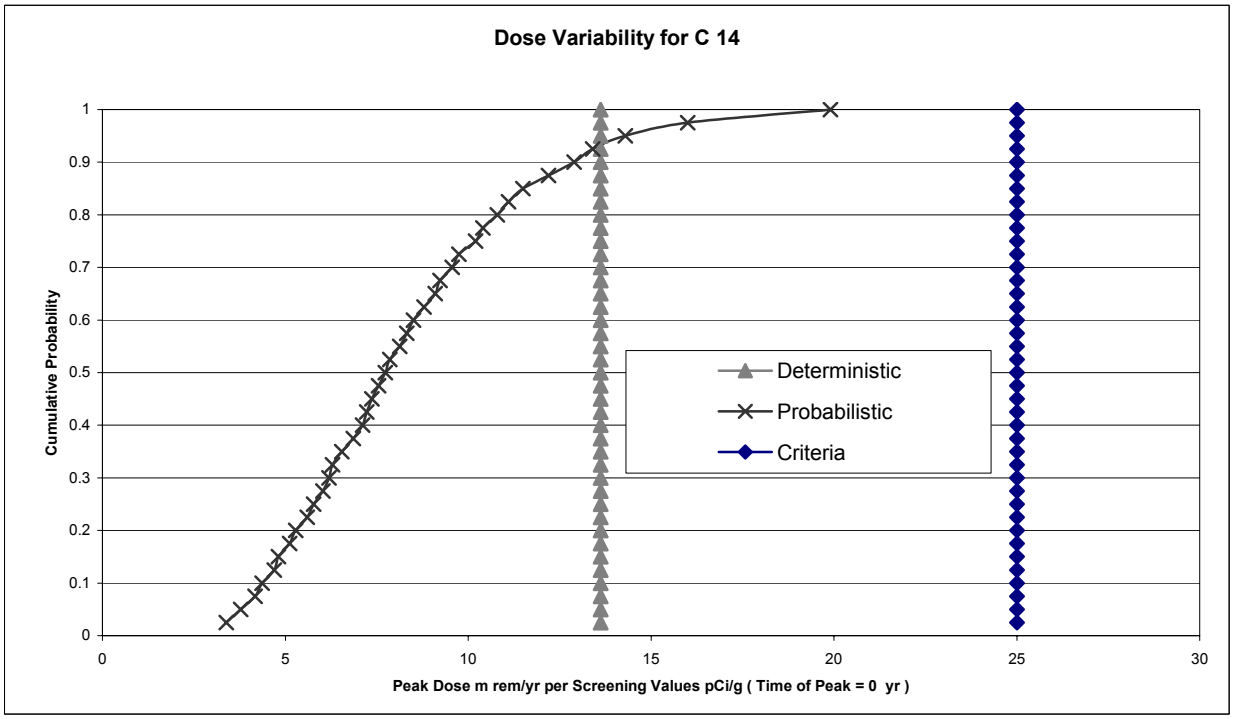

Figure 2-15
Predicted Peak Dose for the NRC Screening DCGL (C-14)

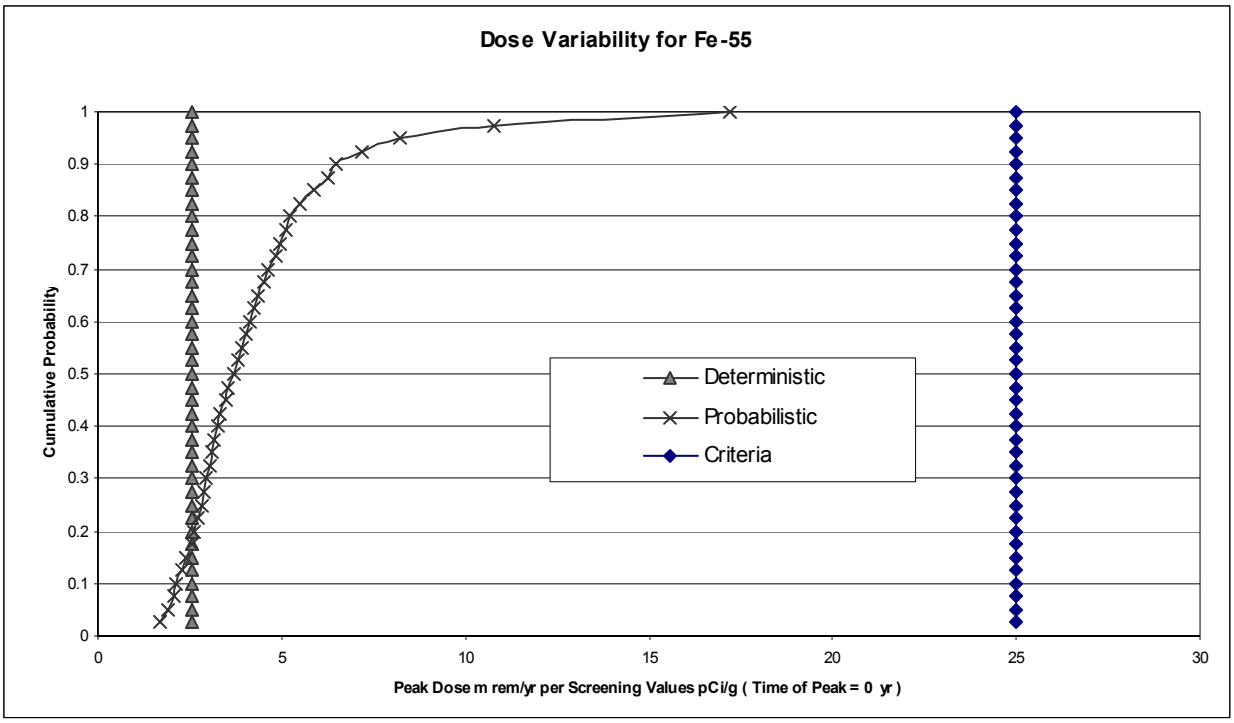

Figure 2-16
Predicted Peak Dose for the NRC Screening DCGL (Fe-55)

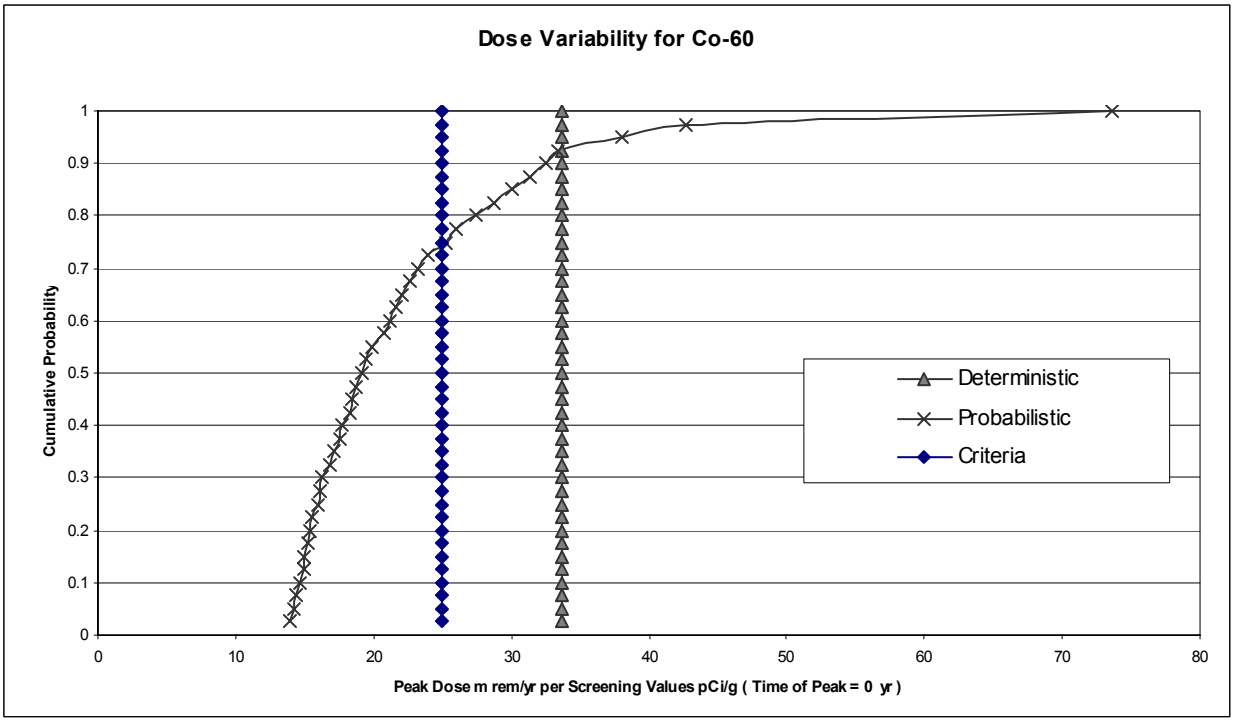

Figure 2-17
Predicted Peak Dose for the NRC Screening DCGL (Co-60)

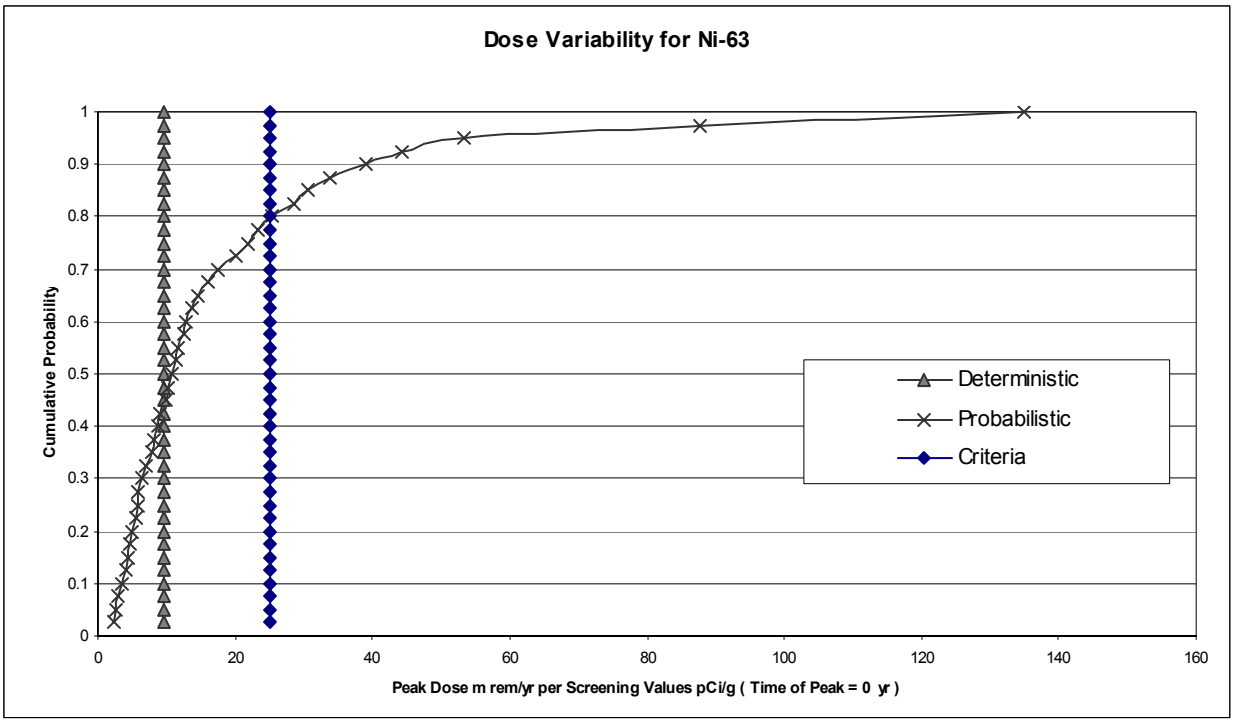

Figure 2-18
Predicted Peak Dose for the NRC Screening DCGL (Ni-63)

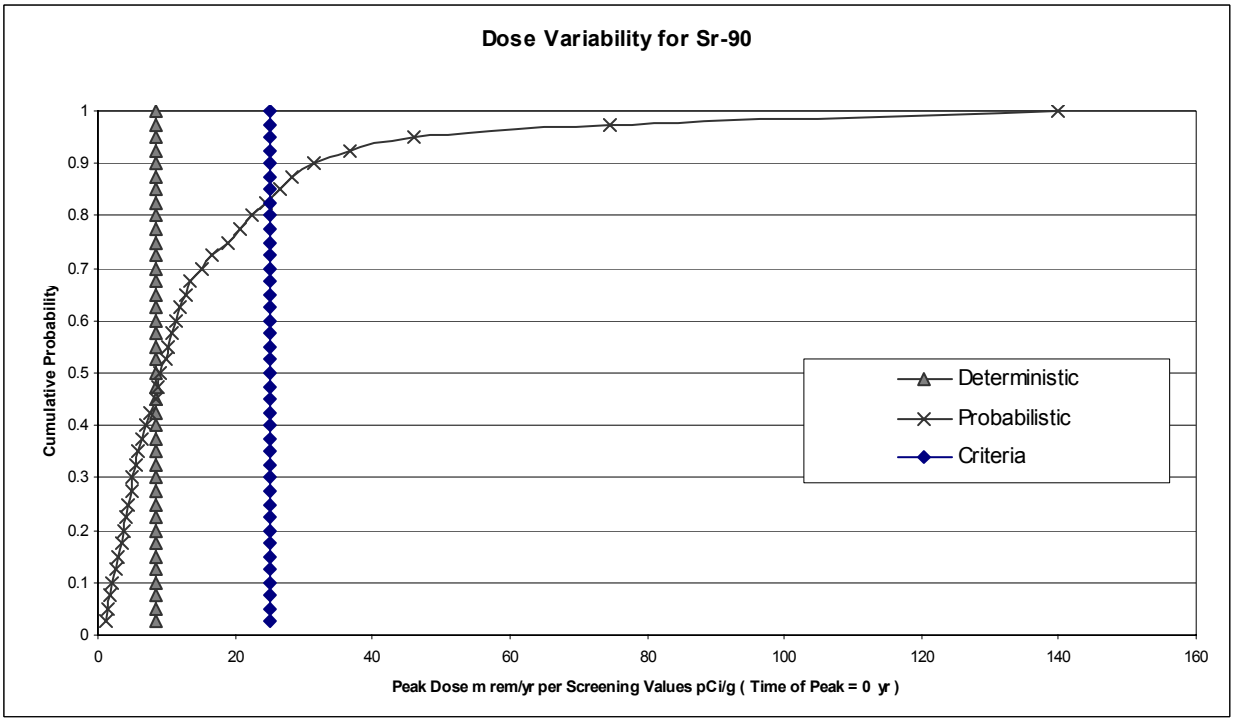

Figure 2-19
Predicted Peak Dose for the NRC Screening DCGL (Sr-90)

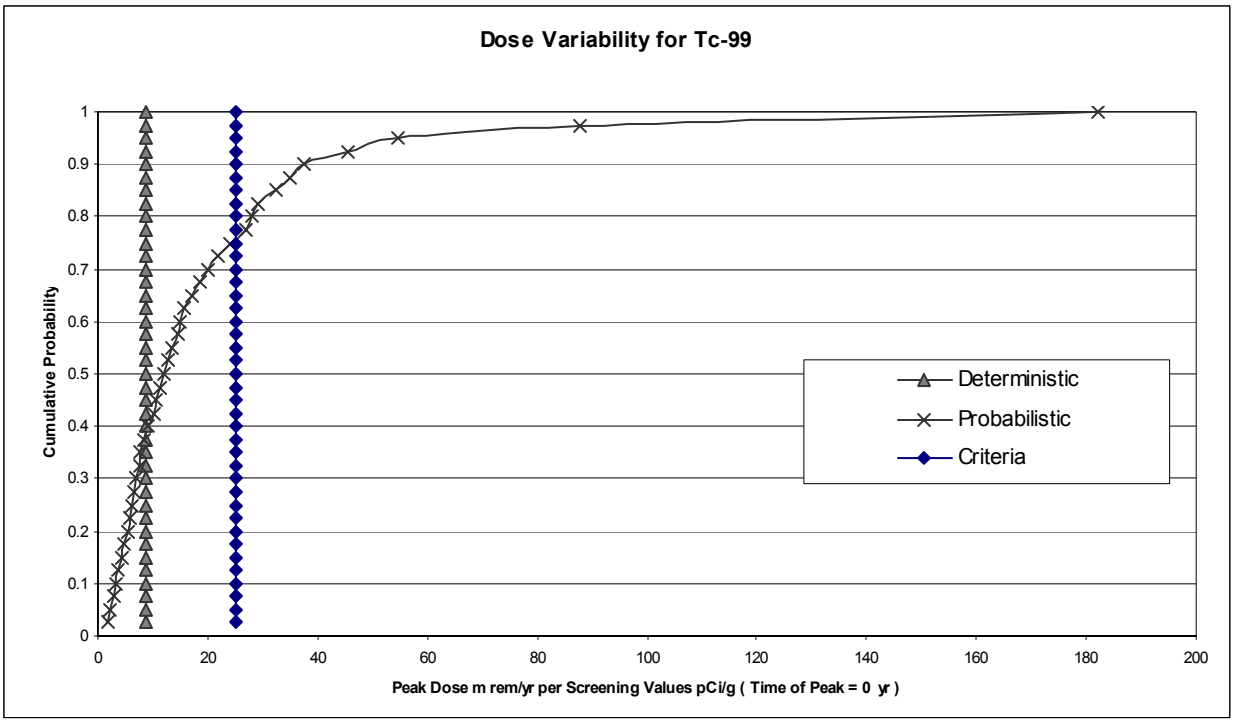

Figure 2-20
Predicted Peak Dose for the NRC Screening DCGL (Tc-99)

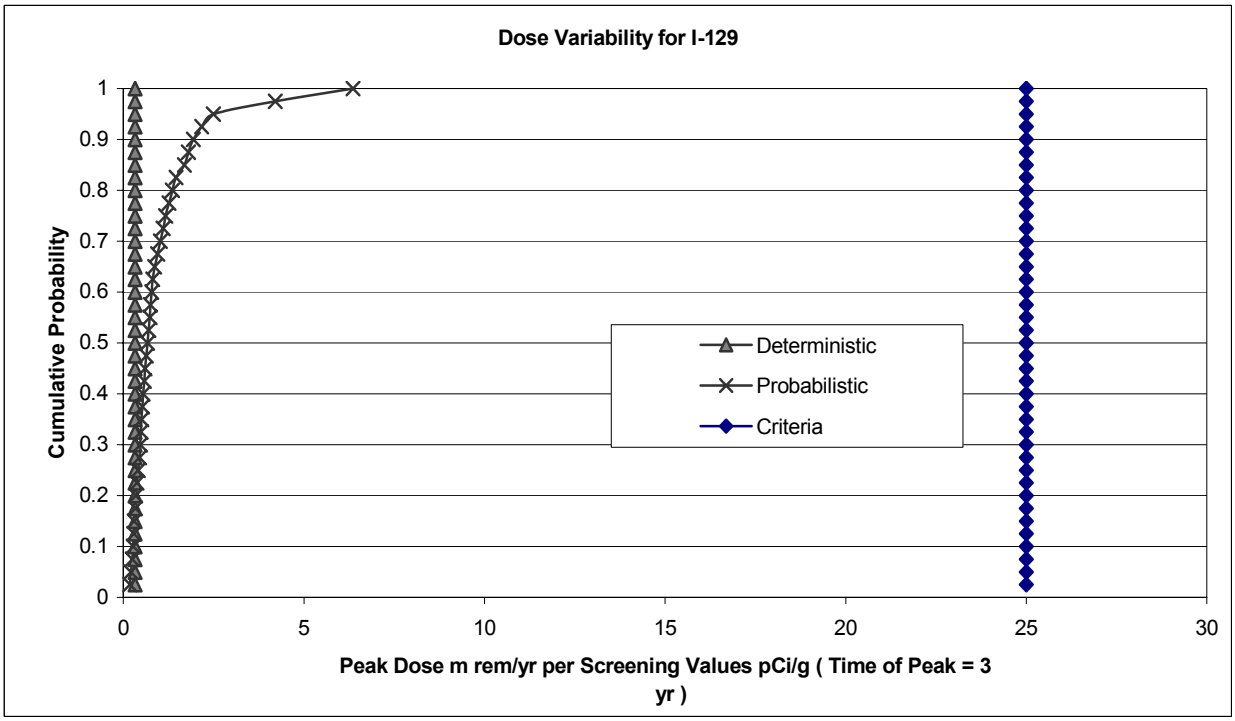

Figure 2-21
Predicted Peak Dose for the NRC Screening DCGL (I-129)

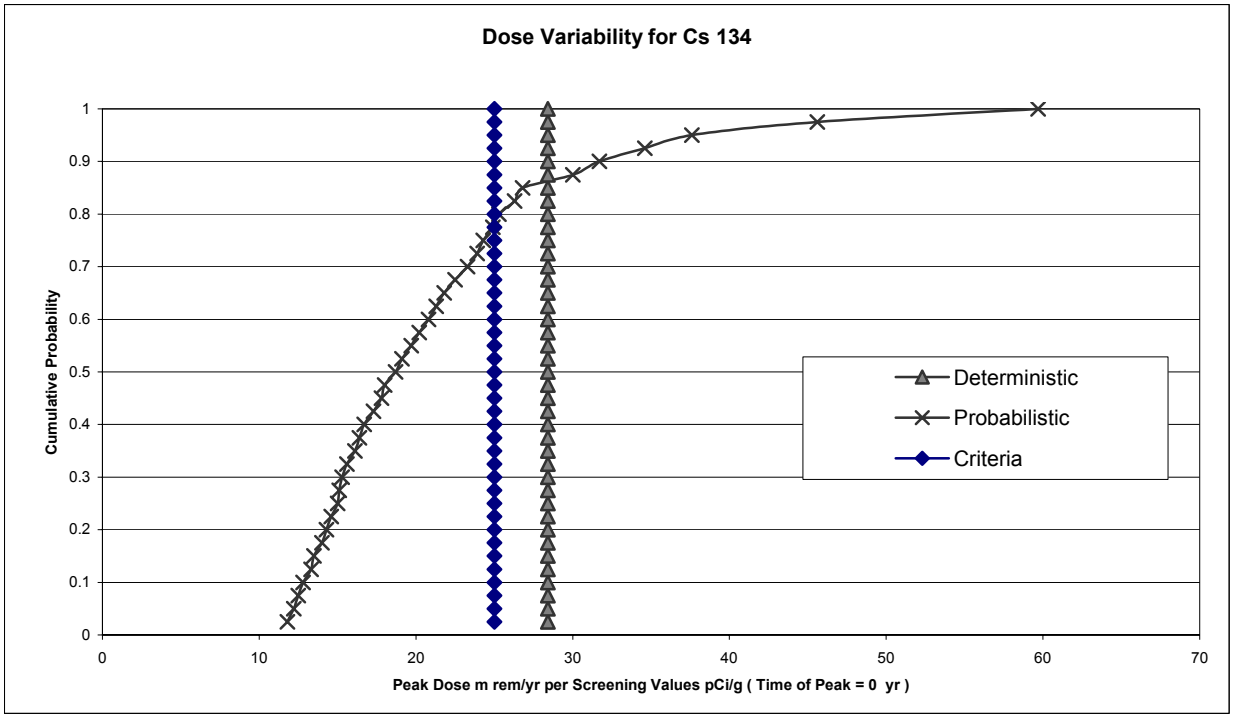

Figure 2-22
Predicted Peak Dose for the NRC Screening DCGL (Cs-134)

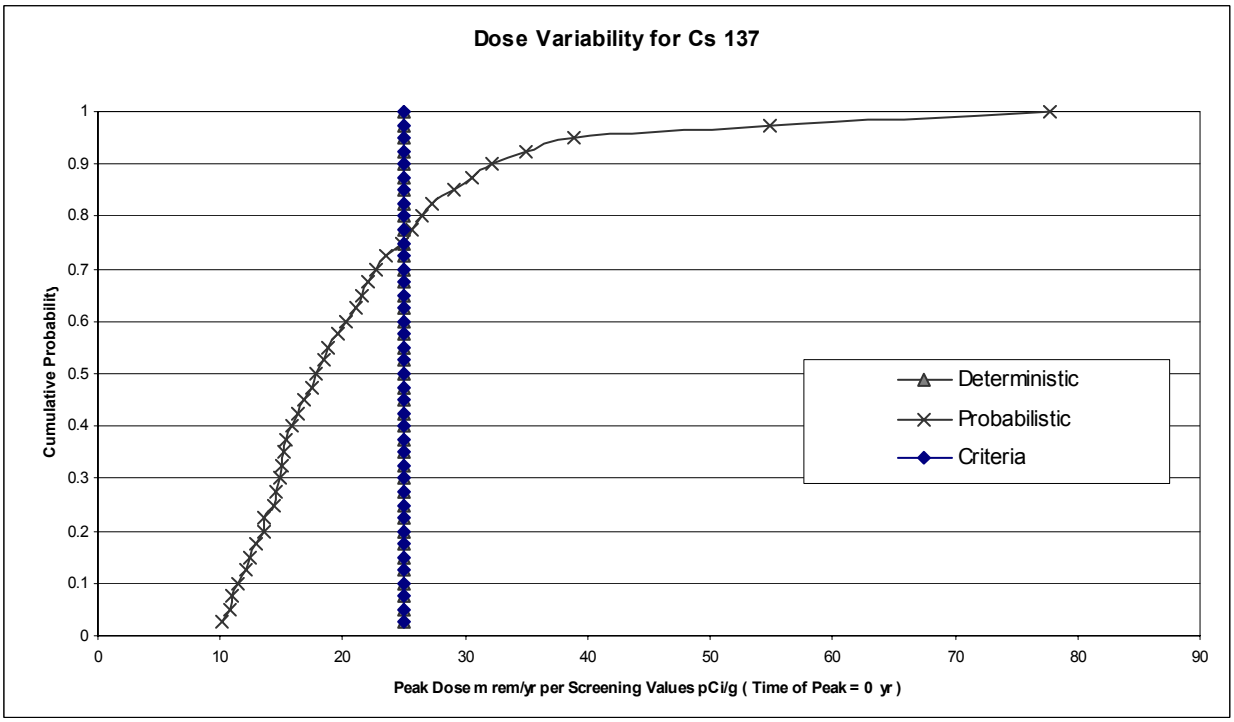

Figure 2-23
Predicted Peak Dose for the NRC Screening DCGL (Cs-137)

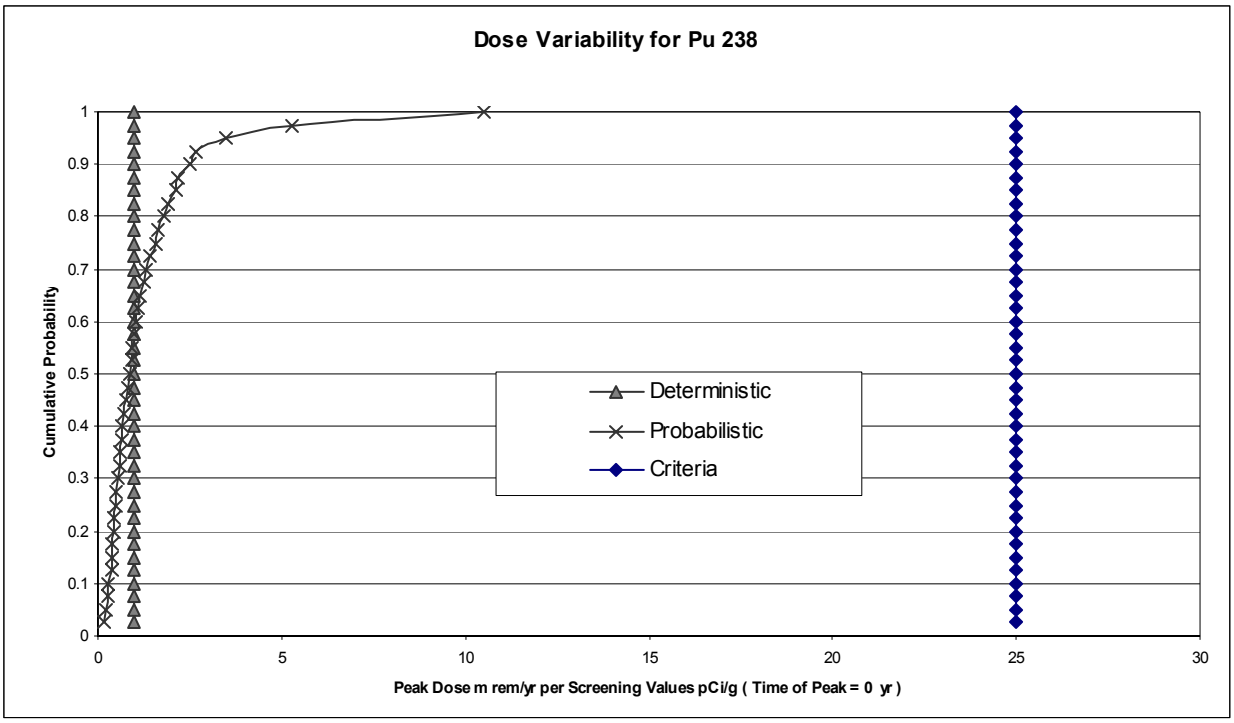

Figure 2-24
Predicted Peak Dose for the NRC Screening DCGL (Pu-238)

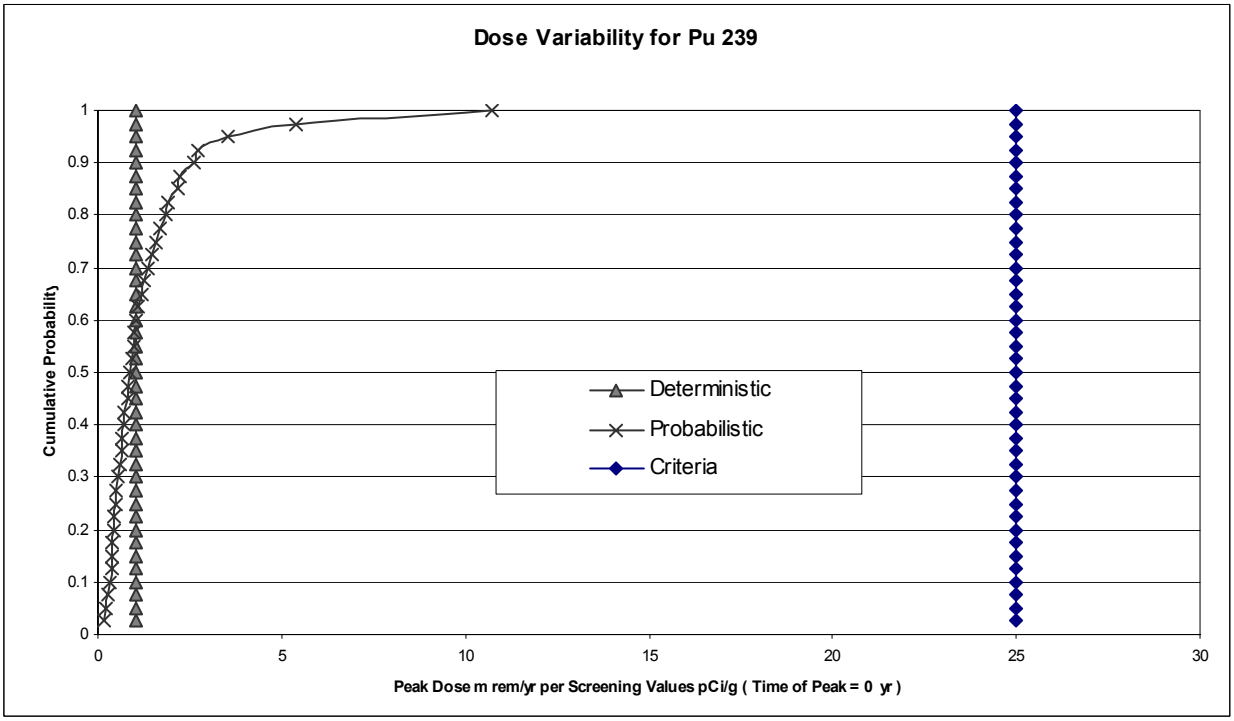

Figure 2-25
Predicted Peak Dose for the NRC Screening DCGL (Pu-239)

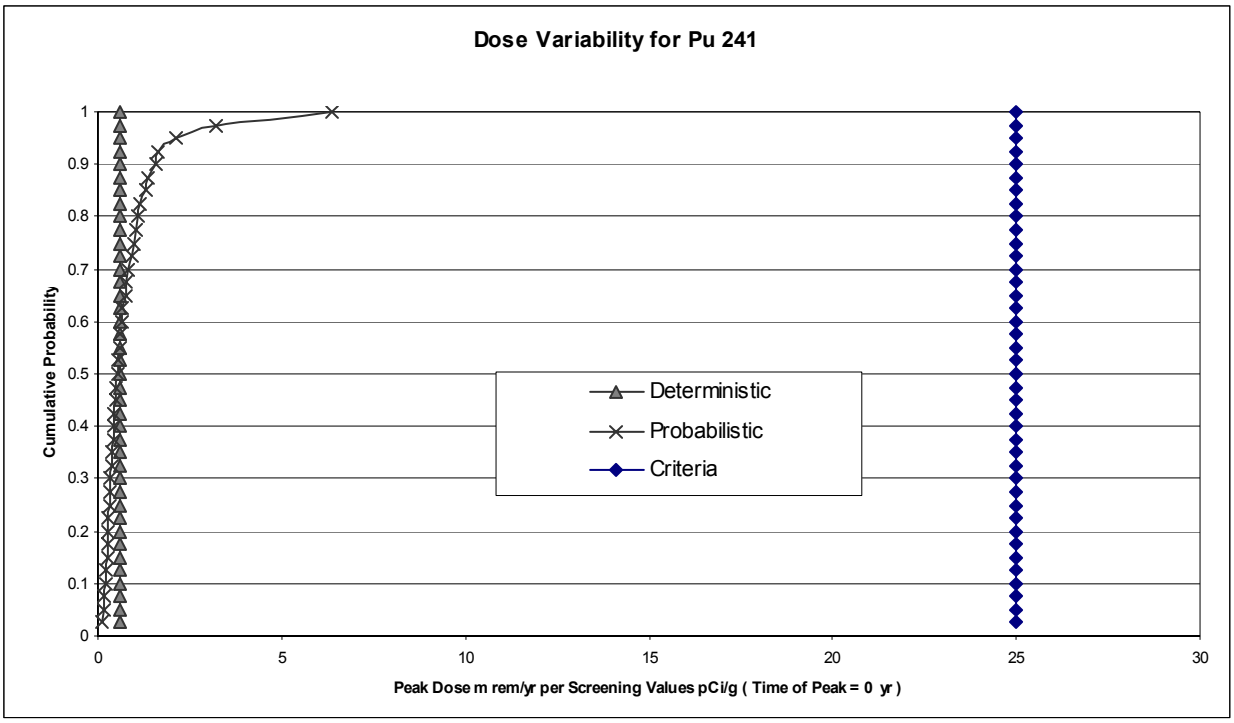

Figure 2-26
Predicted Peak Dose for the NRC Screening DCGL (Pu-241)

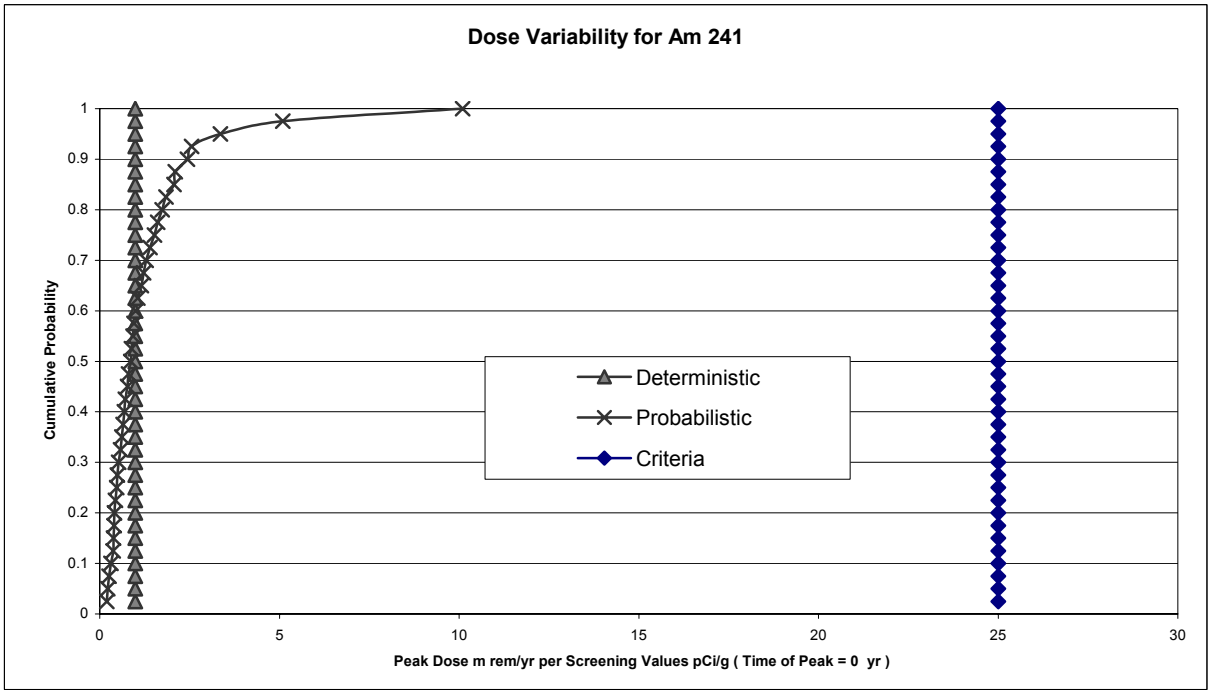

Figure 2-27
Predicted Peak Dose for the NRC Screening DCGL (Am-241)

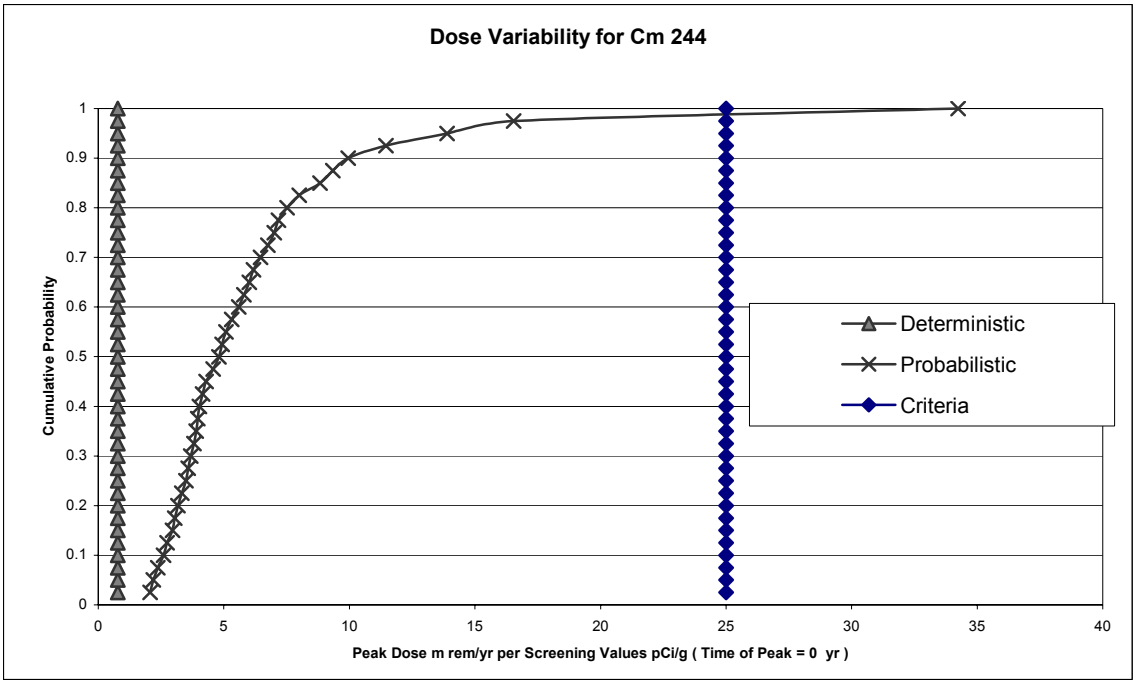

Figure 2-28
Predicted Peak Dose for the NRC Screening DCGL (Cm-244)

3
SITE-SPECIFIC PROBABILISTIC ANALYSIS

The NRC's dose assessment approach is based on a philosophy of moving from simple, prudently conservative calculations toward more realistic simulations, as necessary. if compliance cannot be demonstrated using generic screening analysis, then licensees should proceed to the next phase of analysis in which defensible site specific values are obtained and applied. In a true sense, a site-specific analysis is using scenarios, models, and parameter ranges that are only applicable at a site. However, for a regulatory purpose [NRC, 2000] a site-specific analysis is defined as any dose analysis that is done other than those using the default screening analysis. If a few parameters are changed from the screening methodology, the analysis is defined site-specific. Site-specific data are used to support modifying or eliminating a particular scenario or pathway, or to demonstrate that a parameter or group of parameters can be better represented by site-specific values. Alternative exposure scenarios may be appropriate based on site-specific factors that affect the likelihood and extent of potential future exposure to residual radioactivity. Use of dose assessment for these situations can range from fairly simple site assessments to fairly complex analyses.

In the present study, site-specific dose analysis is narrowly defined as "changes to the default inputs of the RESRAD 6.0 code are made for at least one input parameter in addition to the user-provided site-specific source term information". The following issues are discussed for site-specific analysis:

- Discussion of the key parameters to be considered in a site-specific analysis
- Sources of information for key parameters
- Example computer analyses using site specific parameters

3.1 Key parameters to be considered in a site-specific analysis

The amount of information needed for a site-specific analysis depends on the complexity of the case and the number of site-specific parameters used in the dose analysis. It is prudent to use site-specific information only if the new information results in a difference in the predicted peak dose from the screening dose analysis. In this sense, identification of key parameters that affect the dose prediction in site-specific dose modeling is necessary.

Identifying key parameters in probabilistic dose analysis requires the understanding of the impact of parameter uncertainty range on the predicted dose distributions. This can be performed by using several approaches. These include multivariate linear regression analysis, nominal range sensitivity analysis, probabilistic sensitivity analysis, etc. [Cullen and Frey, 1999].

While correlation coefficients obtained from multivariate regression analysis provide an indication of how the variance in a model output is affected by variance in a model input, probabilistic sensitivity analysis explores the effects of the shape of the input parameter distributions on the changes in the central tendency of the model results. Probabilistic sensitivity analysis involves running simulations in which different subsets of variable and/or uncertain inputs are assigned distributions, while all other inputs are set to their default central value. This approach allows one to identify the effect of interactions among logically-grouped sets of inputs. Since the testing of regulatory compliance by the NRC focuses on the mean of the peak dose or peak of the mean dose, the results from probabilistic sensitivity analysis seem to be more accurate representation of key parameters for the changes of the mean in probabilistic dose analysis.

The key parameters identified from a multivariate linear regression analysis are described in Table 3-1. This is based on the work performed by ANL where the parameter's importance was evaluated by the partial rank correlation coefficients (PRCC). The PRCC estimates the nonlinear monotonic relationship between the output and the input parameters and identifies the contribution of an input parameter to the uncertainties of resultant dose. The results in Table 3 indicate that the external gamma shielding factor and the soil-to-plant transfer factor are the most important among many input parameters.

In the present study, the key parameters were independently identified by using the probabilistic sensitivity analysis. Importance of a parameter was estimated by estimating the range of dose covered between the 5^{th} and 95^{th} percentile dose. Thus the wider the predicted range, the more effect on the peak dose by the input parameter's distribution. The detailed results of this probabilistic sensitivity analysis are shown in Figures 3-1 through 3-13 and the tables in the Appendix (Tables A-1 through A-13). These results are also summarized in the following Table 3-2.

Examining the parameters identified in Table 3-1 and 3-2 tells us that many of the key parameters are actually generic in nature rather than being site-specific. These include time spent indoors and outdoors, shielding factor, plant to meat or milk transfer factor. This is because the exposure scenarios in decommissioning dose analysis are hypothetical. Also the characteristics of future use of the site cannot be exactly determined at the present time. It is also hard to consider the human behavioral parameters such as the consumption of different types of foods as site-specific. Although there may be some regional differences, considering high mobility of the US population, justification of any human food consumption pattern data as site-specific is very difficult.

Due to the variable and uncertain nature of many of the parameters in the list, only few parameters deemed relevant for site-specific analysis. These are the soil-to-plant transfer factor, thickness of unsaturated zone; K_d in the contaminated zone; density of the unsaturated zone, and; contaminated zone total porosity.

Table 3-1
Key Parameters of RESRAD6.0 Identified from Multivariate Linear Regression

	Source area - 100-m2 area & 15-cm thickness	Source area - 10,000-m2 area & 2-m thickness
H-3	Depth of roots; Saturated zone hydraulic conductivity; Saturated zone hydraulic gradient; Thickness of unsaturated zone	Depth of roots; Runoff coefficient; Contaminated zone hydraulic conductivity; Kd in the contaminated zone
C-14	Depth of roots; C-14 evasion layer thickness in soil; Kd in the saturated zone; Kd in the unsaturated zone	Wind speed; Depth of roots; C-14 evasion layer thickness in soil; Kd in the saturated zone
Fe-55	Depth of soil mixing layer; Transfer factor for meat; Soil-to-plant transfer factor; Depth of roots	Transfer factor for meat; Soil-to-plant transfer factor; Depth of roots
Co-60	External gamma shielding factor; Kd in the contaminated zone	External gamma shielding factor; Soil-to-plant transfer factor; Transfer factor for meat
Ni-63	Soil-to-plant transfer factor; Depth of roots; Transfer factor for milk	Soil-to-plant transfer factor; Transfer factor for milk; Depth of roots; Transfer factor for meat
Sr-90	Soil-to-plant transfer factor; Depth of roots; Kd in the contaminated zone; External gamma shielding factor	Soil-to-plant transfer factor; Depth of roots; Transfer factor for meat
Tc-99	Soil-to-plant transfer factor; Depth of roots; Kd in the contaminated zone; Runoff coefficient	Soil-to-plant transfer factor; Depth of roots; Kd in the contaminated zone; Evapotranspiration coefficient
I-129	Soil-to-plant transfer factor; Transfer factor for meat; Depth of roots; Saturated zone hydraulic conductivity	Soil-to-plant transfer factor; Transfer factor for meat; Depth of roots; Saturated zone hydraulic conductivity
Cs-134	External gamma shielding factor; Kd in the contaminated zone	External gamma shielding factor; Soil-to-plant transfer factor; Depth of roots; Transfer factor for meat
Cs-137	External gamma shielding factor; Kd in the contaminated zone	Soil-to-plant transfer factor; External gamma shielding factor; Depth of roots; Transfer factor for meat
Ce-144	External gamma shielding factor	External gamma shielding factor; Soil-to-plant transfer factor
Pu-238	Soil-to-plant transfer factor; Depth of soil mixing layer; Depth of roots; Mass loading factor for inhalation	Soil-to-plant transfer factor; Depth of roots
Pu-239	Soil-to-plant transfer factor; Depth of soil mixing layer; Depth of roots; Mass loading factor for inhalation	Soil-to-plant transfer factor; Depth of roots
Pu-241	Contaminated zone erosion rate; External gamma shielding factor; Kd in the contaminated zone; Depth of roots	Soil-to-plant transfer factor; Depth of roots
Am-241	External gamma shielding factor; Soil-to-plant transfer factor; Depth of roots; Depth of soil mixing layer	Soil-to-plant transfer factor; Depth of roots
Cm-243	External gamma shielding factor; Soil-to-plant transfer factor; Depth of roots; Depth of soil mixing layer	Soil-to-plant transfer factor; External gamma shielding factor; Depth of roots; Transfer factor for milk
Cm-244	Soil-to-plant transfer factor; Depth of soil mixing layer; Depth of roots; Indoor dust filtration factor	Soil-to-plant transfer factor; Depth of roots

Table 3-2
Key Parameters Identified from Probabilistic Sensitivity Analysis (with RESRAD 6.0 based upon the default probabilistic input distributions, in the order of importance)

Nuclide	Key Parameters from the probabilistic sensitivity analysis	Parameters relevant for site-specific analysis
H-3	Human consumption rate of fruit/vegetables/grain; Density of the contaminated zone; Runoff coefficient; Depth of roots Contaminated zone total porosity; Thickness of the unsaturated zone; Kd in the contaminated zone	Density of the contaminated zone; Runoff coefficient; Contaminated zone total porosity; Thickness of the unsaturated zone; Kd in the contaminated zone
C-14	Human consumption rate of fruit/vegetables/grain; Density of contaminated zone; Depth of roots; Thickness of unsaturated zone; Wind speed; Kd in the contaminated zone	Density of the contaminated zone; Thickness of the unsaturated zone; Kd in the contaminated zone
Fe-55	Plant to meat transfer factor; Soil to plant transfer factor; Human consumption rate of fruit/vegetables/grain; Depth of roots	Soil to plant transfer factor
Mn-54	Fraction of time spent indoor; External gamma shielding factor; Soil to plant transfer factor	Soil to plant transfer factor
Co-60	Fraction of time spent indoor; External gamma shielding factor; Soil to plant transfer factor	Soil to plant transfer factor
Ni-63	Soil to plant transfer factor; Plant to milk transfer factor; Depth of roots; Human consumption rate of fruit/vegetables/grain; Human consumption rate of milk; Plant to meat transfer factor	Soil to plant transfer factor
Sr-90	Soil to plant transfer factor; Human consumption rate of fruit/vegetables/grain; Depth of roots; Plant to meat transfer factor	Soil to plant transfer factor
Tc-99	Soil to plant transfer factor; Human consumption rate of fruit/vegetables/grain; Depth of roots; Kd in the contaminated zone; Thickness of unsaturated zone; Contaminated zone total porosity	Soil to plant transfer factor; Kd in the contaminated zone; Thickness of the unsaturated zone; Contaminated zone total porosity
I-129	Thickness of unsaturated zone; Soil to plant transfer factor; Plant to meat transfer factor; Plant to milk transfer factor; Human consumption rate of fruit/vegetables/grain; Depth of roots; Human consumption rate of milk; Kd in contaminated zone; Density of unsaturated zone	Thickness of the unsaturated zone; Soil to plant transfer factor; Kd in the contaminated zone; Density of the unsaturated zone
Cs-134	Fraction of time spent indoor; Soil to plant transfer factor; External gamma shielding factor; Plant to meat transfer factor	Soil to plant transfer factor
Cs-137	Fraction of time spent indoor; Soil to plant transfer factor; External gamma shielding factor; Plant to meat transfer factor	Soil to plant transfer factor
Ce-144	Fraction of time spent indoor; External gamma shielding factor	
Pu-238	Soil to plant transfer factor; Human consumption rate of fruit/vegetables/grain; Depth of roots; Fraction of time spent indoor; Soil ingestion rate	Soil to plant transfer factor
Pu-239	Soil to plant transfer factor; Human consumption rate of fruit/vegetables/grain; Depth of roots; Fraction of time spent indoor; Soil ingestion rate	Soil to plant transfer factor
Am-241	Soil to plant transfer factor; Human consumption rate of fruit/vegetables/grain; Fraction of time spent indoor; Depth of roots; Soil ingestion rate	Soil to plant transfer factor
Cm-244	Soil to plant transfer factor; Human consumption rate of fruit/vegetables/grain	Soil to plant transfer factor

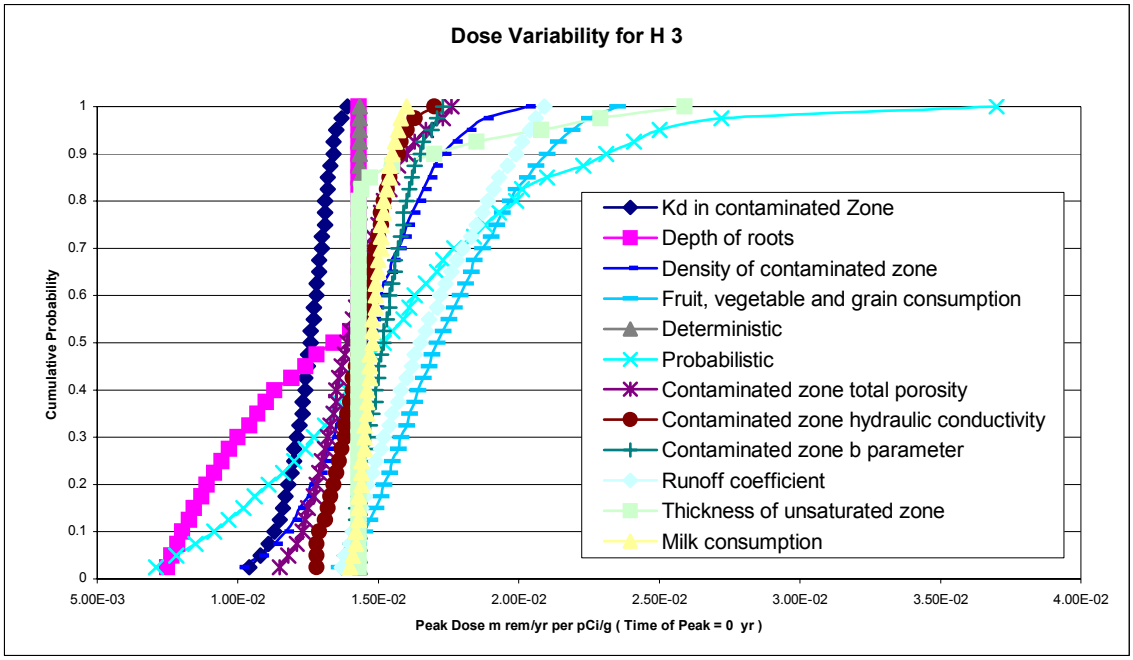

Figure 3-1
Key Parameters in Probabilistic Dose Analysis (H-3)

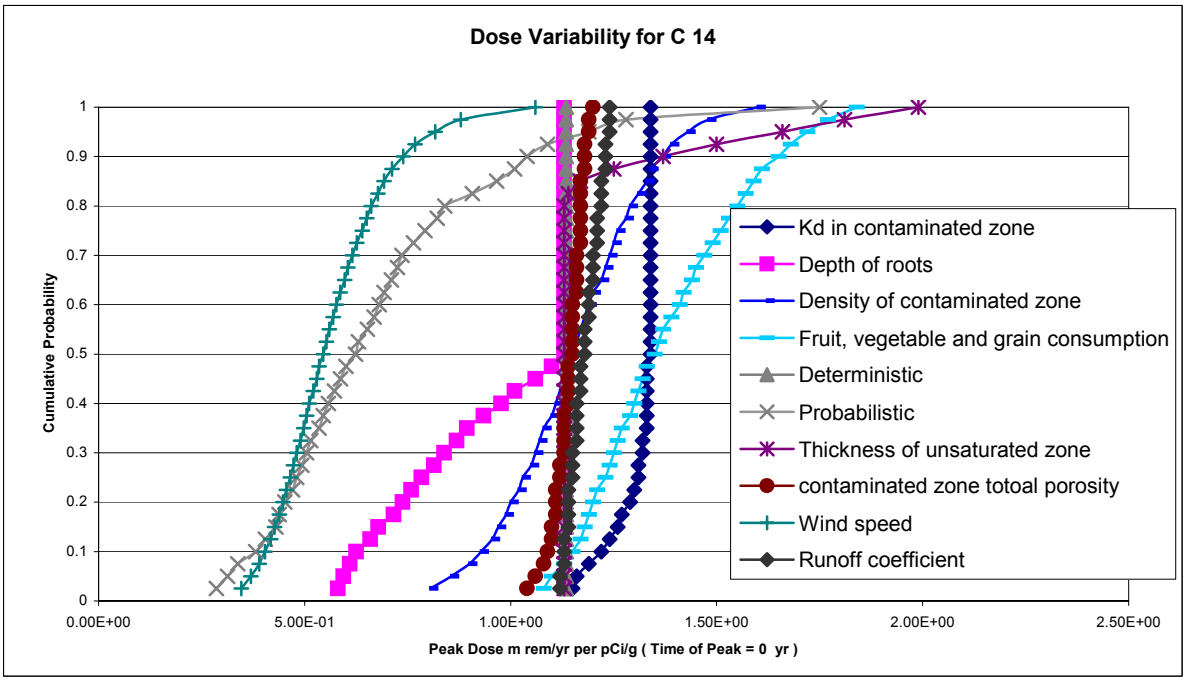

Figure 3-2
Key Parameters in Probabilistic Dose Analysis (C-14)

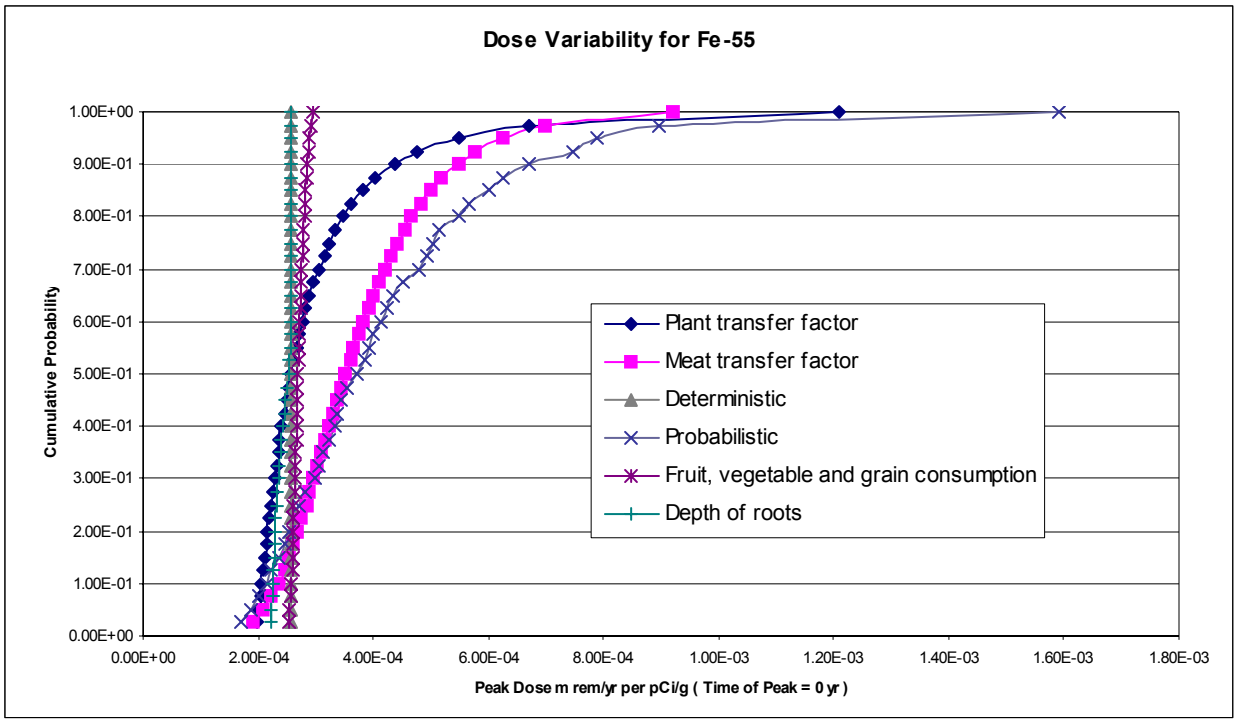

Figure 3-3
Key Parameters in Probabilistic Dose Analysis (Fe-55)

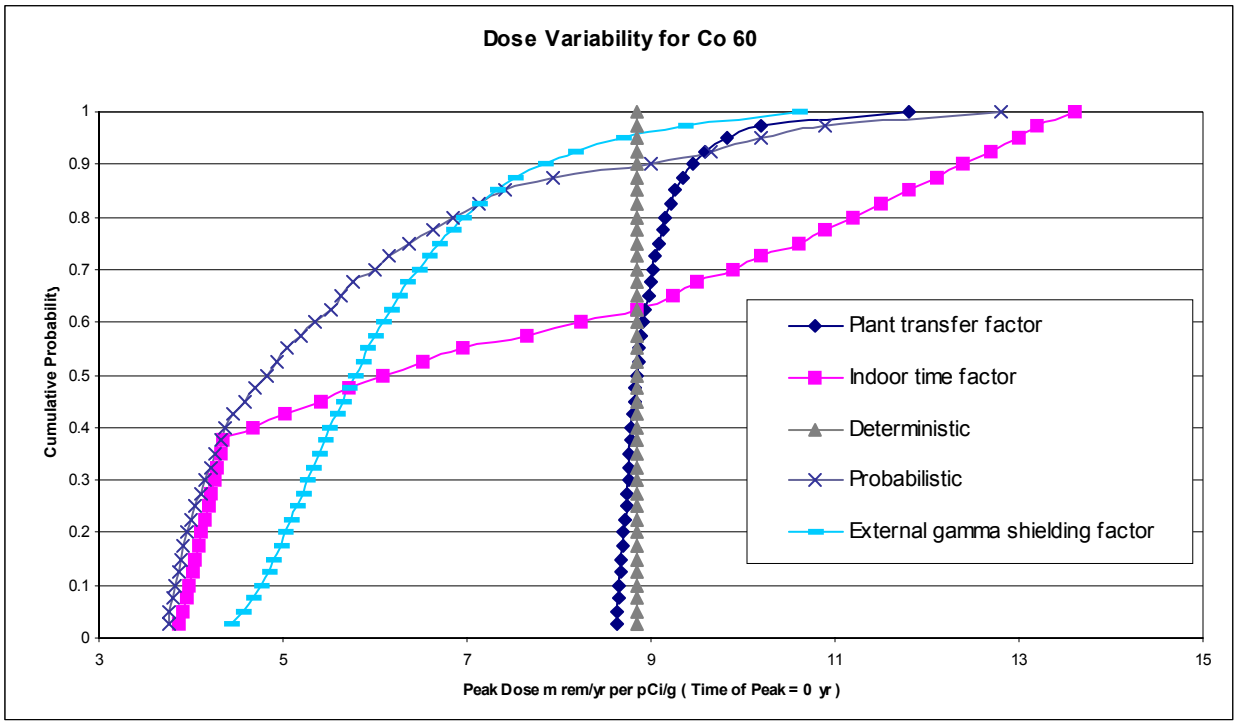

Figure 3-4
Key Parameters in Probabilistic Dose Analysis (Co-60)

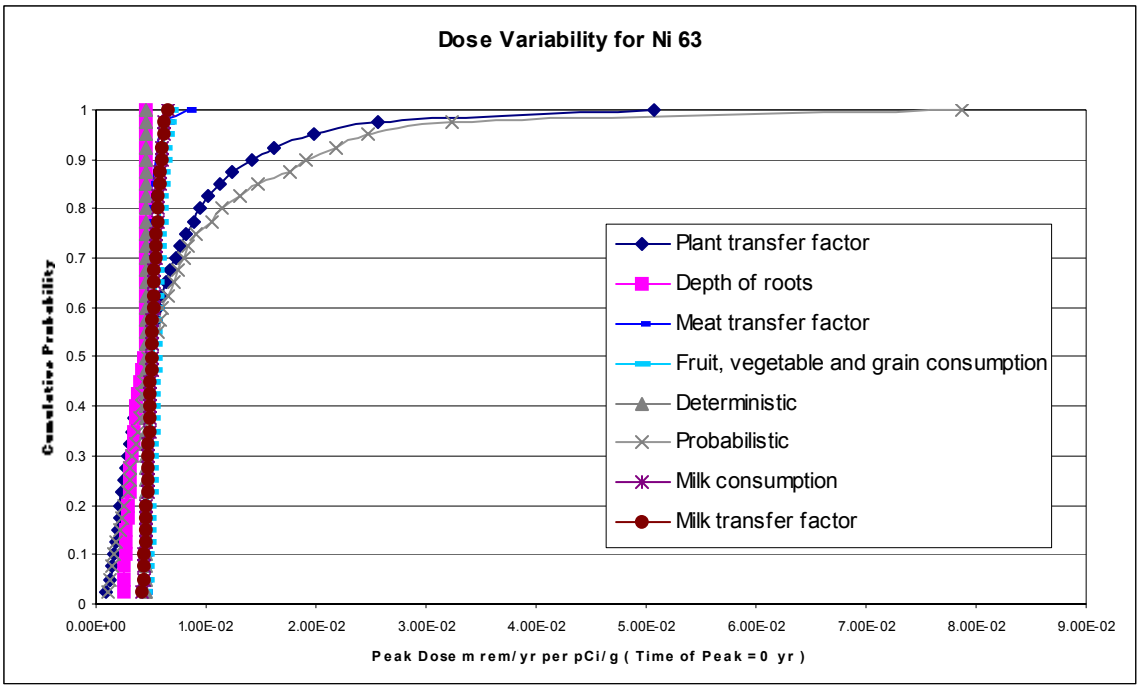

Figure 3-5
Key Parameters in Probabilistic Dose Analysis (Ni-63)

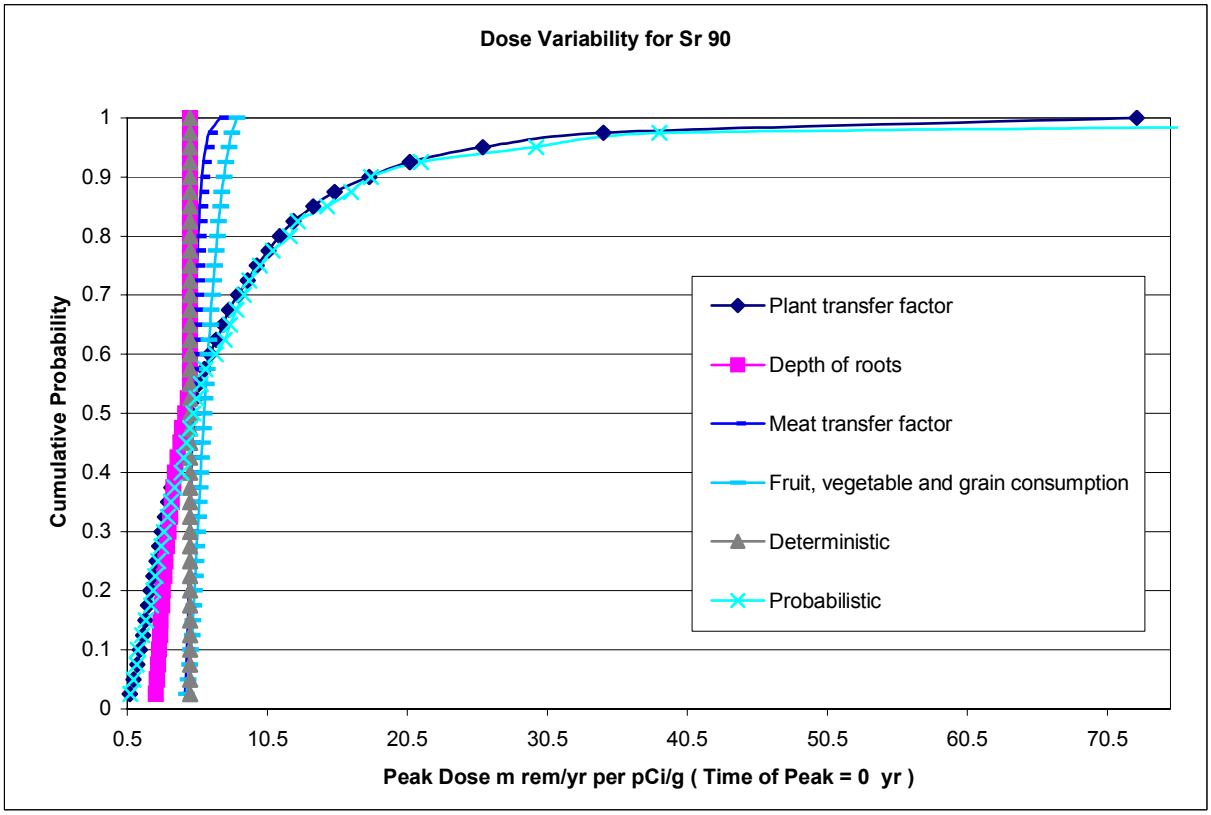

Figure 3-6
Key Parameters in Probabilistic Dose Analysis (Sr-90)

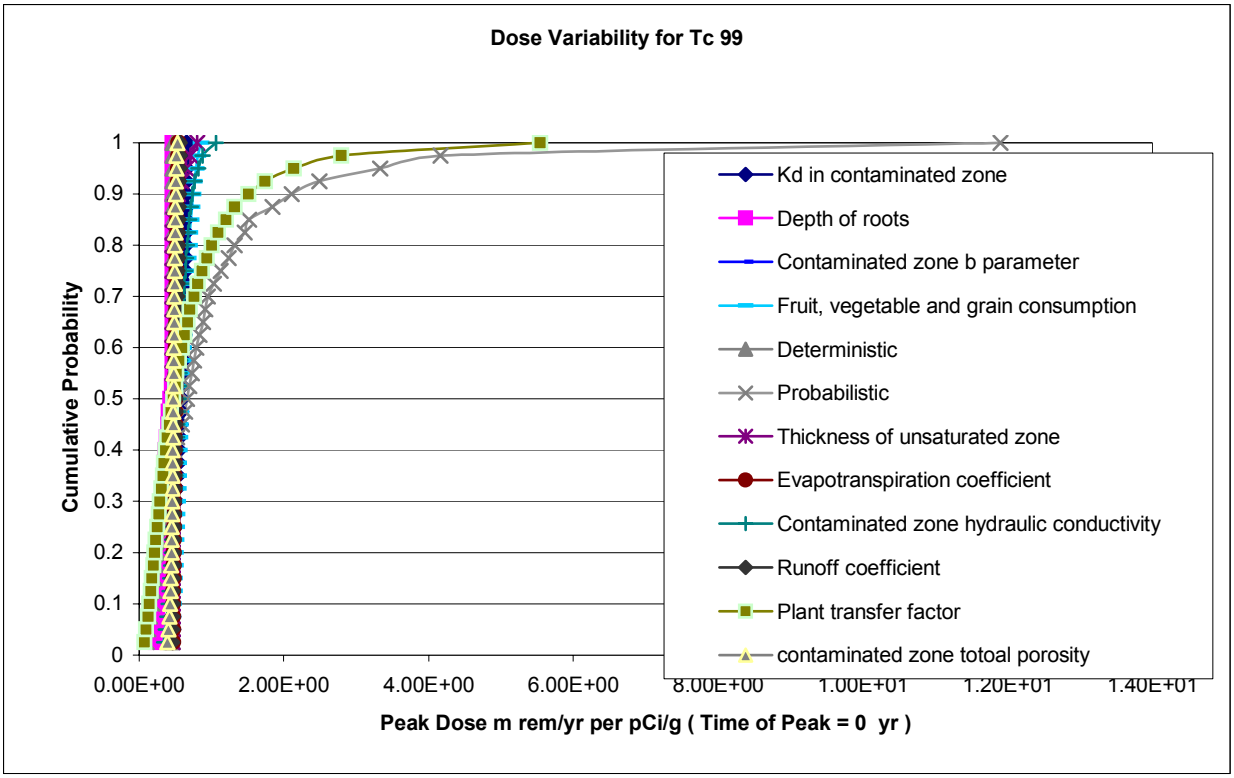

Figure 3-7
Key Parameters in Probabilistic Dose Analysis (Tc-99)

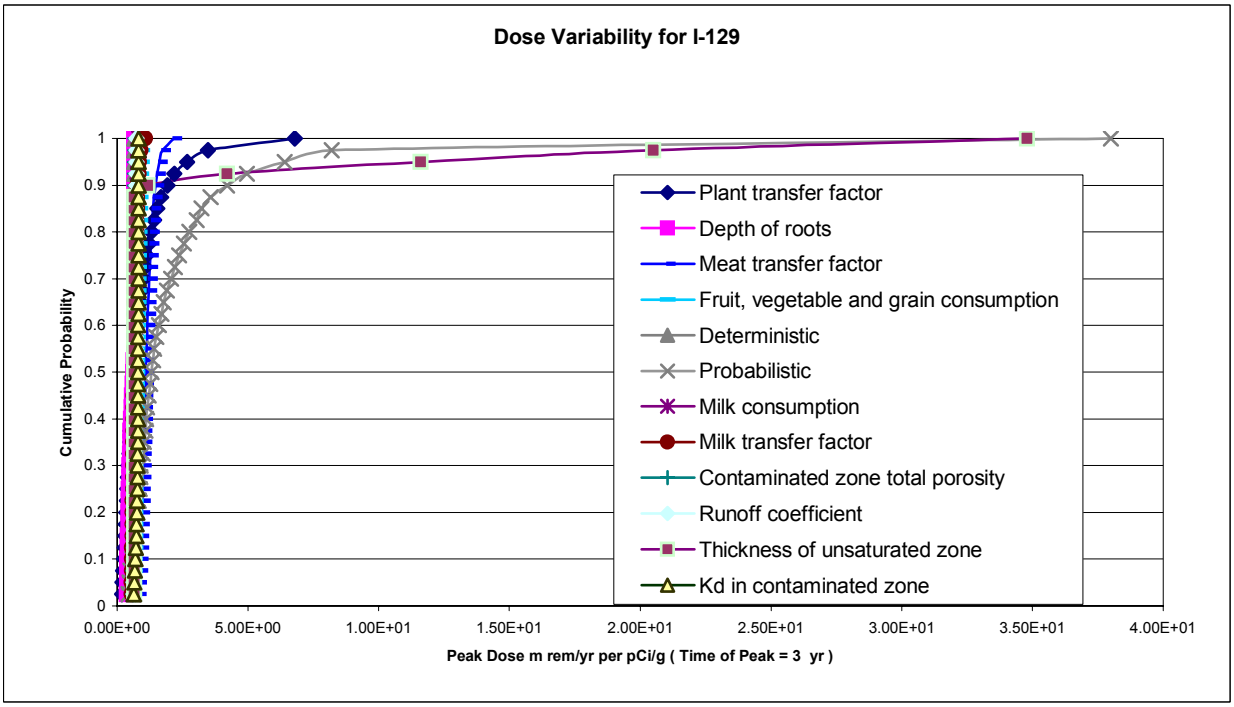

Figure 3-8
Key Parameters in Probabilistic Dose Analysis (I-129)

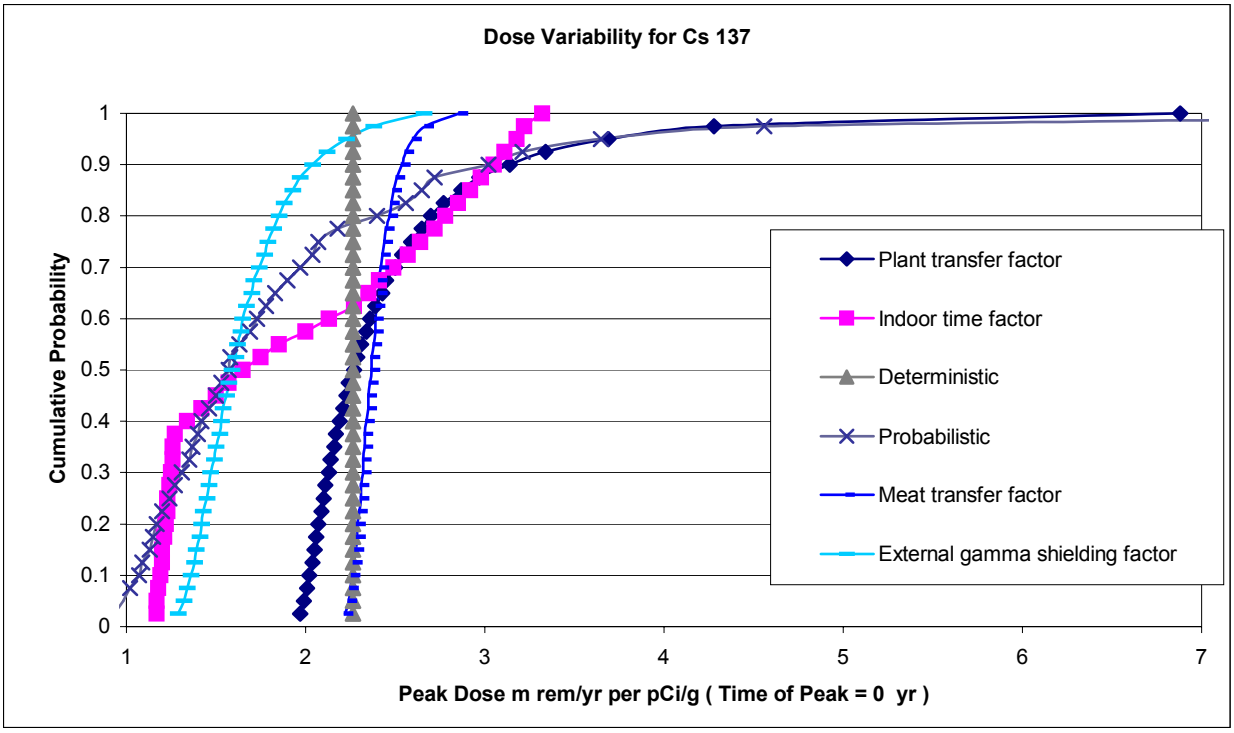

Figure 3-9
Key Parameters in Probabilistic Dose Analysis (Cs-137)

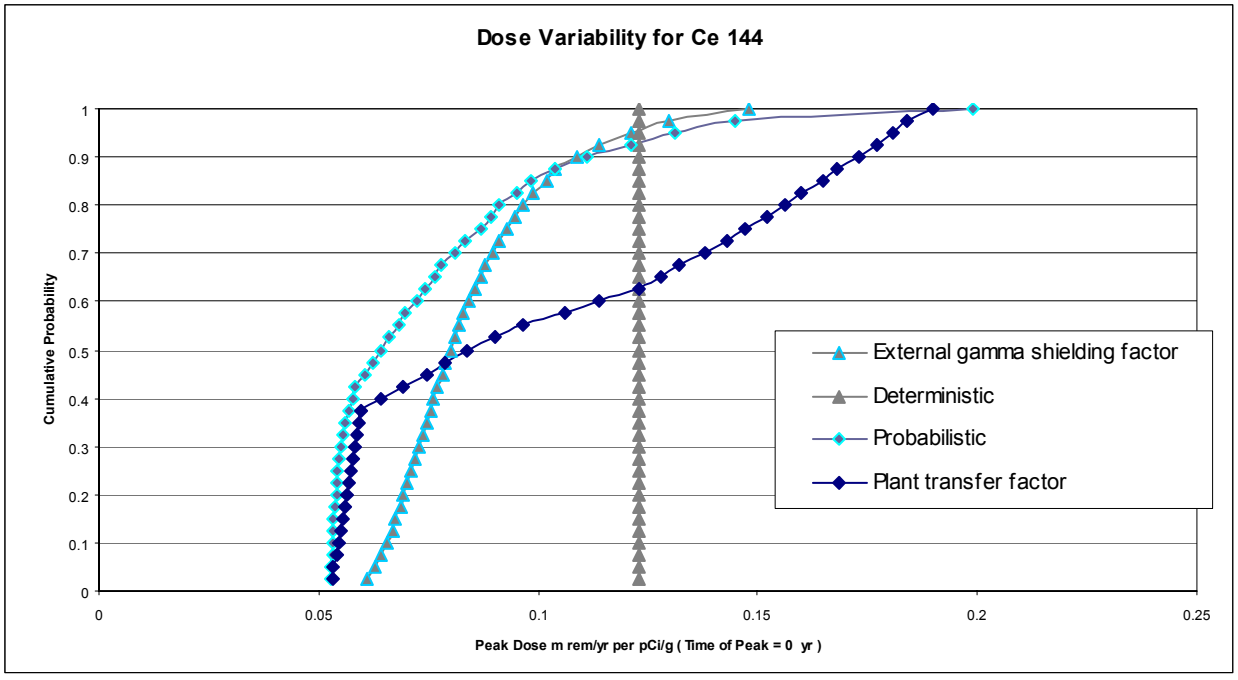

Figure 3-10
Key Parameters in Probabilistic Dose Analysis (Ce-144)

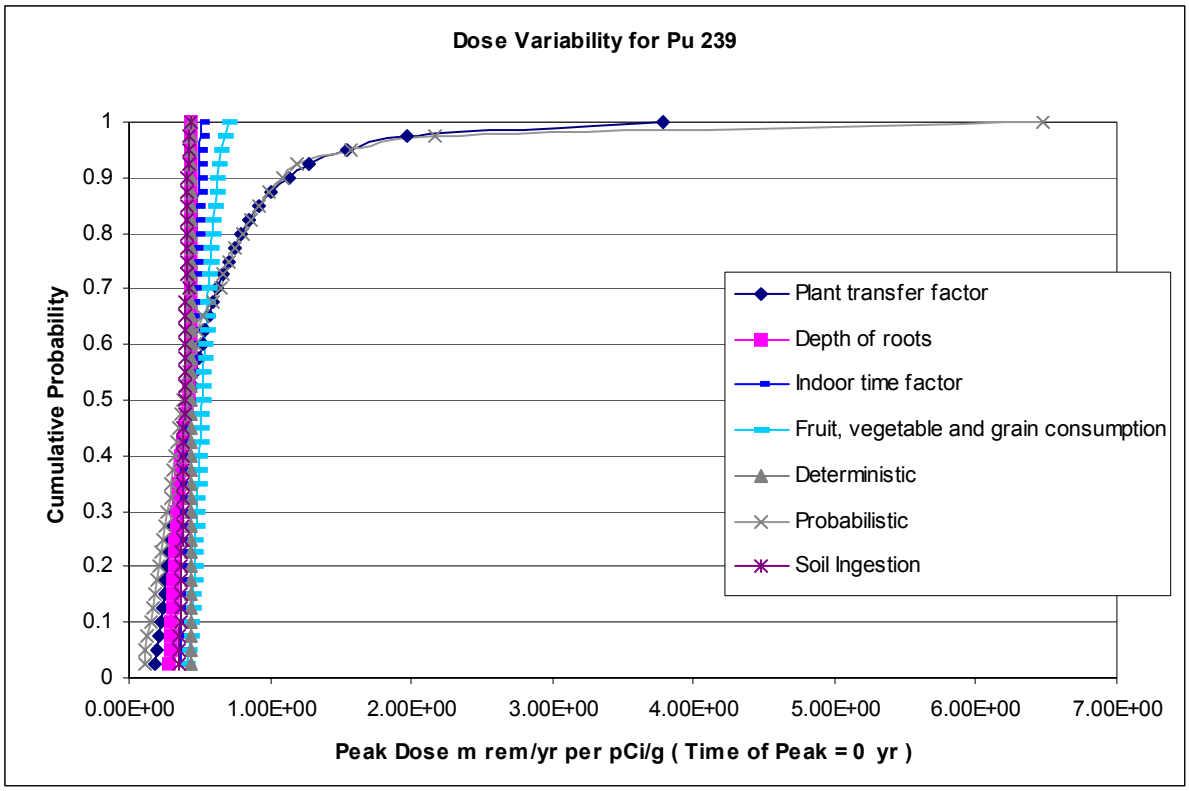

Figure 3-11
Key Parameters in Probabilistic Dose Analysis (Pu-239)

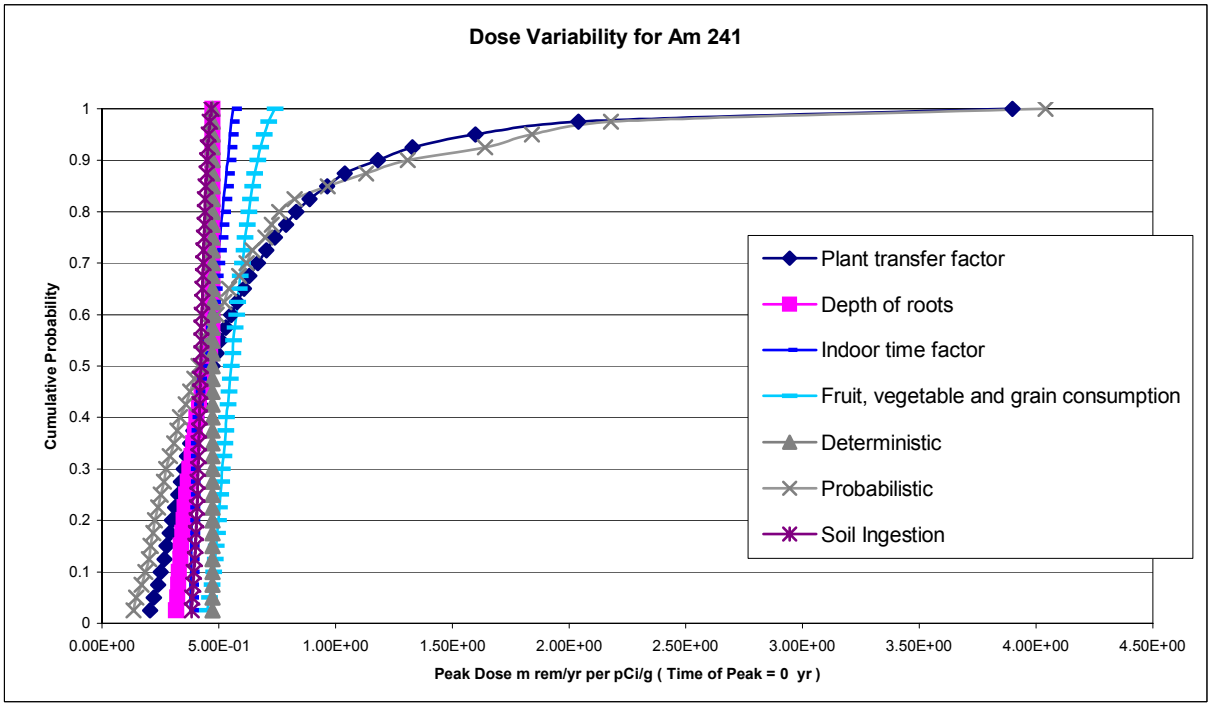

Figure 3-12
Key Parameters in Probabilistic Dose Analysis (Am-241)

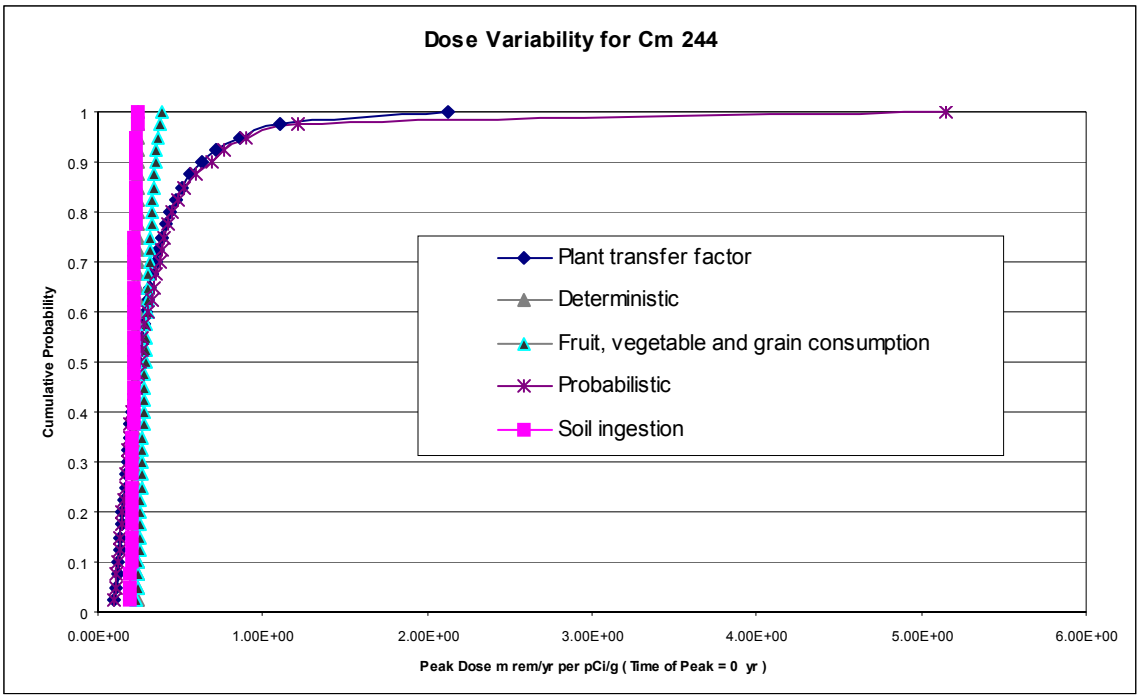

Figure 3-13
Key Parameters in Probabilistic Dose Analysis (Cm-244)

3.2 Sources of information for key parameters

Understanding site features requires field investigations. Some information about physical characteristics of the site, such as thickness of unsaturated zone, can only be obtained from the actual field investigations. Some information can be derived from regional databases relevant to the site. For example, information on the soil type can be available from the USGS database. Determination of soil type enables the characterization of various soil type-specific information such as porosity and density. The soil-type dependent radionuclide-specific parameters such as the K_d value (partition coefficient) and soil-to-transfer factor could be developed using the relevant information available from the literatures.

3.2.1 Porosity, density, saturated hydraulic conductivity

The bulk density of soil can be estimated as a function of soil porosity and the soil particle density as following,

$$\rho_\beta = (1-\varepsilon)\rho_\sigma$$

where ρ_b is the soil bulk density (g/cm^3), ε is the porosity, and ρ_s is the soil particle density. Table 3-3 shows the data from a literature for the porosity and saturated zone hydraulic conductivity for different soil types. In most soils, the mean soil particle density is very close to the density of quartz (2.65 g/cm3), typically the mean component of sandy soils. Clay minerals have a similar density. While the presence of heavy minerals such as iron oxide can increase the mean particle

density or the presence of organic matter can lower it, as a practical matter mean particle density generally varies between 2.6 and 2.7 g/cm3 [Hillel, 1971] and can be represented as a constant of 2.65 g/cm3.

Table 3-3
Estimated Values of Porosity and Saturated Hydraulic Conductivity for Different Soil Textures [Carsel and Parrish, 1988]

Soil Type	Porosity		K_{sat}, Saturated hydraulic conductivity (cm/sec)		Number of samples
	Mean	Standard Deviation	**Mean**	Standard Deviation	
Sand	0.43	0.06	8.22e-03	4.49e-03	246
Loamy sand	0.41	0.09	3.99e-03	3.17e-03	315
Sandy loam	0.41	0.09	1.17e-03	1.37e-03	1183
Sandy clay loam	0.39	0.07	3.23e-04	5.98e-04	214
Loam	0.43	0.10	2.92e-04	4.91e-04	735
Silt loam	0.45	0.08	9.33e-05	2.24e-04	1093
Silt	0.46	0.11	4.89e-05	2.76e-05	82
Clay loam	0.41	0.09	9.93e-05	2.51e-04	364
Silty clay loam	0.43	0.07	1.54e-05	3.38e-05	641
Sandy clay	0.38	0.05	3.55e-05	1.48e-04	46
Silty clay	0.36	0.07	2.19e-06	4.08e-06	374
Clay	0.38	0.09	3.65e-05	1.08e-04	400

The CONSUS-SOIL database electrically accessible through Pennsylvania State University (from http://www.essc.psu.edu) is a composite summary of detailed soil databases (STATSGO databases) for states in the continental US. This CONUS-SOIL database generalizes a variety of soils data, including the USDA soil texture, on a 1 km grid with constant layering.

3.2.2 Soil to plant transfer factor

Soil-to-plant transfer factor represents the extent to which plants absorb radionuclides from soil. It is defined as the quotient of the activity concentration in the plant, expressed on a fresh or dry mass basis, to that in the bulk soil, expressed on a dry mass basis. To reduce the variability caused by differences in the moisture content within the same crop, soil-to-transfer factor can be expressed on a dry mass basis. For dose modeling purposes, conversion to fresh mass is needed.

The soil-to-plant factor depends on the chemical form of the nuclide, its distribution coefficient, the metabolic requirements of the plant, and physicochemical factors in the soil. The form most tightly bound to soil (highest Kd) are also those which exhibit the lowest relative uptake by plants.

A review by Sandia National Lab [Beyeler, et al., 1999] on the soil-to-plant transfer factors states that it is not likely that site-specific information can reduce the uncertainty in concentration factors. This was based on a study done by AECL [Sheppard and Evenden, 1990] where it was observed that the inclusion of environmental variables, such as soil texture and pH, reduces the variability in concentration factors only marginally. The AECL study was based on a 64-site field survey for 23 elements.

However, a more recent study focused on Cs and Sr [Nisbet and Woodman, 2000] found significant relationships between transfer factors for radiostrontium and cesium and soil pH/organic matter status for a few soil-crop combinations accounting for more than 30% of the variability in transfer factor. The study was based on the compilation of database for arable crops from published and unpublished sources as sub-divided into 28 soil-crop combinations, covering four soil types and seven crop groups. Best estimate transfer factors for Cs and Sr were then calculated for the edible parts of the plants. Table 3-4 and 3-5 show the results.

Table 3-4
Geometric Mean and 95% Confidence Intervals for Soil-to-Plant Transfer Factor of Cesium for edible crop parts (Bq/kg dry mass plant per Bq/kg dry mass soil)

Crops	Soil	Number of observations	Number of studies	Geometric mean	95% confidence interval, lower	95% confidence interval, upper
Cereals	Sand	208	25	2.1e-2	1.7e-3	2.5e-1
	Loam	358	23	1.4e-2	4.5e-4	4.2e-1
	Clay	49	11	1.1e-2	5.7e-4	2.1e-1
	Organic soil	54	7	4.3e-2	3.8e-3	4.9e-1
Tubers	Sand	89	13	1.1e-1	1.4e-2	8.9e-1
	Loam	173	14	2.9e-2	2.9e-3	2.8e-1
	Clay	20	5	2.9e-2	3.4e-3	2.5e-1
	Organic soil	15	5	5.5e-2	6.0e-3	5.1e-1
Green vegetables	Sand	72	7	2.1e-1	2.6e-2	1.7
	Loam	100	12	1.2e-1	1.2e-2	1.2
	Clay	34	5	6.6e-2	7.6e-3	5.8e-1
	Organic soil	7	2	2.9e-1	1.6e-2	5.5
Root vegetables	Sand	38	9	5.4e-2	8.7e-3	3.3e-1
	Loam	52	11	3.7e-2	1.5e-3	9.0e-1
	Clay	13	3	2.2e-2	3.5e-3	1.4e-1
	Organic soil	12	4	7.9e-2	3.3e-3	1.9

Table 3-5
Geometric Mean and 95% Confidence Intervals for Soil-to-Plant Transfer Factor of Strontium for edible crop parts (Bq/kg dry mass plant per Bq/kg dry mass soil)

Crops	Soil	Number of observations	Number of studies	Geometric mean	95% confidence interval, lower	95% confidence interval, upper
Cereals	Sand	112	13	2.3e-1	3.0e-2	1.7
	Loam	88	13	1.5e-1	2.2e-2	9.4e-1
	Clay	21	5	7.1e-2	2.2e-2	2.3e-1
	Organic soil	7	3	3.0e-2	7.4e-3	1.2e-1
Tubers	Sand	44	11	2.3e-1	3.9e-2	1.4
	Loam	33	10	2.1e-1	5.3e-2	8.6e-1
	Clay	9	3	9.4e-2	2.8e-2	3.1e-1
	Organic soil	4	4	1.7e-2	5.1e-3	5.5e-2
Green vegetables	Sand	54	6	3.2	4.5e-1	2.2e+1
	Loam	75	7	2.4	6.5e-1	9.1
	Clay	27	4	1.8	8.3e-1	4.0
	Organic soil	1	1	3.3e-1	-	-
Root vegetables	Sand	32	9	1.5	1.2e-1	2.0e+1
	Loam	29	7	1.6	1.9e-1	1.3e+1
	Clay	6	2	1.4	3.4e-1	5.5
	Organic soil	3	2	1.6e-1	9.4e-2	2.6e-1

3.2.3 Partition coefficient (K_d)

Both the multivariate regression analysis and probabilistic sensitivity analysis indicated that the K_d values are important for certain nuclides in probabilistic dose analysis. The values of K_d for nuclides have been compiled by several agencies. However, most of the information is not soil-type specific. Only a limited amount of information is available for soil-type specific values. This soil-type specific information is summarized in Table 8. In this table [Sheppard and Thibault, 1990], three mineral soils were categorized by texture into sand, clay, and loam. The soils that contained more than 70% sand-sized particles were classified as sand soils, and those containing more than 35% clay-sized particles were classified as clay soils. Loam soils had an even distribution of sand-, clay-, and silt-sized particles or consisted of up to 80% silt-sized particles. Organic soils contained more than 30% organic matter and were either classic peat or muck soils, or the litter horizon of a mineral soil.

Table 3-6
Estimated Values of Soil-Specific K_d Values [Sheppard and Thibault, 1990]

Element	Sand		Loam		Clay		Organic	
	geometric mean	geometric standard deviation	geometric mean	geometric standard deviation	geometric mean	geometric standard deviation	geometric mean	geometric standard deviation
Am	1,900	2.6 (16)	9,600	1.4 (20)	8,400	2.6 (11)	112,000	1.7 (5)
C	5	0.8 (3)	20		1		70	
Ce	500	1.6 (12)	8,100	1.5 (5)	20,000	0.5 (4)	3,300	(1)
Cm	4,000	2.4 (2)	18,000	0.7 (4)	6,000		6,000	(1)
Co	60	2.8 (33)	1,300	1.3 (23)	550	1.8 (15)	1,000	1.5 (6)
Cs	280	2.5 (81)	4,600	1.3 (54)	1,900	1.6 (28)	270	3.6 (9)
Fe	220	2.6 (16)	800	0.7 (18)	165	1.6 (7)	600	(1)
H	0.06	0.4 (3)	20		30		75	
I	1.0	2.2 (22)	5	2.0 (33)	1	1.5 (8)	25	2.0 (9)
Ni	400	1.5 (11)	300		650	0.7 (10)	1,100	0.9 (6)
Pu	550	1.7 (39)	1,200	1.2 (21)	5,100	2.1 (18)	1,900	2.6 (7)
Sr	15	1.6 (81)	20	1.7 (43)	110	2.0 (24)	150	1.8 (12)
Tc	0.1	1.8 (19)	0.1	1.1 (10)	1	0.06 (4)	1	1.8 (24)

* If no data existed for a given element, the soil-to-plant transfer factor was used as an indicator of the element's mobility and to predict a Kd value.

A good amount of information for the assessment of soil-type specific Kd values of several elements has also been compiled in a recent EPA study [EPA, 1999]. The study presented the K_d values of various elements as a function of various soil characteristics such as cation exchange capacity (CEC), clay content, and pH. If these quantities are known for the given soils at a site, the relationships developed by EPA can be useful. The elements of importance in nuclear power plant decommissioning dose analysis covered in the EPA work were Cs, Pu, and Sr.

3.2.3.1 Cesium partition coefficient [US EPA, 1999]

For cesium, a strong correlation was demonstrated (r=0.6) between the partition coefficient and the CEC [US EPA] as,

$$\text{Log}(\text{Cs } K_d) = 2.09 + 0.73 \log(\text{CEC})$$

where, K_d is given in ml/g and CEC is given in meq/100g. Because it is CEC values are not readily available, the clay content can be used to estimate the CEC value as following,

$$\text{CEC (meq/100g)} = 4.1 + 0.44*(\text{clay content})$$

where, clay content is given in %.

If mica-like minerals are present, the K_d values will be higher than what is predicted. The uncertainty range for the EPA work in the estimation of cesium partition coefficient is given in Tables 3-7 and 3-8.

Table 3-7
Estimated range of Kd values (ml/g) for cesium based on clay content for system containing <5% mica-like minerals in clay-size fraction and $<10^{-9}$ M aqueous cesium.

Kd (ml/g)	Clay Content (wt %)		
	<4	4-20	20-60
Minimum	10	30	80
Maximum	3,500	9,000	26,700

Table 3-8
Estimated Kd Values (ml/g) for cesium based on Clay content for systems containing >5% mica-like minerals in clay-size fraction and $<10^{-9}$ M aqueous cesium.

Kd (ml/g)	Clay Content (wt %)		
	<4	4-20	20-60
Minimum	30	70	210
Maximum	9,000	22,000	66,700

3.2.3.2 Strontium partition coefficient

Among various regression analyses performed for the K_d values of Sr [EPA, 1999], the following equation has the highest correlation ratio where the K_d value of strontium is correlated with clay content and pH.

$$K_d = 10.5*(CLAY) + 11.2*(pH) - 108 \quad (R^2 = 0.67)$$

The following look-up table (Table 3-9) is also available for the consideration of uncertainty in the estimation of strontium partition coefficient [EPA, 1999].

Table 3-9
Estimated Range of K_d values for Strontium

Kd (ml/g)	CEC (meq/100g)/Clay Content (wt %)								
	3 / <4%			3-10 / 4-20%			10-50 / 20-60%		
	pH			pH			pH		
	<5	5-8	8-10	<5	5-8	8-10	<5	5-8	8-10
Min	1	2	3	10	15	20	100	200	300
Max	40	60	120	150	200	300	1,500	1,600	1,700

3.2.3.3 Plutonium partition coefficient

Based on a detailed set of plutonium K_d measurement [Glover, 1976], the two most significant variables for the estimation of partition coefficient of plutonium were found to be the concentrations of dissolved carbonate (DCARB) and the clay content (CLAY) of the soils [EPA, 1999]. The data set were based on 17 soil samples from 9 different sites that included 7 DOE sites. The regression analysis with these two variables for the partition coefficient of plutonium measured in this study gives the following model (R^2=0.9194), as an example,

$$K_d = -106.1*(DCARB) + 11.2*(CLAY) + 12.5*(DCARB)(CLAY) - 72.4$$

The following look-up table (Table 3-10) provides the information for the uncertainty of K_d values with different clay content and soluble carbonate values [EPA, 1999].

Table 3-10
Estimated Range of K_d Values for Plutonium

Kd (ml/g)	Clay Content (wt %)								
	0-30			31-50			51-70		
	Soluble Carbonate (meq/l)			Soluble Carbonate (meq/l)			Soluble Carbonate (meq/l)		
	0.1-2	3-4	5-6	0.1-2	3-4	5-6	0.1-2	3-4	5-6
Min	5	80	130	380	1,440	2,010	620	1,860	2,440
Max	420	470	520	1,560	2,130	2,700	1,980	2,550	3,130

3.3 Example computer analyses using site-specific parameters

3.3.1 Basic principles

The information obtained from the site-specific investigations represents new pieces of information for the parameters of interest in dose assessment. This is in addition to the prior information available from the code default input distributions or other national databases. If the new site-specific data represents a reasonable picture of the parameter behavior at the site, i.e., the new information is reasonably complete in representing the variability and uncertainty of a parameter at the site, the new information itself is sufficient for site-specific analysis. This can be the case with some directly measurable parameter such as the thickness of unsaturated zone. Relating these distinctively site-specific data to the national database would not be meritorious for site-specific analysis.

However, if the newly obtained information is not based on a complete characterization of the parameter at the given site conditions but rather represents a limited understanding of the behavior of the parameter at the site, use of the new information for site-specific analysis is not technical defensible.

In this case, utilization of the prior information along with the new information is a better approach. Accordingly, combining the new information with the prior default distribution or national data is necessary in site-specific dose assessment. This will better represent the uncertainty/variability of a parameter at the given site conditions.

This combination of information would be relevant for parameters such as soil-to-plant transfer factors and K_d values since complete characterization of the uncertainty of these parameters at the site is extremely difficult, if not impossible. Bayesian updating is very useful for this purpose. Bayesian methods allow the subjective knowledge to be combined with the pre-existing information on the data to yield a better-informed assessment of the uncertainty of a parameter.

In the Bayesian approach, the unknown parameters of a distribution are modeled as random variables. Uncertainty associated with the estimation of the parameters can be combined with the inherent variability of the basic random variable from observations. With this approach, subjective judgments based on intuition, experience, or indirect information are incorporated systematically with observed data to obtain a balanced estimation.

Let Θ be the random variable for the parameter of a distribution, with a prior density function $f'(\theta)$. The prior probability that θ will be between θ_i and $\theta_i+\Delta\theta$ is $f'(\theta_i)\Delta\theta$. Then, if ε is an observed experimental outcome, the prior distribution $f'(\theta)$ can be revised in the light of ε using Bayes' theorem [Ang and Tang, 1975], obtaining the posterior probability that θ will be in $(\theta_i, \theta_i+\Delta\theta)$ as

$$f''(\theta_i)\Delta\theta = \frac{P(\varepsilon \mid \theta_i) f'(\theta_i)\Delta\theta}{\sum_{i=1}^{n} P(\varepsilon \mid \theta_i) f'(\theta_i)\Delta\theta}$$

where $P(\varepsilon \mid \theta_i) = P(\varepsilon \mid \theta_i < \theta < \theta_i + \Delta\theta)$ is the conditional probability or likelihood of observing the experimental outcome ε assuming that the value of the parameter is θ (or within the range, $(\theta_i < \theta < \theta_i + \Delta\theta)$. In the case of very small $\Delta\theta$, this yields the following Bayesian theorem for a continuous probability density function (pdf),

$$f''(\theta) = \frac{P(\varepsilon \mid \theta) f'(\theta)}{\int_{-\infty}^{\infty} P(\varepsilon \mid \theta) f'(\theta) d\theta}$$

$P(\varepsilon \mid \theta)$ is a function of θ and is commonly referred to as the likelihood function of θ and denoted L(θ). The denominator is a normalizing constant required to make $f''(\theta)$ a proper density function.

The Bayesian updating can be performed in several ways including the use of conjugate pairs or sampling from normal distributions, etc. [Ling, 2000]. Combining with conjugate pairs is an analytical approach to obtain the posterior distribution if the prior and the likelihood functions are conjugate distributions. As an example, for normal pairs, the posterior is also normal. Its statistical parameters μ" and σ" can be calculated as [Ang and Tang, 1975]:

Mean: $\mu'' = \frac{\mu' \cdot \sigma^2 + \mu \cdot \sigma'^2}{\sigma^2 + \sigma'^2}$

Standard deviation: $\sigma'' = \sqrt{\frac{\sigma^2 \cdot \sigma'^2}{\sigma^2 + \sigma'^2}}$

where μ', σ' are the parameters for prior distribution, μ, σ are the parameters for site-specific distribution. Similarly for lognormal pairs, by taking logarithmic transform, the parameters are:

Mean (after logarithmic transform):

$$\mu_{\ln}'' = \frac{\mu_{\ln}' \cdot \sigma_{\ln}^2 + \mu_{\ln} \cdot \sigma_{\ln}'^2}{\sigma_{\ln}^2 + \sigma_{\ln}'^2}$$

Standard deviation (after logarithmic transform):

$$\sigma_{\ln}'' = \sqrt{\frac{\sigma_{\ln}^2 \cdot \sigma_{\ln}'^2}{\sigma_{\ln}^2 + \sigma_{\ln}'^2}}$$

3.3.2 Example Analysis

For the demonstration of site-specific dose analysis methodology, an actual nuclear power plant site undergoing decommissioning was used. The radionuclides analyzed in this study were Cs-137 and Sr-90. The sampling results indicated that the contamination was mainly in the surface

soils. Investigations at the site found that the soils in the impacted area of the plant was 97% alpena gravelly sandy loam.

For both of these nuclides, the key parameter in site-specific probabilistic dose analysis is the soil-to-plant transfer factor (as seen in Tables 3 and 4). Thus, the efforts were focused on developing site-specific input distribution for the soil-to-plant transfer factor of Cs-137 and Sr-90.

Based on the understanding of the soil-type at the site, new probabilistic distributions of soil-to-plant transfer factor were developed (as described below). At the same time, this newly developed information does not fully capture the uncertainty and variability of the parameter at the site due to the limitations of the data used. Therefore, the original default input distribution is still useful and is considered a prior baseline information. The new data was combined with this prior-existing body of knowledge to improve the quality of the data for a given site.

Tables 3-11 and 3-12 list the information used to determine the soil-to-plant transfer factors of Cs-137 and Sr-90 for the given soil-type of the site. The values are in the unit of pCi/kg(dry plant mass)/pCi/kg(dry soil). A conversion factor was used to convert the dry plant mass to wet plant mass for the use as RESRAD input.

Table 3-11
Soil-to-plant transfer factor for Cs in loam - pCi/kg(dry)/pCi/kg(dry)

Crops	Number of observations	Number of studies	Geometric mean	Geometric Standard Deviation	95% confidence interval, lower	95% confidence interval, upper
Cereals	358	23	1.4e-2	5.67	4.5e-4	4.2e-1
Tubers	173	14	2.9e-2	3.18	2.9e-3	2.8e-1
Green vegetables	100	12	1.2e-1	3.24	1.2e-2	1.2
Root vegetables	52	11	3.7e-2	5.10	1.5e-3	9.0e-1

Table 3-12
Soil-to-plant transfer factor for Sr in loam - pCi/kg(dry)/pCi/kg(dry)

Crops	Number of observations	Number of studies	Geometric mean	Geometric standard deviation	95% confidence interval, lower	95% confidence interval, upper
Cereals	88	13	1.5e-1	2.55	2.2e-2	9.4e-1
Tubers	33	10	2.1e-1	2.05	5.3e-2	8.6e-1
Green vegetables	75	7	2.4	1.97	6.5e-1	9.1
Root vegetables	29	7	1.6	2.91	1.9e-1	1.3e+1

From the tables, the "site-specific" soil-to-plant transfer factor for each crop category was identified as lognormally distributed as following (as natural logarithm of the geometric mean ± natural logarithm of geometric standard deviation):

Cs-137:	Leafy	-2.12 ± 1.18
	Root	-3.30 ± 1.63
	Fruit	-3.54 ± 1.16
	Grain	-4.27 ± 1.74
Sr-90:	Leafy	0.88 ± 0.68
	Root	0.47 ± 1.07
	Fruit	-1.56 ± 0.72
	Grain	-1.90 ± 0.94

In this estimation, it was assumed that: green vegetables represent the category "leafy"; root vegetables represent the category "root"; tubers represent the category "fruit", and; cereals represent the category "grain". Then, the average soil-to-plant transfer factor for the nuclide was estimated by combining four categories of crops, i.e., leafy, root, fruit, and grain, into an average value. This was necessary because RESRAD uses only a single input value for a plant's soil-to-plant transfer factor. The averaging was done by using the human consumption rate of each crop as weighting factors [Gnanapragasam and Yu, 1997]. The Monte Carlo method was adopted for this combination using the following consumption rates: Leafy – 21.4 kg/yr, Root – 44.6 kg/yr, Fruit – 52.8 kg/yr, and Grain – 14.4 kg/yr. The resulting soil-to-plant transfer factor constructed from this approach was (as a lognormal distribution):

Cs-137:	-2.5742 ± 0.8686
Sr-90:	0.2368 ± 0.6262

Or, the corresponding geometric mean and geometric standard deviation of the distribution are:

Cs-137: 0.0762 pCi/kg (dry)/ pCi/kg (dry), 2.3693.

Sr-90: 1.2672 pCi/kg (dry)/ pCi/kg (dry), 1.8705.

The dry-to-wet weight conversion factor applied was obtained from the ratio of the default transfer factor for wet mass to dry mass listed in a NCRP report [NCRP, 1999]: 0.2 and 0.075 for Cs and Sr, respectively. Then the new geometric mean of the soil-to-plant transfer factor on a wet-plant mass basis is 0.0152 pCi/kg (wet)/ pCi/kg (dry) for ^{137}Cs and 0.095 pCi/kg (wet)/ pCi/kg (dry) for ^{90}Sr.

Written with the format in lognormal distribution, the new information developed are:

Cs-137: -4.1865 ± 0.8686

Sr-90: -2.3539 ± 0.6262

For Bayesian updating or combination of information, assumptions need to be made for the likelihood of observing the new information given the prior information. This likelihood is dependent upon the errors in both the old information and the new information (e.g., spatial and temporal variability, measurement errors, any unrecognized and/or correlated errors). It is difficult to recognize these errors due to the compiled nature of the data used. It was assumed that the likelihood of observing the new information given the prior national data is represented by the probability distributions of the parameters developed from site-specific investigations. In other words, the probability of observing the new information given the prior default information is one. This implies that there is no error in obtaining the new information other than what is represented by the probability distributions of the parameters and the prior national data does not affect the observation made in the site-specific investigations. As far as the details of the Bayesian updating is concerned, conjugate pair method was used since the data used were normally or lognormally distributed.

The results of Bayesian updating for the soil-to-plant transfer factor for both ^{137}Cs and ^{90}Sr are as following.

For Cs-137:

Prior distribution: -3.22 ± 0.9933

New site-specific distribution: -4.1865 ± 0.8686.

Posterior distribution: -3.7677 ± 0.6539.

For Sr-90:

Prior distribution: -1.2 ± 0.9933

New site-specific distribution: -2.3539 ± 0.6262.

Posterior distribution: -2.0257 ± 0.5297.

The process of Bayesian updating is graphically shown in Figures 3-14 and 3-15 (for ^{137}Cs) and Figures 3-16 and 3-17 (for ^{90}Sr).

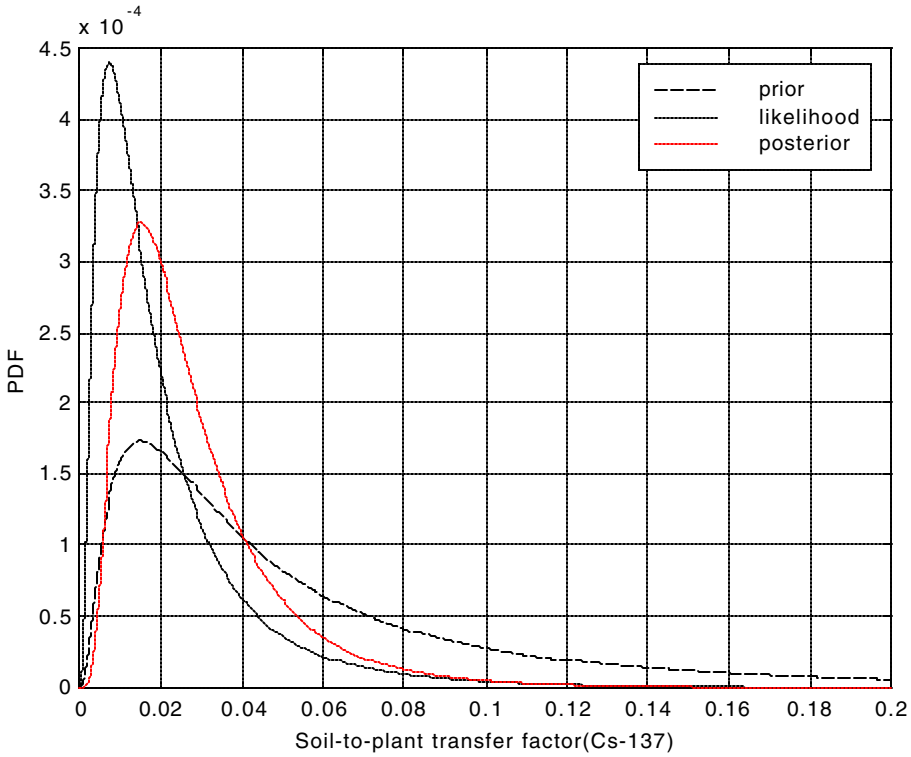

Figure 3-14
The pdfs of the prior, likelihood, and posterior distribution – Cs-137

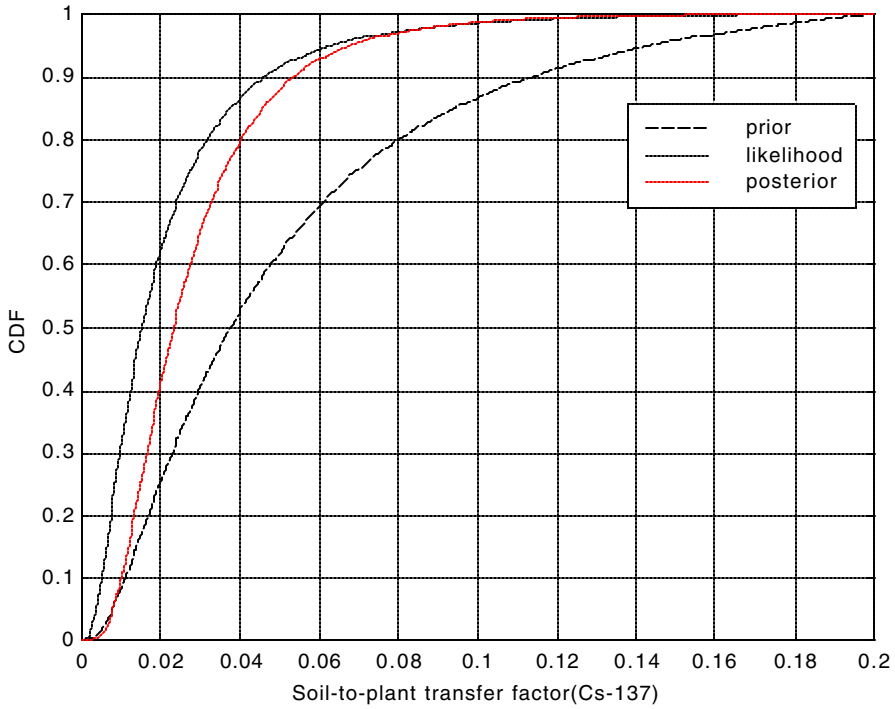

Figure 3-15
The cumulative distribution functions (cdfs) of the prior, likelihood, and posterior distribution – Cs-137

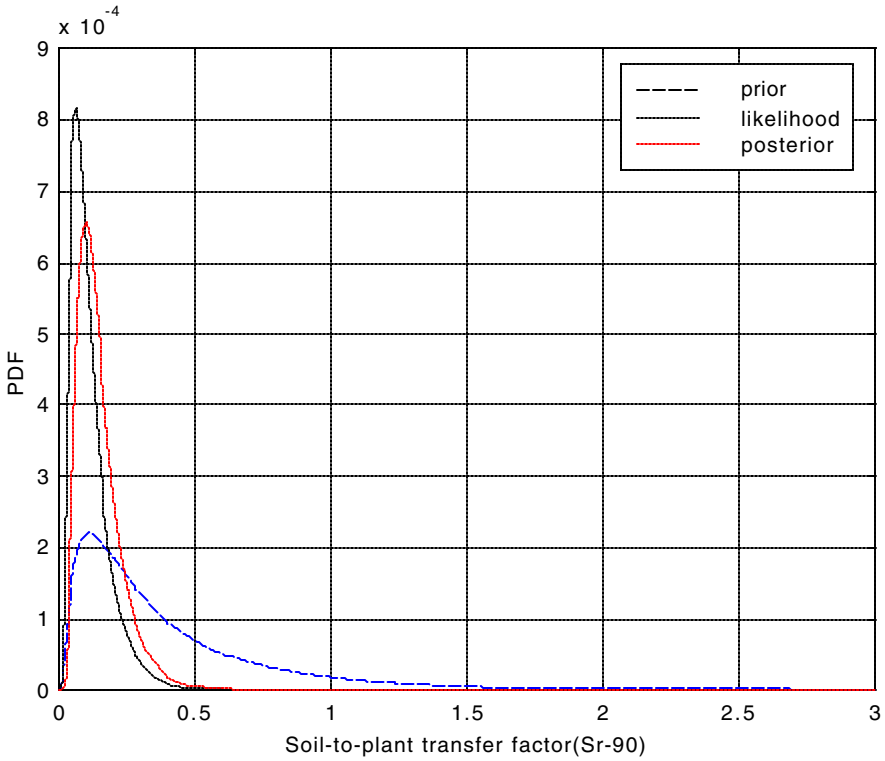

Figure 3-16
The pdfs of the prior, likelihood, and posterior distribution – Sr-90

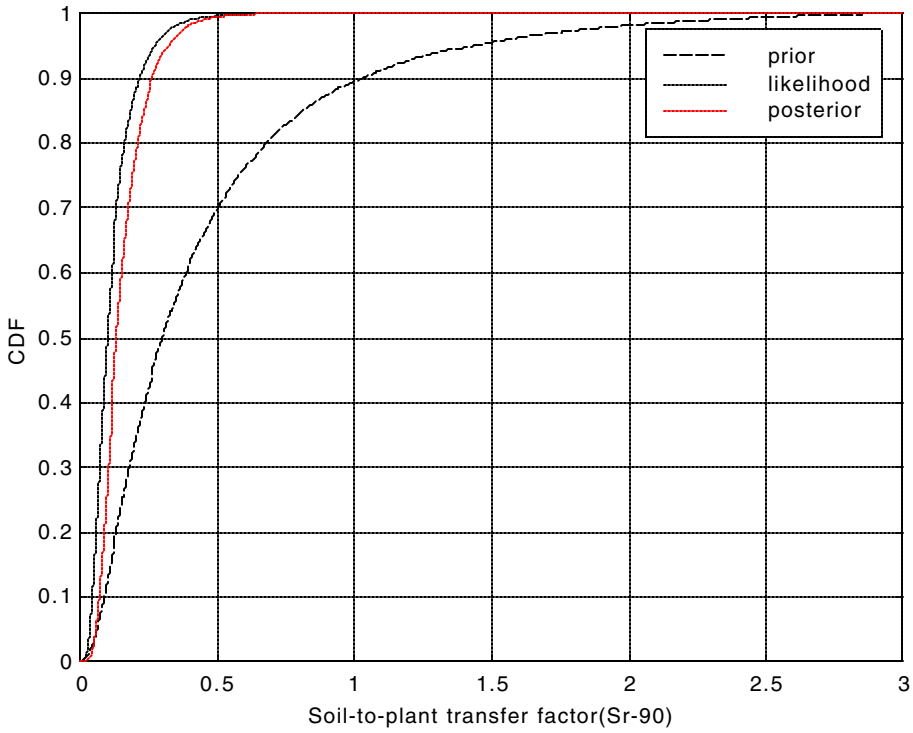

Figure 3-17
The cdfs of the prior, likelihood, and posterior distribution – Sr-90

3.3.2.1 Dose Analysis Results

The predicted peak dose distributions are compared between the screening probabilistic analysis and site-specific analysis for ^{137}Cs and ^{90}Sr. The results are shown in Table 3-13. For the mean of the peak dose, the results indicated that the peak dose is reduced by a factor of 1.3 and 3.3 for ^{137}Cs and ^{90}Sr, respectively, by using the new site-specific soil-to-plant transfer factors. This indicates potentially a significant benefit in actual plant decommissioning.

Table 3-13
Comparison of Peak Dose (mrem/yr) Distributions between Screening and Site-Specific Probabilistic Dose Analysis (per 1 pCi/g)

	Cs-137		Sr-90	
	Screening	Site-specific	Screening	Site-specific
5%	0.957	0.939	0.943	0.887
10%	1.04	1.00	1.42	1.10
25%	1.30	1.14	2.58	1.52
50%	1.64	1.39	5.18	2.33
75%	2.17	1.71	10.8	3.51
90%	2.99	2.15	18.5	4.80
95%	3.93	2.43	26.3	5.84
Mean of the peak	2.00	1.53	9.56	2.87
Peak of the mean	2.00	1.53	9.56	2.87
Geom. Standard deviation	1.62	1.37	2.82	1.81

3.3.2.2 DCGL Analysis Results

Use of site-specific data resulting in the decrease in the predicted peal dose will also lead into a higher DCGL for a given site in comparison to the DCGL from screening methodology. This effect on DCGL is shown in Table 16. In this table, the DCGL values for several critical points, e.g., 50%, 90%, and 95% confidence levels (corresponding to Pcri=0.5, 0.1, and 0.05), are listed.

Table 3-14
Comparison of the DCGL (pCi/g) calculated between the Screening and Site-Specific Probabilistic Dose Analysis

	Cs-137		Sr-90	
	Screening	Site-specific	Screening	Site-specific
Pcrit = 0.5	15.2	18.0	4.83	10.7
Pcrit = 0.1	8.36	11.6	1.35	5.21
Pcrit = 0.05	6.36	10.3	0.95	4.28
Based on the peak of the mean	12.5	16.3	2.62	8.71
Based on the mean of the peak	12.5	16.3	2.62	8.71
NRC screening value	11		1.7	

For the given site, the DCGL changed from 12.5 and 2.62 pCi/g to 16.3 and 8.7 pCi/g, for ^{137}Cs and ^{90}Sr, respectively. This indicates a significant benefit of using site-specific soil-to-plant transfer factors especially for ^{90}Sr.

4
DESCRIPTION OF THE PROBABILISTIC ANALYSIS AND ITS INTERPRETATION

4.1 Probabilistic Dose Analysis

Dose analysis relies upon predictive mathematical/computer models to project the human dose from a hypothetical radiation exposure in the future from the presence of residual radioactivity. Due to the necessarily limited nature of the available data and models and the need to extrapolate the known database in time, uncertainties naturally arise. More specifically, uncertainties are due to (i) the limited scientific understanding of important processes; (ii) the inadequacy of mathematical representations which require simplifications of physical processes and their temporal and spatial aggregation; and (iii) the limited ability to measure model parameters and inputs. These uncertainties need to be understood in terms of their impact on model predictions and decisions involved including regulatory compliance demonstration.

Model uncertainty refers to the uncertainty regarding abstracting a real system and its evolution into a form that can be mathematically modeled. Model uncertainty results from limitations in the models used to represent complex system behavior, including the system's evolution (future site conditions, processes, and events), for a specific site and engineering design. This includes uncertainty about the interpretation and use of data and assumptions about heterogeneity, system dimensionality, and initial boundary conditions, etc. [Yim and Simonson, 2000] The NRC does not require the quantification of the model uncertainty in probabilistic dose analysis as long as the computer models used are accepted by the NRC.

Parameter uncertainty refers to the uncertainty in the data, parameters, and coefficients used in the models. Parameter uncertainty is attributed to a number of sources, including: uncertainty associated with laboratory and field measurements; uncertainty in determining parameter and coefficient values used in a model; and uncertainty associated with the intrinsic heterogeneity of natural systems. Parameter uncertainty is quantitatively assessed in a probabilistic dose analysis through Monte Carlo analysis [Morgan and Henrion, 1990; NCRP, 1996]: Input parameter uncertainties and their impacts on the estimated dose are analyzed. The end point of the analysis is an annual dose to a member of a “critical group”. In random Monte Carlo analysis, a random number generator is used to generate uniformly distributed numbers between 0 and 1 for each uncertain variable. Since all CDF’s ranges from zero to 1, uniformly distributed random numbers are used to represent the fractile of the random variable for which a sample is to be generated. In Latin Hypercube Sampling (LHS) Monte Carlo analysis, each input distribution is divided into N_{obs} (the number of observations/samples) nonoverlapping regions of equal probability where one sample value is drawn at random from each region [Morgan and Henrion, 1990; Kamboj et al., 2000]. The analysis is composed of the following steps [IAEA, 1989]:

1) List all potentially important uncertain parameters.

2) Within a conceivable range of possibly applicable values for uncertain parameters, specify a probability distribution that quantitatively expresses the state of knowledge about the parameter values.

3) Determine and account for dependencies that are suspected to exist among parameters (cross-correlations).

4) Generate random "realizations" of parameters using Monte-Carlo or Latin Hypercube Sampling of distributions.

5) Calculate dose-versus-time for each sampled set of distributions.

6) Continue the steps 4 and 5 until the maximum number of realizations is achieved.

7) Produce distribution of model predictions and determine the peak of the mean dose versus time.

8) Perform any desired statistical analysis of the predicted dose results. This includes deriving quantitative statements of uncertainty in terms of a probability or confidence interval about the assessed dose and identifying the parameters according to their relative contribution to the overall uncertainty in the dose prediction.

9) Present and interpret the results of the analysis.

A set of outputs (equal in number to the number of realizations) is produced in a probabilistic analysis. These outputs can be represented as probability density functions (pdfs) and as cumulative distribution functions (cdfs) for the interpretation of the results.

Deterministic dose analyses uses a single value for each parameter, resulting in a single dose value at each simulation time step. Deterministic analysis is simple to implement and easy to communicate to non-technical audience. But it doesn't allow consideration of combinations of input parameters thus does not provide information on uncertainty of results. Accordingly, deterministic analysis requires pessimistic estimates of model parameters, usually leading to overly conservative evaluation. For the deterministic analysis to be useful for appropriate decision, deterministic analyses need to be demonstrably conservative. However, it may not be possible to identify conservative values a priori.

In comparison to the deterministic dose analysis, the advantages of probabilistic analysis are:

1) Uncertainties in the dose analysis or DCGL derivation are quantified;

2) Conservatism is reduced by specifying the distribution of input parameter values instead of selecting only one value;

3) By explicitly representing the uncertainty, simulations of complex environmental systems and representation of the performance of the system can be more accurate;

4) Incorporating uncertainty analysis into dose modeling provides broadened dimension for decision making.

4.2 Key Terms in Probabilistic Analysis

4.2.1 Random variable

A random phenomenon is an empirical phenomenon characterized by the property that its observation under a given set of circumstances does not always lead to the same observed outcome (so that there is no deterministic regularity). In other words, there is usually a range of measured or observed values; moreover, within this range certain values may occur more frequently than others. If recorded data of a variable exhibit scatter or dispersion, the value of the variable cannot be predicted with certainty. Such a variable is known as a random variable, and its value (or ranges of values) can be predicted only with an associated probability.

All uncertainties, whether they are associated with inherent variability or with prediction error, may be assessed in statistical terms, and the evaluation of their significance is accomplished using concepts and methods that are embodied in the theory of probability.

4.2.2 Probability

Probability is the conceptual and theoretical basis for modeling and analyzing uncertainty. When we speak of probability, we are referring to the occurrence of an event relative to other events; there is (implicitly at least) more than one possibility, since otherwise the problem would be deterministic. For quantitative purposes, probability can be considered as a numerical measure of the likelihood of occurrence of an event relative to a set of alternative events.

Accordingly, the first requirement in the formulation of a probabilistic problem is the identification of the set of all possibilities (that is, the possibility space) and the event of interest. Probabilities are then associated with specific events within a particular possibility space. In probabilistic dose analysis, the events are the possible human dose outcomes from an analysis.

Probability is treated as a measure necessary and useful in problems where more than one event or outcome is possible. In calculating the probability of an event, a basis for assigning probability measures to the various possible outcomes is necessary. The assignment may be based on prior conditions (or deduced on the basis of prescribed assumptions), or based on the results of empirical observations, or both. Thus the usefulness of a calculated probability will depend on the appropriateness of the basis for its determination. We observe that the validity of the *a priori* basis for calculating probability depends on the reasonableness of the underlying assumptions, whereas the empirical relative frequency basis must rely on a large amount of observational data. When data are limited, the relative frequency by itself may have limited usefulness. Another basis for calculating probability involves the combination of intuitive or subjective assumptions with experimental observations. The proper vehicle for this combination is Bayes' theorem, and the result is known as the Bayesian probability.

4.2.3 Probability distribution

As was stated earlier, a random phenomenon is an empirical phenomenon characterized by the property that its observation under a given set of circumstances does not always lead to the same observed outcome (so that there is no deterministic regularity). The possible outcome of a random phenomenon can be identified numerically. Such an outcome or event may be identified through the value(s) of a function; such a function is a random variable. The value of a random variable (or range of values) represents a distinct event. A random variable is usually denoted with a capital letter.

Since the value of a random variable represents an event, it can assume a numerical value with an associated probability. The rule for describing the probability measures associated with all the values of a random variable is "probability distribution."

If X is a random variable, its probability distribution can always be described by its cumulative distribution function (cdf), which is

$$F_X(x) \equiv P(X \le x)$$

Here X is a discrete random variable if only certain discrete values of x have positive probabilities. Alternatively, X is a continuous random variable if probability measures are defined for any value of x. A random variable may also be both discrete and continuous.

For a discrete random variable X, its probability distribution is described in terms of a probability mass function (pmf) - a function expressing P(X=x) for all x. Therefore, if X is a discrete random variable with pmf $p_x(x_i) \equiv P(X = x_i)$, its distribution function is

$$F_X(x) = P(X \le x) = \sum_{all\, x_i \le x} P(X = x_i) = \sum_{all\, x_i \le x} p_X(x_i)$$

If X is continuous, probabilities are associated with intervals on the real line (since events are defined as intervals on the real line). At a specific value of X, such as X=x, only the density of probability is defined. Thus for a continuous random variable, the probability distribution is described in terms of a probability density function (pdf). If $f_X(x)$ is the pdf of X, the probability of X in the interval (a,b] is

$$P(a < X \le b) = \int_a^b f_X(x)dx$$

The corresponding distribution function is

$$F_X(x) \equiv P(X \le x) = -\int_{-\infty}^{x} f_X(\xi)d\xi$$

If $F_X(x)$ has a derivative, then $f_X(x) \equiv dF_X(x)/dx$

$f_X(x)$, pdf, is not a probability; however, $f_X(x)dx = P(x < X \leq x + dx)$ is the probability that values of X will be in the interval (x,x+dx].

Any function used to represent the probability distribution of a random variable must necessarily satisfy the axioms of probability. The function must be nonnegative and the probabilities associated with all possible values of the random variable must add up to 1.0

In other words, if $F_X(x)$ is the distribution function of X, then it must have the following properties:

(a) $F_X(-\infty)=0$; $F_X(+\infty)=1.0$

(b) $F_X(X) \geq 0$, and is nondecreasing with x.

(c) It is continuous with x.

Conversely, any function possessing these properties is a bona fide cumulative distribution function. The cdf helps provide quantitative insight regarding the percentiles of the distributions. The probabilistic characteristics of a random variable would be described completely if the form of the distribution function (or equivalently its pdf or pmf) and the associated parameters are specified. In practice, the form of the distribution function may not be known; consequently, approximate descriptors of a random variable are often necessary.

4.2.4 Correlations

If the behavior of random variable is related to another random variable, these variables are correlated. The statistic that provides an index of the degree to which the two variables are related is called the correlation coefficient. The numerical value of the correlation coefficient falls between two extreme values, +1 (for perfect positive correlation) and –1 (for perfect negative correlation). A perfect correlation exists when all the points in a scattergram fall on a perfectly straight line. The correlation coefficient is defined as the normalized covariance as following:

$$\rho = \frac{Cov(X,Y)}{\sigma_X \sigma_Y}$$

The covariance can be calculated from the data as following:

$$Cov(X,Y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)}$$

where, n is the sample size.

4.3 Interpretation of the Results from Probabilistic Dose Analysis

The probabilistic analysis is a useful tool to support various decisions involved in dose analysis by showing the distribution of potential dose for a range of possible input parameter values. In probabilistic dose analysis, for a single run, dose to the average member of the critical group is calculated for each set of sampled parameter values for the given source term as a function of time for the entire simulation period. From this single run, dose at each time step and a peak dose to the average member of the critical group can be identified. Multiple independent runs of similar simulation will then produce distributions of dose values at each simulation time step and the peak dose. Thus in probabilistic dose analysis, the distribution of peak dose and the dose at each simulation time step are constructed. In RESRAD 6.0 analysis, the summary output distribution of the dose is the distribution of peak dose over each 1,000-year period.

The most important results of probabilistic analysis are the central value of the random variable and a measure of the dispersion of its values. These are represented by the summary statistics. Summary statistics include quantities such as the mean, median, variance, and percentile of a distribution. A skewness measure may also be important and useful when the underlying distribution is known to be nonsymmetric.

The mean or median represents central tendency of a distribution. The mean is the value of a random variable for which the weighted probability mass for all values less than the mean is equal to the weighted probability mass for all values greater than the mean. The weighting is based upon the distance of a value of the random variable from the mean. Thus the mean can be considered a center of gravity of a distribution (probability density function).

The median is the point such that exactly half of the probability is associated with values less than the median and half of the probability is associated with values greater than the median. The median is also known as the mid-point or 50^{th} percentile of the distribution. Another measure of central tendency of possible interest is the mode. The mode is the most likely value and is associated with a maximum of the probability density function.

The mean, median, and mode are the same for unimodal, symmetric distributions such as normal distribution. For a unimodal, positively skewed distributions (long tails to the right), such as lognormal distributions, the mean will be larger than the median, and the median will be larger than the mode. In extreme cases, it is possible for the mean to be above the 90^{th} percentile of the distribution. The median is sometimes a more robust measure of central tendency, because it is not sensitive to the shape of the tail of a distribution, or to the presence of outliers in a data set, as is the mean.

The variance of a distribution is a measure of its spread or dispersion. It is the expected value of the square of the difference between the mean and the sample values. The standard deviation is the square root of variance.

The percentile value is very useful in the interpretation of the probabilistic analysis. The p_{th} percentile, X_p, of a distribution is a value such that there is a probability p/100 that the actual value of the random variable will be less than that value. Therefore, for example, the 90^{th} percentile value corresponds to the value of X which corresponds to the cumulative distribution

function value of 90%. In many engineering analysis, the 90th or 95th percentile value of a distribution is often used as decision cutoff.

The results of probabilistic results are used to determine the compliance with the dose criterion, to determine the relative importance of the contributions of the uncertainties in the input parameters to the total uncertainty, or to determine the relationships between the uncertain variables. Also the results of probabilistic analysis can be used as a basis for determining the cost-effectiveness of obtaining additional information or data on input parameters.

For the compliance testing, NRC requires the peak of the mean dose to be less than 25 mrem per year. The peak of the mean dose represents the maximum value in the mean dose curve that is composed of the mean dose values at each simulation time step. A similar but different term, the mean of the peak dose, represents the mean value of the peak dose values calculated from each simulation runs for the entire simulation period.

Since the peak of the mean dose is equal to the mean of the peak for almost all the nuclides analyzed in this study, the compliance can be tested based on the comparison of the mean of the peak dose distribution with the 25 mrem/yr limit.

The results of correlation analysis can be used to examine how much of the uncertainty in the results is attributable to which input parameters and to identify key parameters through multivariate linear regression analysis for the dose output and the inputs. Probabilistic sensitivity analysis as discussed in section 3.1 is effective in identifying the key parameters in terms of the impact on the central tendency of a dose distribution.

4.4 Differences Between the Peak of the Mean and the Mean of the Peak, and Pros and Cons of their Use for Regulatory Compliance Demonstration

As stated in section 4.3, the peak of the mean dose represents the maximum value in the mean dose curve that is composed of the mean dose values at each simulation time step. The mean of the peak dose represents the mean value of the peak dose values calculated from each simulation runs for the entire simulation period. In principle, the two values can be different. In fact, if the time of peak dose occurrence changes between simulations, the peak of the mean dose is smaller than the mean of the peak. However, if the time of occurrence of the peak dose does not change in different runs of the simulation, the two quantities are the same. Regulatory compliance demonstration requires the peak of the mean dose to be less than 25 mrem/year.

For the radionuclides examined in this study, it was found that the peak dose occurs at time zero for all of the nuclides listed in Table 1 except for I-129. In this case, the time of peak will not change among different simulations and the peak of the mean and the mean of the peak is always the same. Therefore the mean of the peak values can be equivalently used for regulatory compliance demonstration. One example of this is shown in Figure 4-1. The curves plotted represent the human dose from 1 pCi/g of ^{137}Cs in the soil for the next 300 years from the residential farmer scenario. Each run in the figure represents different input values. Since the peak dose occurs at time zero, the peak of the mean is the maximum of the mean dose curve obtained from different simulations. In this case the maximum is always at time zero. The mean of the peak dose is the mean value of the dose at time zero where peak occurs.

If the peak dose does not occur at time zero, it is possible for the time of peak occurrence to change between simulations. This is shown in Figure 4-2 for I-129 (for 1 pCi/g contamination). The time of peak dose in each simulation is not fixed in the figure. The results from this test simulation for I-129 predicted the peak of the mean dose of 163 mrem/yr in comparison to the mean of the peak dose of 167 mrem/yr. Thus the peak of the mean dose is slightly smaller than the mean of the peak dose. However, the difference was very small.

In summary, distinguishing the difference between the mean of the peak dose from the peak of the mean dose is not necessary in probabilistic dose analysis unless the nuclide shows the time of peak to be different from time zero (^{129}I, in this study). Even for the case of the peak dose occurring at time other than zero, the difference between the peak of the mean and the mean of the peak is expected to be very small.

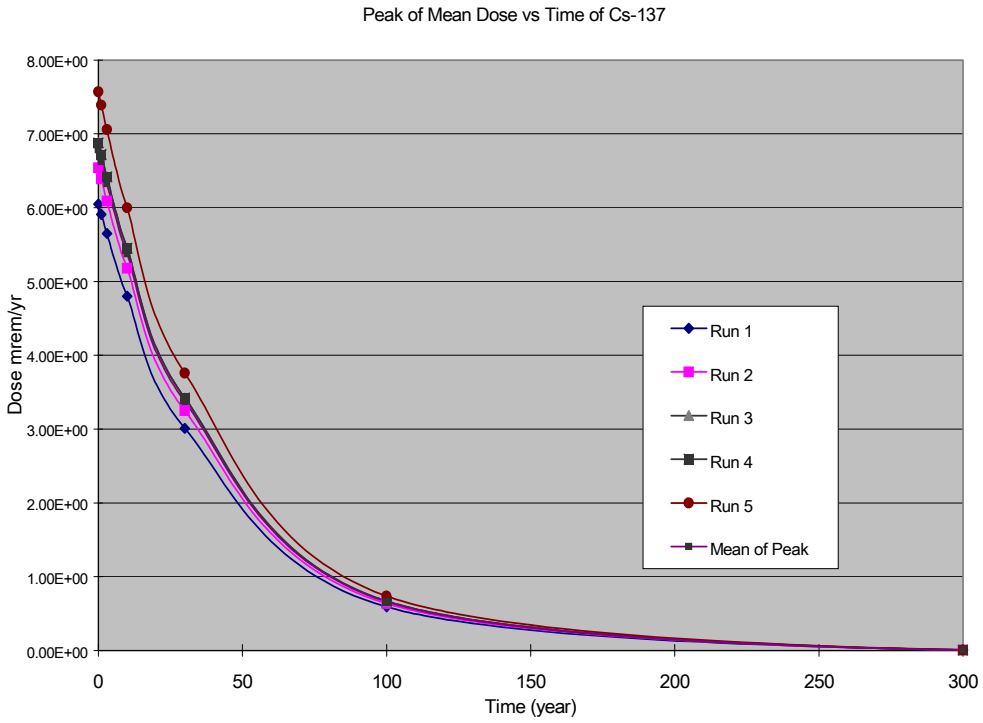

Figure 4-1
Comparison of the Peak of the Mean and the Mean of the Peak Dose for Cs-137

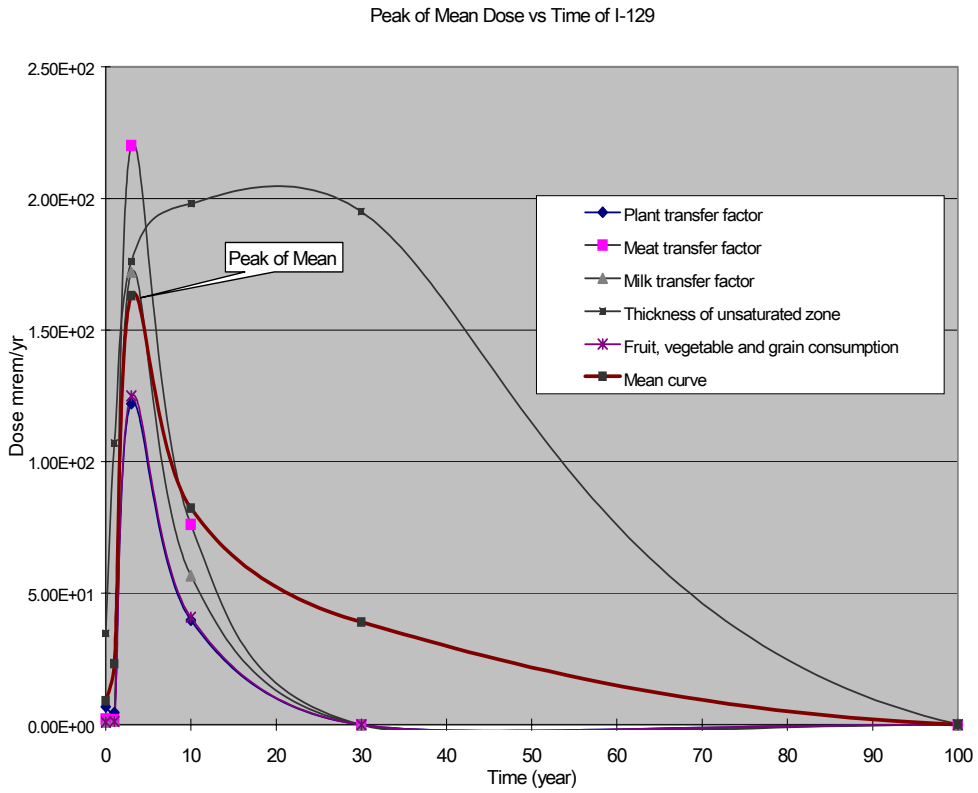

Figure 4-2
Comparison of the Peak of the Mean and the Mean of the Peak Dose for I-129

4.5 Explanation of the Type of Distribution to be Used for Input Variables

4.5.1 General guidelines in assigning probability distributions

A number of distribution functions are useful to describe/construct the probability distribution of an input variable. Selection of a certain type of probability distribution can be preferred in this process because the input parameter may represent an underlying physical process or because the necessary statistical information (including probability tables) about the parameter is available widely. The distributions should reflect our degree of belief; i.e., true but unknown variable lies within the stated range. When assigning distributions, overly restrictive ranges that reflect unwarranted precision should be avoided. Also, overly broad ranges that could cause "risk dilution" should be avoided [Thaggard, 2000].

4.5.2 Specific guidelines [Haimes, et al., 1994; Cullen and Frey, 1999]

4.5.2.1 When large amount of relevant data is available

The distribution can be dictated by data through the development of empirical distribution.

4.5.2.2 When sufficient amount of relevant data is available

A parametric probability distribution model can be developed from the data. Selection of the distribution model can be from the understanding of the underlying physical processes or from the analysis of the shape of the curve represented by the data. For the underlying physical processes represented by different probability distributions, please refer to section 4.5.4

For the analysis of the shape of the curve, the skewness and kurtosis of the data need to be calculated. Skewness is the asymmetry of a distribution. It is based on the third central moment of the distribution. The third central moment can be estimated from a data set using the following relation,

$$m_3 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^3}{n}$$

The skewness is given by the third central moment divided by the cube of the standard deviation

$$\gamma_1 = \frac{m_3}{\sigma^3} \; (= \beta_1^2, \textit{ in Figure } 48)$$

Kurtosis refers to the peakedness of a distribution. Kurtosis is estimated based upon the fourth central moment of the distribution. The fourth central moment can be calculated from a data set as following,

$$m_4 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^4}{n}$$

Kurtosis is the fourth central moment of the distribution divided by the square of the variance:

$$\beta_2 = \frac{m_4}{\sigma^4}$$

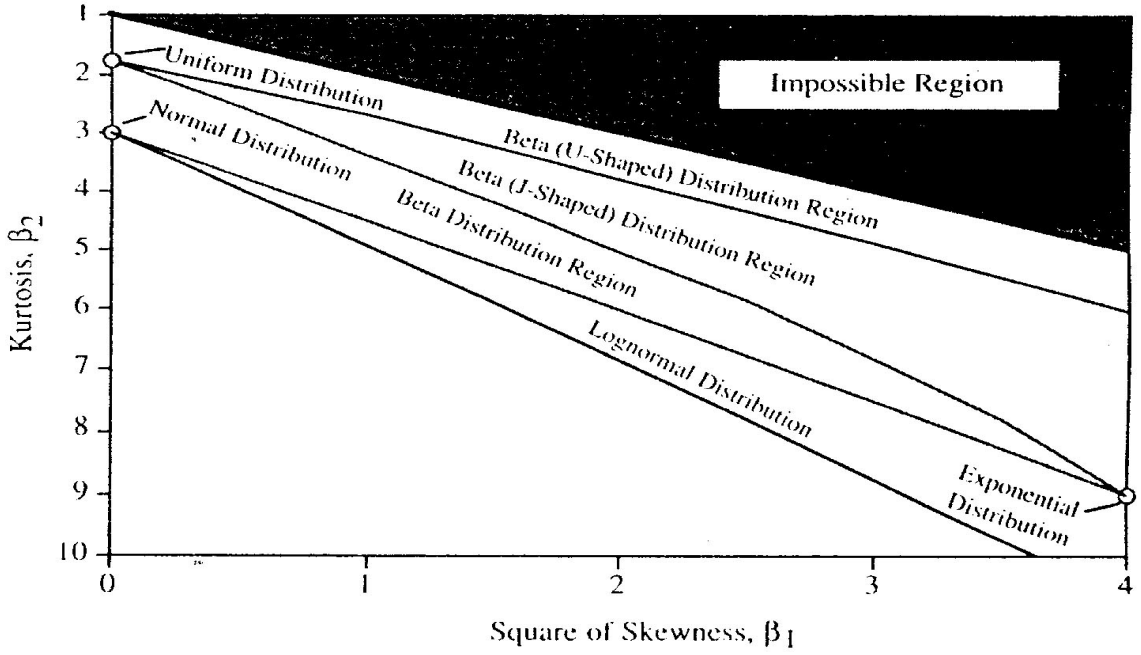

Figure 4-3
β_1-β_2 plane depicting several common parametric probability distributions [Hahn and Shapiro, 1967]

Both measures can be useful when trying to select probability distribution models to fit data sets. Figure 4-3 displays the relationship between the square of the skewness and kurtosis of many standard parametric probability distributions. The normal distribution, the uniform and exponential distributions are represented by single points on the given plane. The lognormal, gamma, and Weibull distributions have very similar curves on the plane also, although only the lognormal distribution was shown in the plane. The lognormal and gamma distributions are very similar for moderate or low skewness data. Also the Weibull distribution can take on shapes similar to the lognormal and gamma. The beta distribution can take on a variety of shapes, including positively and negatively skewed data, and therefore is represented by areas, rather than lines, in the plane.

When selecting a distribution, the point represented by the kurtosis and the square of the skewness of a particular data set should be identified on this plane. Any distributions closely located to this point can be candidate distributions to fit the data. Usually, it is recommended to develop two or three alternative distributions and to select the best one based on the goodness-of-fit testing [Cullen and Frey, 1999; Ang and Tang, 1975].

4.5.2.3 When only a limited amount of data or data partly relevant are available

In this case, some combination of expert judgment and data is called for. Bayes' theorem is useful for this purpose. A practical example of combining information using Bayesian updating was given in the section 2.3. In this case, the prior information can be from regional or national database or from the knowledge about the physical processes.

4.5.2.4 When very limited data are available

There are peer-reviewed probability distribution models for various parameters including parameters in environmental transport [Binkowitz and Wartenberg, 2001; McKone, 1994; Copeland et al., 1994; NCRP, 1999]. For the limited information, combination of the information using Bayes' theorem as indicated above can be considered. The following suggestions in Table 4-1 can be useful in this discussion [Cullen and Frey, 1999; Haimes et al., 1994; Thaggard, 2000]:

Table 4-1
Suggestions on the selection of probability distribution model with very limited data

Nature of data	Assigned probability model	Other caveats
Min. and max. only	Uniform	Useful when relative error is small and for screening purpose.
Min., max. and mode (most likely)	Triangular	Useful when relative error is small and for screening purpose.
Expected value only	Exponential	
Expected value and standard deviation only	Normal	When used for positive quantity, the standard deviation should not be more than 20~30% of the mean.
Expected value, standard deviation, min., and max.	Beta	
Mean occurrence rate between arrival of independent events	Poisson	
Min. and max. only with a large relative error (>factor of 10)	Loguniform	
Min., max. and mode (most likely) with a large relative error	Log-triangular	
Uncertainties are expressed on a multiplicative order-of-magnitude basis or when there is a probability of obtaining extreme large values	Lognormal	

When distributions are estimated from incomplete data, the followings need to be considered [Haimes et al., 1994].

- Using previous experience: Even if only two data points are available at your own site, it makes no sense to use uniform distribution if we have a national or regional data set that indicates the parameters behaves ~ lognormal.
- Using expert opinion: If there are no adequate surrogates or components to model, expert opinion can be used to determine the distribution parameters and further characterize by assigning a distribution to the expert opinion itself [Morgan and Henrion, 1990]. One should attempt to bound the pdf by asking questions: How large can the upper bound be? How small can the lower bound be? How important is the analytical form of the pdf to the findings? What is the best estimate based on expert opinion?
- Sensitivity analysis: If a sensitivity analysis indicates that the parameter does not contribute significantly to the overall resulting output distribution, it may be appropriate to use the incomplete data as being done. If the sensitivity analysis indicates that the parameter is important in evaluating the output distribution, then a decision may be made that more data are required/collected for the intended probabilistic dose analysis.

4.5.2.5 When essentially no relevant data are available

Primarily expert judgment is used, often about “soft factors” that are hard to measure. It is hard to suggest a prior criteria for selection here, as it really depends upon the situation.

4.5.3 Characteristics of distributions

The following is a principle for the selection of particular probability distribution models [Cullen and Frey, 1999; Ang and Tang, 1975; Hahn and Shapiro, 1967].

4.5.3.1 The normal distribution

The theoretical justification for the normal distribution comes from the observation that the means of samples tend to be normally distributed in the limit ("Central Limit Theorem" - The distribution of means of independent observations from any distribution, or any combination of distributions, converges to a normal distribution as the number of observations becomes large). The normal distribution is also a limiting form of the binomial distribution as the sample size gets large.

The normal distribution is useful for modeling situations in which the uncertain quantity is subject to many different sources of uncertainty or error. The normal distribution is a good representation for some physical processes and physiological characteristics. Examples of the application of normal distribution include (1) the distribution of air pollution concentrations in the crosswind and vertical directions (2) human heights (3) the water content of human skin.

There are also caveats for using normal distribution: The normal distribution is not a default that can be assumed to apply unless proven otherwise. The normal distribution has infinite tails.

Therefore, when a normal distribution is used to represent a physical quantity which must be nonnegative, one must be careful that the coefficient of variation is less than approximately 0.3. If the coefficient of variation is much higher than this, there is a significant probability of predicting negative values. Then normality assumption may be highly inappropriate.

4.5.3.2 The lognormal distribution

If the natural logarithm of a random variable behaves as normal, the random variable is described by the lognormal distribution. The lognormal distribution is one of the most widely used distributional forms in probabilistic environmental assessment. It has a number of useful characteristics relevant to physical quantities. For example, it assumes only non-negative values in the common two parameter form. Also, it describes random variables resulting from multiplicative processes. The lognormal distribution is also often used to represent large, asymmetric uncertainties.

In many settings, the concentrations of pollutants tend to be approximately lognormal. The distribution of particle sizes of many atmospheric aerosols tends to be approximately lognormal. Products, ratios, and powers of lognormals are themselves lognormal. Other examples of the application of lognormal distribution include human body weights, human food consumption rates, human soil ingestion rates, and the duration of showering.

Caveats for using lognormal distribution are: The lognormal distribution is tail-heavy. The lognormal may not be the most appropriate distribution if one is concerned with obtaining a good fit to the upper tail. A less tail-heavy distribution , such as Weibull, gamma, or beta, may provide a better fit to the upper percentiles of a particular data set.

4.5.3.3 The binomial distribution

The binomial distribution is applicable to a situation that has the following characteristics:

(a) Dichotomous outcomes - Uncertain events occur in a sequence, each one having one of two possible outcomes - success/failure, heads/tails, yes/no, true-false, on/off, live/die, and so on.

(b) Constant probability - Each event, or trial has the same probability of success (p).

(c) Independence - The outcome of each trial is independent of the outcomes of the other trials (i.e., the probability of success dose not depend on the preceding outcomes.)

4.5.3.4 The Poisson distribution

The Poisson distribution is useful to describe the occurrence of a rare event.

The Poisson distribution requires the following assumptions - Poisson process.

(a) An event can occur at random and at any time or any point in space.

(b) The occurrence of an event in a given time (or space) interval is independent of that in any other non-overlapping intervals.

(c) At any specific point, the probability of occurrence of an event is small. This simply means that the events do not happen too frequently. The probability of occurrence of an event in a small interval is proportional to the size of the interval.

For events described by the Poisson process, this distribution describes the number of events occurring within a fixed time interval.

While the binomial distribution is good for representing success in several trials, the Poisson distribution is good for representing occurrences of a particular event over time or space. Such space-time problems may be modeled also with the Bernoulli sequence by dividing the time or space into small intervals. If the event can occur at any instant (or at any point in space), it may occur more than once at a given time or space interval. In such case, the occurrences of the event may be more appropriately modeled with a Poisson sequence.

An example of uncertain quantity represented by the Poisson distribution is the number of accidents occurring within a fixed time interval or the number of radioactive disintegration over a fixed time interval.

4.5.3.5 The exponential distribution

If events occur according to a Poisson process, then the time till the first occurrence of the event has an exponential distribution. - The exponential distribution is useful for representing the time interval between successive, random, independent events that occur at a constant rate. Such events are said to occur as a purely random Poisson process.

For example, the time between equipment failures, accidents, and storm events can be represented by an exponential distribution. Exponential distribution has also be applied to represent the concentration of contaminants in indoor and outdoor air.

4.5.3.6 The gamma distribution

The gamma distribution describes the time required for the occurrence of a specified number of events, given a Poisson process: If the occurrence of an event constitute a Poisson process, then the time until the k_{th} occurrence of the event is described by the gamma distribution.

The gamma distribution is also useful as a general-purpose probability distribution to fit a negatively skewed data. It is useful for representing quantities like the time between events for non-random event processes, the time to complete a task, and the sum of independent exponential random variables. When the shape parameter is equal to 1, the gamma becomes a exponential distribution.

4.5.3.7 The beta distribution

The beta distribution is a very flexible distribution, with a finite upper and lower bound. It can describe both negatively and positively skewed data. It is useful if the probability distribution (PDF) is bounded between two finite limits. Commonly a two-parameter form of the beta distribution, bounded by 0 and 1, is used to represent judgments about uncertainty. It is useful in Bayesian statistics because the beta can easily be updated to account for new data while retaining prior information.

Examples of uncertain quantity represented by the beta distribution include the fraction of time individuals spend engaging in various activities, bioavailability factors for metals, the concentration of heavy metals in an aquatic system, the age of underground storage tanks, and the partitioning of hazardous air pollutants in a power plant,

4.5.3.8 The uniform distribution

The uniform distribution is a special case of the beta distribution. The uniform distribution is a very simple distribution, requiring an assumption about the range of possible values. The uniform distribution is useful for representing subjective judgments about uncertainty when an expert is only willing/able to estimate an upper and lower bound for a quantity.

Published examples of the representation of model inputs by the uniform distribution include skin permeability, the ventilation rate of a house, soil loading on skin, the ratio of concentrations of indoor and outdoor air, ingestion rate of soil by cattle, and the duration of the growing season of plant crops.

4.5.3.9 The loguniform distribution

This is a variation of the uniform distribution where the log-transformed random variable is assumed to be uniformly distributed. It is useful in cases where inputs cover a large range of values, but little is known about the shape of their underlying distribution.

4.5.3.10 Triangular distribution

The triangular distribution is useful when only upper and lower bounds and most likely values are known. It is also often used to represent subjective judgments of the maximum value, minimum value, and mode of a random variable. Triangular distributions may be symmetric or asymmetric. When uncertainties are very large and asymmetric, a log-triangular distribution may be more appropriate.

4.5.3.11 The Weibull distribution

The Weibull distribution is useful for representing processes such as the time to completion or time to failure. It is a flexible distribution that can assume negatively skewed, symmetric, or positively skewed shapes. The distribution may also be used to represent non-negative physical quantities. Weibull distribution has been applied to such data sets as wind speed, time between climatic events and lifetime of a waste package.

5
REFERENCES

Ang, A. H-S. and W. H. Tang, Probability Concepts in Engineering Planning and Design, Vol. 1 – Basic Principles, John Wiley and Sons, New York, 1975.

Beyeler, W. E., et al., "Residual Radioactive Contamination from Decommissioning, Parameter Analysis," Draft Report for Comment, Sandia National Laboratories, NUREG/CR-5512, Vol. 3, October 1999.

Binkowitz, B. S. and D. Wartenberg, "Disparity in Quantitative Risk Assessment: A Review of Input Distributions," Risk Analysis, Vol. 21, No. 1, pp. 75-90, 2001

Carsel and Parrish, "Developing Joint Probability Distributions of Soil Water Retention Characteristics," Water Resources Research, Vol. 24, No. 5, pp. 755-769, 1988

Copeland, T. L., A. M. Holbrow, J. M. Otani, K. T. Connor, and D. J. Paustenbach, "Use of Probabilistic Methods to Understand the Conservatism in California's Approach to Assessing Health Risks Posed by Air Contaminants," Journal of Air and Waste Management Association, Vol. 44, pp. 1399-1413, 1994.

Cullen, A. C. and H. C. Frey, Probabilistic Techniques in Exposure Assessment, Plenum Press, New York, NY, 1999.

EPA, "Understanding Variations in Partition Coefficient, Kd, Values," EPA 402-R-99-004A, Volume I and II, August 1999.

EPA, "An Estimation of the Daily Food Intake Based on Data from the 1977-1978 USDA Nationwide Food Consumption Survey," EPA-520/1-84-015, Office of Radiation Programs, Environmental Protection Agency, Washington, DC, 1984a.

EPA, "Understanding Variation in Partition Coefficient, Kd Values," EPA 402-R-99-004B, Vol. 2, Office of Air and Radiation, Environmental Protection Agency, Washington, DC, 1999.

Glover, P. A., F. J. Miner, and W. O. Polzer, "Plutonium and Americium Behavior in the Soil/Water Environment I. Sorption of Plutonium and Americium by Soils," Proceedings of Actinide-Sediment Reactions Working Meeting, Seattle, WA, pp. 225-254, BNWL-2117, Battelle Pacific Northwest Laboratories, 1976.

Gnanapragasam, E. K. and C. Yu, "Application of the RESRAD Computer Code to VAMP Scenario S," ANL/EAD/TM-70, Argonne National Laboratory, 1997

Hahn, G. and S. S. Shapiro, Statistical Models in Engineering, John Wiley & Sons, New York, 1967.

Haimes, Y. Y., T. Barry, and J. H. Lambert, "When and How Can You Specify a Probability Distribution When You Don't Know Much?," Risk Analysis, Vol. 14, No. 5, pp. 661-703, 1994.

Hillel, Soil and Water, Academic Press, New York, 1971.

IAEA (International Atomic Energy Agency), "Evaluating the Reliability of Predictions Made Using Environmental Transfer Models," IAEA Safety Series 100, International Atomic Energy Agency, Vienna, 1989.

Kamboj, S., et al., "Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes," NUREG/CR-6676, ANL/EAD/TM-89, Argonne National Laboratory, 2000.

Ling, X., "Bayesian Analysis for Site-Specific Dose modeling in Nuclear Power Plant Decommissioning," MS Thesis, Department of Nuclear Engineering, North Carolina State University, 2001.

McKone, T. E., "Uncertainty and variability in Human Exposures to Soil Contaminants through Home-Grown Foods: A Monte-Carlo Approach," Risk Analysis, Vol. 14, No. 4, pp. 449-463, 1994.

Morgan, M. G. and M. Henrion, Uncertainty, Cambridge University Press, Cambridge, UK, 1990.

NCRP, "A Guide for Uncertainty Analysis in Dose and Risk Assessments Related to Environmental Contamination," NCRP Commentary No. 14, , National Council on Radiation Protection and Measurements, 1996.

NCRP, "Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies," NCRP Report No. 129, National Council on Radiation Protection and Measurements, 1999.

Nisbet, A. F. and R. F. M. Woodman, "Soil-To-Plant Transfer Factors for Radiocesium and Radiostrontium in Agricultural Systems," Health Physics, Vol. 78, No. 3, pp. 279-288, 2000.

NRC (Nuclear Regulatory Commission), "Radiological Criteria for License Termination," (10 CFR Parts 20, 30, 40, 50, 51, 70, and 72), Federal Register, Vol. 62, pp. 39058-39092 (62 FR 39058), July 21, 1997.

NRC (Nuclear Regulatory Commission), "NMSS Decommissioning Standard Review Plan," NUREG-1727, US Nuclear Regulatory Commission, September 2000.

Sheppard, M. I. And W. G. Evenden, "Charcateristics of Plant Concentration Ratios Assessed in a 64-Site Field Survey of 23 Elements," Journal of Environmental Radioactivity, Vol. 11, pp. 15-36, 1990.

Sheppard, M. I. and D. H. Thibault, "Default Soil Solid/Liquid Partition Coefficient for Four Major Soil Types: A Compendium," Health Physics, Vol. 59, No. 4, pp. 471-482, 1990.

Thaggard, M., "Treatment of Uncertainty in NRC Decommissioning," Public Workshop on Guidance for Implementing 10 CFR, Subpart E, Radiological Criteria for License Termination, Nuclear Regulatory Commission, June 8, 2000.

Yim, M.-S., "Comparisons of Decommissioning Dose Modeling Codes for Nuclear Power Plant Use: RESRAD and DandD," EPRI TR-112874, Electric Power Research Institute, 1999.

Yim, M.-S. and S. A. Simonson, "Performance Assessment Models for Low Level Radioactive Waste Disposal Facilities: A Review," Progress in Nuclear Energy, Vol. 36, No. 1, pp. 1-38, 2000.

Yu, C. et al., "Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes," NUREG/CR-6697, ANL/EAD/TM-98, US Nuclear Regulatory Commission, May 2000.

A
IDENTIFICATION OF KEY PARAMETERS IN PROBABILISTIC DOSE ANALYSIS USING RESRAD 6.0

Table A-1
Identification of Key Parameters in Probabilistic Dose Analysis (H-3)

H 3	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	1.02E-02	1.35E-02	23.08%	
	Kd in unsaturated zone	1.43E-02	1.43E-02	0.00%	
	Kd in saturated zone	1.43E-02	1.43E-02	0.00%	
	Plant transfer factor	1.43E-02	1.43E-02	0.00%	
	Meat transfer factor	1.43E-02	1.43E-02	0.00%	
	Milk transfer factor	1.43E-02	1.43E-02	0.00%	
	Fish transfer factor	1.43E-02	1.43E-02	0.00%	
cover/hydrau	Density of contaminated zone	1.08E-02	1.82E-02	51.75%	
	Contaminated zone erosion rate	1.43E-02	1.43E-02	0.00%	
	Contaminated zone total porosity	1.18E-02	1.67E-02	34.27%	
	Contaminated zone hydraulic conductivity	1.28E-02	1.60E-02	22.38%	
	Contaminated zone b parameter	1.38E-02	1.69E-02	21.68%	
	Evapotranspiration coefficient	1.44E-02	1.48E-02	2.80%	
	Wind speed	1.41E-02	1.43E-02	1.40%	
	Runoff coefficient	1.34E-02	2.04E-02	48.95%	
Saturated zone	Density of saturated zone	1.43E-02	1.43E-02	0.00%	
	Saturated zone total porosity	1.43E-02	1.43E-02	0.00%	
	Saturated zone effective porosity	1.43E-02	1.43E-02	0.00%	
	Saturated zone hydraulic conducitivity	1.43E-02	1.43E-02	0.00%	
	Saturated zone hydraulic gradient	1.43E-02	1.43E-02	0.00%	
	Saturated zone b parameter	1.43E-02	1.43E-02	0.00%	
	Well pump intake depth	1.43E-02	1.43E-02	0.00%	
unsaturated zone	Thickness of unsaturated zone	1.43E-02	1.85E-02	29.37%	
	Density of unsaturtaed zone	1.43E-02	1.43E-02	0.00%	
	Total porosity of Unsaturated zone	1.43E-02	1.43E-02	0.00%	
	Effective porosity of Unsaturated zone	1.43E-02	1.43E-02	0.00%	
	Hydraulic conductivity of Unsaturated zone	1.43E-02	1.43E-02	0.00%	
	b parameter of Unsaturated zone	1.43E-02	1.44E-02	0.70%	
Occupancy	Inhalation rate	1.42E-02	1.44E-02	1.40%	
	Mass loading for inharation	1.43E-02	1.43E-02	0.00%	
	Indoor dust filtration factor	1.43E-02	1.43E-02	0.00%	
	External gamma shielding factor	1.43E-02	1.43E-02	0.00%	
	Indoor time factor	1.42E-02	1.45E-02	2.10%	
Ingestion Dietary	Fruit, vegetable and grain consumption	1.39E-02	2.19E-02	55.94%	
	Milk consumption	1.41E-02	1.57E-02	11.19%	
	Soil ingestion	1.43E-02	1.43E-02	0.00%	
	Drinking water intake	1.43E-02	1.43E-02	0.00%	
	Aquatic food	1.43E-02	1.43E-02	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	1.43E-02	1.43E-02	0.00%	
	Depth of roots	7.64E-03	1.43E-02	46.57%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-2
Identification of Key Parameters in Probabilistic Dose Analysis (C-14)

C14	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	1.16E+00	1.34E+00	15.79%	
	Kd in unsaturated zone	1.13E+00	1.13E+00	0.00%	
	Kd in saturated zone	1.13E+00	1.13E+00	0.00%	
	Plant transfer factor	1.13E+00	1.13E+00	0.00%	
	Meat transfer factor	1.13E+00	1.13E+00	0.00%	
	Milk transfer factor	1.13E+00	1.13E+00	0.00%	
	Fish transfer factor	1.13E+00	1.13E+00	0.00%	
cover/hydrau	Density of contaminated zone	8.56E-01	1.43E+00	50.35%	
	Contaminated zone erosion rate	1.13E+00	1.13E+00	0.00%	
	Contaminated zone total porosity	1.06E+00	1.19E+00	11.40%	
	Contaminated zone hydraulic conductivity	1.09E+00	1.17E+00	7.02%	
	Contaminated zone b parameter	1.06E+00	1.15E+00	7.89%	
	Evapotranspiration coefficient	1.14E+00	1.22E+00	7.02%	
	Wind speed	3.70E-01	8.17E-01	39.21%	
	Runoff coefficient	1.12E+00	1.24E+00	10.53%	
Saturated zone	Density of saturated zone	1.13E+00	1.13E+00	0.00%	
	Saturated zone total porosity	1.13E+00	1.13E+00	0.00%	
	Saturated zone effective porosity	1.13E+00	1.13E+00	0.00%	
	Saturated zone hydraulic conducitivity	1.13E+00	1.13E+00	0.00%	
	Saturated zone hydraulic gradient	1.13E+00	1.13E+00	0.00%	
	Saturated zone b parameter	1.13E+00	1.13E+00	0.00%	
	Well pump intake depth	1.13E+00	1.13E+00	0.00%	
unsaturated zone	Thickness of unsaturated zone	1.13E+00	1.66E+00	46.49%	
	Density of unsaturtaed zone	1.13E+00	1.13E+00	0.00%	
	Total porosity of Unsaturated zone	1.13E+00	1.13E+00	0.00%	
	Effective porosity of Unsaturated zone	1.13E+00	1.13E+00	0.00%	
	Hydraulic conductivity of Unsaturated zone	1.13E+00	1.13E+00	0.00%	
	b parameter of Unsaturated zone	1.13E+00	1.17E+00	3.51%	
Occupancy	Inhalation rate	1.13E+00	1.13E+00	0.00%	
	Mass loading for inharation	1.13E+00	1.13E+00	0.00%	
	Indoor dust filtration factor	1.13E+00	1.13E+00	0.00%	
	External gamma shielding factor	1.13E+00	1.13E+00	0.00%	
	Indoor time factor	1.13E+00	1.13E+00	0.00%	
Ingestion Dietary	Fruit, vegetable and grain consumption	1.10E+00	1.72E+00	54.39%	
	Milk consumption	1.12E+00	1.22E+00	8.77%	
	Soil ingestion	1.13E+00	1.13E+00	0.00%	
	Drinking water intake	1.13E+00	1.13E+00	0.00%	
	Aquatic food	1.13E+00	1.13E+00	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	1.13E+00	1.13E+00	0.00%	
	Depth of roots	5.94E-01	1.13E+00	47.02%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-3
Identification of Key Parameters in Probabilistic Dose Analysis (Fe-55)

Fe 55	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	2.49E-04	2.57E-04	3.11%	
	Kd in unsaturated zone	2.57E-04	2.57E-04	0.00%	
	Kd in saturated zone	2.57E-04	2.57E-04	0.00%	
	Plant transfer factor	2.00E-04	5.50E-04	136.19%	
	Meat transfer factor	2.08E-04	6.27E-04	163.04%	
	Milk transfer factor	2.54E-04	2.66E-04	4.67%	
	Fish transfer factor	2.57E-04	2.57E-04	0.00%	
cover/hydrau	Density of contaminated zone	2.57E-04	2.57E-04	0.00%	
	Contaminated zone erosion rate	2.57E-04	2.57E-04	0.00%	
	Contaminated zone total porosity	2.57E-04	2.57E-04	0.00%	
	Contaminated zone hydraulic conductivity	2.57E-04	2.57E-04	0.00%	
	Contaminated zone b parameter	2.57E-04	2.57E-04	0.00%	
	Evapotranspiration coefficient	2.57E-04	2.57E-04	0.00%	
	Wind speed	2.57E-04	2.57E-04	0.00%	
	Runoff coefficient	2.57E-04	2.57E-04	0.00%	
Saturated zone	Density of saturated zone	2.57E-04	2.57E-04	0.00%	
	Saturated zone total porosity	2.57E-04	2.57E-04	0.00%	
	Saturated zone effective porosity	2.57E-04	2.57E-04	0.00%	
	Saturated zone hydraulic conducitivity	2.57E-04	2.57E-04	0.00%	
	Saturated zone hydraulic gradient	2.57E-04	2.57E-04	0.00%	
	Saturated zone b parameter	2.57E-04	2.57E-04	0.00%	
	Well pump intake depth	2.57E-04	2.57E-04	0.00%	
unsaturated zone	Thickness of unsaturated zone	2.57E-04	2.57E-04	0.00%	
	Density of unsaturtaed zone	2.57E-04	2.57E-04	0.00%	
	Total porosity of Unsaturated zone	2.57E-04	2.57E-04	0.00%	
	Effective porosity of Unsaturated zone	2.57E-04	2.57E-04	0.00%	
	Hydraulic conductivity of Unsaturated zone	2.57E-04	2.57E-04	0.00%	
	b parameter of Unsaturated zone	2.57E-04	2.57E-04	0.00%	
Occupancy	Inhalation rate	2.57E-04	2.57E-04	0.00%	
	Mass loading for inharation	2.57E-04	2.57E-04	0.00%	
	Indoor dust filtration factor	2.57E-04	2.57E-04	0.00%	
	External gamma shielding factor	2.57E-04	2.57E-04	0.00%	
	Indoor time factor	2.47E-04	2.65E-04	7.00%	
Ingestion Dietary	Fruit, vegetable and grain consumption	2.55E-04	2.90E-04	13.62%	
	Milk consumption	2.56E-04	2.61E-04	1.95%	
	Soil ingestion	2.45E-04	2.55E-04	3.89%	
	Drinking water intake	2.57E-04	2.57E-04	0.00%	
	Aquatic food	2.57E-04	2.57E-04	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	2.57E-04	2.57E-04	0.00%	
	Depth of roots	2.24E-04	2.57E-04	12.84%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-4
Identification of Key Parameters in Probabilistic Dose Analysis (Co-60)

Co 60	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	8.63E+00	8.85E+00	2.49%	
	Kd in unsaturated zone	8.85E+00	8.85E+00	0.00%	
	Kd in saturated zone	8.85E+00	8.85E+00	0.00%	
	Plant transfer factor	8.64E+00	9.82E+00	13.33%	
	Meat transfer factor	8.78E+00	9.54E+00	8.59%	
	Milk transfer factor	8.84E+00	8.89E+00	0.56%	
	Fish transfer factor	8.85E+00	8.85E+00	0.00%	
cover/hydrau	Density of contaminated zone	8.85E+00	8.85E+00	0.00%	
	Contaminated zone erosion rate	8.85E+00	8.85E+00	0.00%	
	Contaminated zone total porosity	8.85E+00	8.85E+00	0.00%	
	Contaminated zone hydraulic conductivity	8.85E+00	8.85E+00	0.00%	
	Contaminated zone b parameter	8.85E+00	8.85E+00	0.00%	
	Evapotranspiration coefficient	8.85E+00	8.85E+00	0.00%	
	Wind speed	8.85E+00	8.85E+00	0.00%	
	Runoff coefficient	8.85E+00	8.85E+00	0.00%	
Saturated zone	Density of saturated zone	8.85E+00	8.85E+00	0.00%	
	Saturated zone total porosity	8.85E+00	8.85E+00	0.00%	
	Saturated zone effective porosity	8.85E+00	8.85E+00	0.00%	
	Saturated zone hydraulic conducitivity	8.85E+00	8.85E+00	0.00%	
	Saturated zone hydraulic gradient	8.85E+00	8.85E+00	0.00%	
	Saturated zone b parameter	8.85E+00	8.85E+00	0.00%	
	Well pump intake depth	8.85E+00	8.85E+00	0.00%	
unsaturated zone	Thickness of unsaturated zone	8.85E+00	8.85E+00	0.00%	
	Density of unsaturtaed zone	8.85E+00	8.85E+00	0.00%	
	Total porosity of Unsaturated zone	8.85E+00	8.85E+00	0.00%	
	Effective porosity of Unsaturated zone	8.85E+00	8.85E+00	0.00%	
	Hydraulic conductivity of Unsaturated zone	8.85E+00	8.85E+00	0.00%	
	b parameter of Unsaturated zone	8.85E+00	8.85E+00	0.00%	
Occupancy	Inhalation rate	8.85E+00	8.85E+00	0.00%	
	Mass loading for inharation	8.85E+00	8.85E+00	0.00%	
	Indoor dust filtration factor	8.85E+00	8.85E+00	0.00%	
	External gamma shielding factor	4.56E+00	8.69E+00	46.67%	
	Indoor time factor	3.91E+00	1.30E+01	102.71%	
Ingestion Dietary	Fruit, vegetable and grain consumption	8.84E+00	8.98E+00	1.58%	
	Milk consumption	8.85E+00	8.86E+00	0.11%	
	Soil ingestion	8.85E+00	8.85E+00	0.00%	
	Drinking water intake	8.85E+00	8.85E+00	0.00%	
	Aquatic food	8.85E+00	8.85E+00	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	8.85E+00	8.85E+00	0.00%	
	Depth of roots	8.72E+00	8.85E+00	1.47%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-5
Identification of Key Parameters in Probabilistic Dose Analysis (Ni-63)

Ni 63	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	4.59E-03	4.59E-03	0.00%	
	Kd in unsaturated zone	4.59E-03	4.59E-03	0.00%	
	Kd in saturated zone	4.59E-03	4.59E-03	0.00%	
	Plant transfer factor	1.20E-02	1.98E-02	405.33%	
	Meat transfer factor	4.31E-03	5.85E-03	33.56%	
	Milk transfer factor	3.39E-03	8.31E-03	107.21%	
	Fish transfer factor	4.59E-03	4.59E-03	0.00%	
cover/hydrau	Density of contaminated zone	4.59E-03	4.59E-03	0.00%	
	Contaminated zone erosion rate	4.59E-03	4.59E-03	0.00%	
	Contaminated zone total porosity	4.59E-03	4.59E-03	0.00%	
	Contaminated zone hydraulic conductivity	4.59E-03	4.59E-03	0.00%	
	Contaminated zone b parameter	4.59E-03	4.59E-03	0.00%	
	Evapotranspiration coefficient	4.59E-03	4.59E-03	0.00%	
	Wind speed	4.59E-03	4.59E-03	0.00%	
	Runoff coefficient	4.59E-03	4.59E-03	0.00%	
Saturated zone	Density of saturated zone	4.59E-03	4.59E-03	0.00%	
	Saturated zone total porosity	4.59E-03	4.59E-03	0.00%	
	Saturated zone effective porosity	4.59E-03	4.59E-03	0.00%	
	Saturated zone hydraulic conducitivity	4.59E-03	4.59E-03	0.00%	
	Saturated zone hydraulic gradient	4.59E-03	4.59E-03	0.00%	
	Saturated zone b parameter	4.59E-03	4.59E-03	0.00%	
	Well pump intake depth	4.59E-03	4.59E-03	0.00%	
unsaturated zone	Thickness of unsaturated zone	4.59E-03	4.59E-03	0.00%	
	Density of unsaturtaed zone	4.59E-03	4.59E-03	0.00%	
	Total porosity of Unsaturated zone	4.59E-03	4.59E-03	0.00%	
	Effective porosity of Unsaturated zone	4.59E-03	4.59E-03	0.00%	
	Hydraulic conductivity of Unsaturated zone	4.59E-03	4.59E-03	0.00%	
	b parameter of Unsaturated zone	4.59E-03	4.59E-03	0.00%	
Occupancy	Inhalation rate	4.59E-03	4.59E-03	0.00%	
	Mass loading for inharation	4.59E-03	4.59E-03	0.00%	
	Indoor dust filtration factor	4.59E-03	4.59E-03	0.00%	
	External gamma shielding factor	4.59E-03	4.59E-03	0.00%	
	Indoor time factor	4.59E-03	4.59E-03	0.00%	
Ingestion Dietary	Fruit, vegetable and grain consumption	4.49E-03	6.35E-03	40.53%	
	Milk consumption	4.29E-03	6.13E-03	40.10%	
	Soil ingestion	4.59E-03	4.59E-03	0.00%	
	Drinking water intake	4.59E-03	4.59E-03	0.00%	
	Aquatic food	4.59E-03	4.59E-03	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	4.59E-03	4.59E-03	0.00%	
	Depth of roots	2.56E-03	4.59E-03	44.24%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-6
Identification of Key Parameters in Probabilistic Dose Analysis (Sr-90)

Sr 90	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	4.66E+00	5.00E+00	6.81%	
	Kd in unsaturated zone	4.99E+00	4.99E+00	0.00%	
	Kd in saturated zone	4.99E+00	4.99E+00	0.00%	
	Plant transfer factor	9.41E-01	2.59E+01	500.18%	
	Meat transfer factor	4.68E+00	6.13E+00	29.06%	
	Milk transfer factor	4.86E+00	5.27E+00	8.22%	
	Fish transfer factor	4.99E+00	4.99E+00	0.00%	
cover/hydrau	Density of contaminated zone	4.98E+00	4.99E+00	0.20%	
	Contaminated zone erosion rate	4.99E+00	4.99E+00	0.00%	
	Contaminated zone total porosity	4.99E+00	4.99E+00	0.00%	
	Contaminated zone hydraulic conductivity	4.99E+00	4.99E+00	0.00%	
	Contaminated zone b parameter	4.99E+00	4.99E+00	0.00%	
	Evapotranspiration coefficient	4.99E+00	4.99E+00	0.00%	
	Wind speed	4.99E+00	4.99E+00	0.00%	
	Runoff coefficient	4.99E+00	4.99E+00	0.00%	
Saturated zone	Density of saturated zone	4.99E+00	4.99E+00	0.00%	
	Saturated zone total porosity	4.99E+00	4.99E+00	0.00%	
	Saturated zone effective porosity	4.99E+00	4.99E+00	0.00%	
	Saturated zone hydraulic conducitivity	4.99E+00	4.99E+00	0.00%	
	Saturated zone hydraulic gradient	4.99E+00	4.99E+00	0.00%	
	Saturated zone b parameter	4.99E+00	4.99E+00	0.00%	
	Well pump intake depth	4.99E+00	4.99E+00	0.00%	
unsaturated zone	Thickness of unsaturated zone	4.99E+00	4.99E+00	0.00%	
	Density of unsaturtaed zone	4.99E+00	4.99E+00	0.00%	
	Total porosity of Unsaturated zone	4.99E+00	4.99E+00	0.00%	
	Effective porosity of Unsaturated zone	4.99E+00	4.99E+00	0.00%	
	Hydraulic conductivity of Unsaturated zone	4.99E+00	4.99E+00	0.00%	
	b parameter of Unsaturated zone	4.99E+00	4.99E+00	0.00%	
Occupancy	Inhalation rate	4.99E+00	4.99E+00	0.00%	
	Mass loading for inharation	4.99E+00	4.99E+00	0.00%	
	Indoor dust filtration factor	4.99E+00	4.99E+00	0.00%	
	External gamma shielding factor	4.98E+00	4.99E+00	0.20%	
	Indoor time factor	4.97E+00	4.99E+00	0.40%	
Ingestion Dietary	Fruit, vegetable and grain consumption	4.83E+00	7.76E+00	58.72%	
	Milk consumption	4.94E+00	5.20E+00	5.21%	
	Soil ingestion	4.98E+00	4.99E+00	0.20%	
	Drinking water intake	4.99E+00	4.99E+00	0.00%	
	Aquatic food	4.99E+00	4.99E+00	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	4.99E+00	4.99E+00	0.00%	
	Depth of roots	2.63E+00	4.99E+00	47.29%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-7
Identification of Key Parameters in Probabilistic Dose Analysis (Tc-99)

Tc 99	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Top 10 Key Parameters
Soil concentration	Kd in contaminated zone	4.68E-01	6.55E-01	40.13%	
	Kd in unsaturated zone	4.66E-01	4.66E-01	0.00%	
	Kd in saturated zone	4.66E-01	4.66E-01	0.00%	
	Plant transfer factor	9.63E-02	2.14E+00	438.56%	
	Meat transfer factor	4.65E-01	4.69E-01	0.86%	
	Milk transfer factor	4.57E-01	4.96E-01	8.37%	
	Fish transfer factor	4.66E-01	4.66E-01	0.00%	
cover/hydrau	Density of contaminated zone	4.66E-01	4.66E-01	0.00%	
	Contaminated zone erosion rate	4.66E-01	4.66E-01	0.00%	
	Contaminated zone total porosity	4.07E-01	5.13E-01	22.75%	
	Contaminated zone hydraulic conductivity	4.26E-01	4.97E-01	15.24%	
	Contaminated zone b parameter	4.03E-01	4.77E-01	15.88%	
	Evapotranspiration coefficient	4.69E-01	5.41E-01	15.45%	
	Wind speed	4.66E-01	4.66E-01	0.00%	
	Runoff coefficient	4.57E-01	5.57E-01	21.46%	
Saturated zone	Density of saturated zone	4.66E-01	4.66E-01	0.00%	
	Saturated zone total porosity	4.66E-01	4.66E-01	0.00%	
	Saturated zone effective porosity	4.66E-01	4.66E-01	0.00%	
	Saturated zone hydraulic conducitivity	4.66E-01	4.66E-01	0.00%	
	Saturated zone hydraulic gradient	4.66E-01	4.66E-01	0.00%	
	Saturated zone b parameter	4.66E-01	4.66E-01	0.00%	
	Well pump intake depth	4.66E-01	4.66E-01	0.00%	
unsaturated zone	Thickness of unsaturated zone	4.66E-01	6.46E-01	38.63%	
	Density of unsaturtaed zone	4.66E-01	4.66E-01	0.00%	
	Total porosity of Unsaturated zone	4.66E-01	4.66E-01	0.00%	
	Effective porosity of Unsaturated zone	4.66E-01	4.66E-01	0.00%	
	Hydraulic conductivity of Unsaturated zone	4.66E-01	4.66E-01	0.00%	
	b parameter of Unsaturated zone	4.66E-01	4.74E-01	1.72%	
Occupancy	Inhalation rate	4.66E-01	4.66E-01	0.00%	
	Mass loading for inharation	4.66E-01	4.66E-01	0.00%	
	Indoor dust filtration factor	4.66E-01	4.66E-01	0.00%	
	External gamma shielding factor	4.66E-01	4.66E-01	0.00%	
	Indoor time factor	4.66E-01	4.66E-01	0.00%	
Ingestion Dietary	Fruit, vegetable and grain consumption	4.49E-01	7.85E-01	72.10%	
	Milk consumption	4.64E-01	4.79E-01	3.22%	
	Soil ingestion	4.66E-01	4.66E-01	0.00%	
	Drinking water intake	4.66E-01	4.66E-01	0.00%	
	Aquatic food	4.66E-01	4.66E-01	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	4.66E-01	4.66E-01	0.00%	
	Depth of roots	2.44E-01	4.66E-01	47.64%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-8
Identification of Key Parameters in Probabilistic Dose Analysis (I-129)

I 129	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	6.52E-01	8.12E-01	24.62%	
	Kd in unsaturated zone	6.50E-01	6.50E-01	0.00%	
	Kd in saturated zone	6.50E-01	6.50E-01	0.00%	
	Plant transfer factor	2.03E-01	2.67E+00	379.54%	
	Meat transfer factor	8.23E-01	1.61E+00	121.08%	
	Milk transfer factor	5.58E-01	8.43E-01	43.85%	
	Fish transfer factor	6.50E-01	6.50E-01	0.00%	
cover/hydrau	Density of contaminated zone	6.38E-01	6.61E-01	3.54%	
	Contaminated zone erosion rate	6.50E-01	6.50E-01	0.00%	
	Contaminated zone total porosity	6.13E-01	6.82E-01	10.62%	
	Contaminated zone hydraulic conductivity	6.26E-01	6.70E-01	6.77%	
	Contaminated zone b parameter	6.11E-01	6.57E-01	7.08%	
	Evapotranspiration coefficient	6.53E-01	7.18E-01	10.00%	
	Wind speed	6.50E-01	6.50E-01	0.00%	
	Runoff coefficient	6.41E-01	7.33E-01	14.15%	
Saturated zone	Density of saturated zone	6.50E-01	6.50E-01	0.00%	
	Saturated zone total porosity	6.50E-01	6.50E-01	0.00%	
	Saturated zone effective porosity	6.50E-01	6.50E-01	0.00%	
	Saturated zone hydraulic conducitivity	6.50E-01	6.50E-01	0.00%	
	Saturated zone hydraulic gradient	6.50E-01	6.50E-01	0.00%	
	Saturated zone b parameter	6.50E-01	6.50E-01	0.00%	
	Well pump intake depth	6.50E-01	6.50E-01	0.00%	
unsaturated zone	Thickness of unsaturated zone	6.50E-01	1.16E+01	1684.62%	
	Density of unsaturtaed zone	6.50E-01	6.50E-01	0.00%	
	Total porosity of Unsaturated zone	6.50E-01	6.50E-01	0.00%	
	Effective porosity of Unsaturated zone	6.50E-01	6.50E-01	0.00%	
	Hydraulic conductivity of Unsaturated zone	6.50E-01	6.50E-01	0.00%	
	b parameter of Unsaturated zone	6.50E-01	6.50E-01	0.00%	
Occupancy	Inhalation rate	6.50E-01	6.50E-01	0.00%	
	Mass loading for inharation	6.50E-01	6.50E-01	0.00%	
	Indoor dust filtration factor	6.50E-01	6.50E-01	0.00%	
	External gamma shielding factor	6.47E-01	6.50E-01	0.46%	
	Indoor time factor	6.43E-01	6.56E-01	2.00%	
Ingestion Dietary	Fruit, vegetable and grain consumption	6.35E-01	9.18E-01	43.54%	
	Milk consumption	6.21E-01	7.97E-01	27.08%	
	Soil ingestion	6.45E-01	6.49E-01	0.62%	
	Drinking water intake	6.50E-01	6.50E-01	0.00%	
	Aquatic food	6.50E-01	6.50E-01	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	6.50E-01	6.50E-01	0.00%	
	Depth of roots	3.81E-01	6.50E-01	41.38%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-9
Identification of Key Parameters in Probabilistic Dose Analysis (Cs-137)

Cs 137	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	2.24E+00	2.27E+00	1.32%	
	Kd in unsaturated zone	2.27E+00	2.27E+00	0.00%	
	Kd in saturated zone	2.27E+00	2.27E+00	0.00%	
	Plant transfer factor	1.99E+00	3.69E+00	75.02%	
	Meat transfer factor	2.24E+00	2.60E+00	15.89%	
	Milk transfer factor	2.24E+00	2.35E+00	4.85%	
	Fish transfer factor	2.27E+00	2.27E+00	0.00%	
cover/hydrau	Density of contaminated zone	2.27E+00	2.27E+00	0.00%	
	Contaminated zone erosion rate	2.27E+00	2.27E+00	0.00%	
	Contaminated zone total porosity	2.27E+00	2.27E+00	0.00%	
	Contaminated zone hydraulic conductivity	2.27E+00	2.27E+00	0.00%	
	Contaminated zone b parameter	2.27E+00	2.27E+00	0.00%	
	Evapotranspiration coefficient	2.27E+00	2.27E+00	0.00%	
	Wind speed	2.27E+00	2.27E+00	0.00%	
	Runoff coefficient	2.27E+00	2.27E+00	0.00%	
Saturated zone	Density of saturated zone	2.27E+00	2.27E+00	0.00%	
	Saturated zone total porosity	2.27E+00	2.27E+00	0.00%	
	Saturated zone effective porosity	2.27E+00	2.27E+00	0.00%	
	Saturated zone hydraulic conducitivity	2.27E+00	2.27E+00	0.00%	
	Saturated zone hydraulic gradient	2.27E+00	2.27E+00	0.00%	
	Saturated zone b parameter	2.27E+00	2.27E+00	0.00%	
	Well pump intake depth	2.27E+00	2.27E+00	0.00%	
unsaturated zone	Thickness of unsaturated zone	2.27E+00	2.27E+00	0.00%	
	Density of unsaturtaed zone	2.27E+00	2.27E+00	0.00%	
	Total porosity of Unsaturated zone	2.27E+00	2.27E+00	0.00%	
	Effective porosity of Unsaturated zone	2.27E+00	2.27E+00	0.00%	
	Hydraulic conductivity of Unsaturated zone	2.27E+00	2.27E+00	0.00%	
	b parameter of Unsaturated zone	2.27E+00	2.27E+00	0.00%	
Occupancy	Inhalation rate	2.27E+00	2.27E+00	0.00%	
	Mass loading for inharation	2.27E+00	2.27E+00	0.00%	
	Indoor dust filtration factor	2.27E+00	2.27E+00	0.00%	
	External gamma shielding factor	1.32E+00	2.23E+00	40.16%	
	Indoor time factor	1.17E+00	3.18E+00	88.70%	
Ingestion Dietary	Fruit, vegetable and grain consumption	2.26E+00	2.39E+00	5.74%	
	Milk consumption	2.26E+00	2.31E+00	2.21%	
	Soil ingestion	2.26E+00	2.27E+00	0.44%	
	Drinking water intake	2.27E+00	2.27E+00	0.00%	
	Aquatic food	2.27E+00	2.27E+00	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	2.27E+00	2.27E+00	0.00%	
	Depth of roots	2.10E+00	2.27E+00	7.50%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-10
Identification of Key Parameters in Probabilistic Dose Analysis (Ce-144)

Ce 144	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	1.23E-01	1.23E-01	0.00%	
	Kd in unsaturated zone	1.23E-01	1.23E-01	0.00%	
	Kd in saturated zone	1.23E-01	1.23E-01	0.00%	
	Plant transfer factor	1.21E-01	1.33E-01	9.76%	
	Meat transfer factor	1.23E-01	1.23E-01	0.00%	
	Milk transfer factor	1.23E-01	1.23E-01	0.00%	
	Fish transfer factor	1.23E-01	1.23E-01	0.00%	
cover/hydrau	Density of contaminated zone	1.23E-01	1.23E-01	0.00%	
	Contaminated zone erosion rate	1.23E-01	1.23E-01	0.00%	
	Contaminated zone total porosity	1.23E-01	1.23E-01	0.00%	
	Contaminated zone hydraulic conductivity	1.23E-01	1.23E-01	0.00%	
	Contaminated zone b parameter	1.23E-01	1.23E-01	0.00%	
	Evapotranspiration coefficient	1.23E-01	1.23E-01	0.00%	
	Wind speed	1.23E-01	1.23E-01	0.00%	
	Runoff coefficient	1.23E-01	1.23E-01	0.00%	
Saturated zone	Density of saturated zone	1.23E-01	1.23E-01	0.00%	
	Saturated zone total porosity	1.23E-01	1.23E-01	0.00%	
	Saturated zone effective porosity	1.23E-01	1.23E-01	0.00%	
	Saturated zone hydraulic conducitivity	1.23E-01	1.23E-01	0.00%	
	Saturated zone hydraulic gradient	1.23E-01	1.23E-01	0.00%	
	Saturated zone b parameter	1.23E-01	1.23E-01	0.00%	
	Well pump intake depth	1.23E-01	1.23E-01	0.00%	
unsaturated zone	Thickness of unsaturated zone	1.23E-01	1.23E-01	0.00%	
	Density of unsaturtaed zone	1.23E-01	1.23E-01	0.00%	
	Total porosity of Unsaturated zone	1.23E-01	1.23E-01	0.00%	
	Effective porosity of Unsaturated zone	1.23E-01	1.23E-01	0.00%	
	Hydraulic conductivity of Unsaturated zone	1.23E-01	1.23E-01	0.00%	
	b parameter of Unsaturated zone	1.23E-01	1.23E-01	0.00%	
Occupancy	Inhalation rate	1.23E-01	1.23E-01	0.00%	
	Mass loading for inharation	1.23E-01	1.23E-01	0.00%	
	Indoor dust filtration factor	1.23E-01	1.23E-01	0.00%	
	External gamma shielding factor	6.28E-02	1.21E-01	47.32%	
	Indoor time factor	5.35E-02	1.81E-01	103.66%	
Ingestion Dietary	Fruit, vegetable and grain consumption	1.23E-01	1.25E-01	1.63%	
	Milk consumption	1.23E-01	1.23E-01	0.00%	
	Soil ingestion	1.23E-01	1.23E-01	0.00%	
	Drinking water intake	1.23E-01	1.23E-01	0.00%	
	Aquatic food	1.23E-01	1.23E-01	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	1.23E-01	1.23E-01	0.00%	
	Depth of roots	1.22E-01	1.23E-01	0.81%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-11
Identification of Key Parameters in Probabilistic Dose Analysis (Pu-239)

Pu239	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	4.39E-01	4.39E-01	0.00%	
	Kd in unsaturated zone	4.39E-01	4.39E-01	0.00%	
	Kd in saturated zone	4.39E-01	4.39E-01	0.00%	
	Plant transfer factor	1.94E-01	1.54E+00	306.61%	
	Meat transfer factor	4.36E-01	4.45E-01	2.05%	
	Milk transfer factor	4.39E-01	4.39E-01	0.00%	
	Fish transfer factor	4.39E-01	4.39E-01	0.00%	
cover/hydrau	Density of contaminated zone	4.39E-01	4.39E-01	0.00%	
	Contaminated zone erosion rate	4.39E-01	4.39E-01	0.00%	
	Contaminated zone total porosity	4.39E-01	4.39E-01	0.00%	
	Contaminated zone hydraulic conductivity	4.39E-01	4.39E-01	0.00%	
	Contaminated zone b parameter	4.39E-01	4.39E-01	0.00%	
	Evapotranspiration coefficient	4.39E-01	4.39E-01	0.00%	
	Wind speed	4.22E-01	4.37E-01	3.42%	
	Runoff coefficient	4.39E-01	4.39E-01	0.00%	
Saturated zone	Density of saturated zone	4.39E-01	4.39E-01	0.00%	
	Saturated zone total porosity	4.39E-01	4.39E-01	0.00%	
	Saturated zone effective porosity	4.39E-01	4.39E-01	0.00%	
	Saturated zone hydraulic conducitivity	4.39E-01	4.39E-01	0.00%	
	Saturated zone hydraulic gradient	4.39E-01	4.39E-01	0.00%	
	Saturated zone b parameter	4.39E-01	4.39E-01	0.00%	
	Well pump intake depth	4.39E-01	4.39E-01	0.00%	
unsaturated zone	Thickness of unsaturated zone	4.39E-01	4.39E-01	0.00%	
	Density of unsaturtaed zone	4.39E-01	4.39E-01	0.00%	
	Total porosity of Unsaturated zone	4.39E-01	4.39E-01	0.00%	
	Effective porosity of Unsaturated zone	4.39E-01	4.39E-01	0.00%	
	Hydraulic conductivity of Unsaturated zone	4.39E-01	4.39E-01	0.00%	
	b parameter of Unsaturated zone	4.39E-01	4.39E-01	0.00%	
Occupancy	Inhalation rate	4.30E-01	4.50E-01	4.56%	
	Mass loading for inharation	4.15E-01	4.23E-01	1.82%	
	Indoor dust filtration factor	4.33E-01	4.55E-01	5.01%	
	External gamma shielding factor	4.39E-01	4.39E-01	0.00%	
	Indoor time factor	3.63E-01	5.03E-01	31.89%	
Ingestion Dietary	Fruit, vegetable and grain consumption	4.27E-01	6.57E-01	52.39%	
	Milk consumption	4.39E-01	4.39E-01	0.00%	
	Soil ingestion	3.57E-01	4.24E-01	15.26%	
	Drinking water intake	4.39E-01	4.39E-01	0.00%	
	Aquatic food	4.39E-01	4.39E-01	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	4.39E-01	4.39E-01	0.00%	
	Depth of roots	2.92E-01	4.39E-01	33.49%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-12
Identification of Key Parameters in Probabilistic Dose Analysis (Am-241)

Am 241	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	4.68E-01	4.74E-01	1.27%	
	Kd in unsaturated zone	4.72E-01	4.72E-01	0.00%	
	Kd in saturated zone	4.72E-01	4.72E-01	0.00%	
	Plant transfer factor	2.21E-01	1.60E+00	292.16%	
	Meat transfer factor	4.70E-01	4.75E-01	1.06%	
	Milk transfer factor	4.72E-01	4.72E-01	0.00%	
	Fish transfer factor	4.72E-01	4.72E-01	0.00%	
cover/hydrau	Density of contaminated zone	4.71E-01	4.72E-01	0.21%	
	Contaminated zone erosion rate	4.72E-01	4.72E-01	0.00%	
	Contaminated zone total porosity	4.72E-01	4.72E-01	0.00%	
	Contaminated zone hydraulic conductivity	4.72E-01	4.72E-01	0.00%	
	Contaminated zone b parameter	4.72E-01	4.72E-01	0.00%	
	Evapotranspiration coefficient	4.72E-01	4.73E-01	0.21%	
	Wind speed	4.54E-01	4.69E-01	3.18%	
	Runoff coefficient	4.72E-01	4.73E-01	0.21%	
Saturated zone	Density of saturated zone	4.72E-01	4.72E-01	0.00%	
	Saturated zone total porosity	4.72E-01	4.72E-01	0.00%	
	Saturated zone effective porosity	4.72E-01	4.72E-01	0.00%	
	Saturated zone hydraulic conducitivity	4.72E-01	4.72E-01	0.00%	
	Saturated zone hydraulic gradient	4.72E-01	4.72E-01	0.00%	
	Saturated zone b parameter	4.72E-01	4.72E-01	0.00%	
	Well pump intake depth	4.72E-01	4.72E-01	0.00%	
unsaturated zone	Thickness of unsaturated zone	4.72E-01	4.72E-01	0.00%	
	Density of unsaturtaed zone	4.72E-01	4.72E-01	0.00%	
	Total porosity of Unsaturated zone	4.72E-01	4.72E-01	0.00%	
	Effective porosity of Unsaturated zone	4.72E-01	4.72E-01	0.00%	
	Hydraulic conductivity of Unsaturated zone	4.72E-01	4.72E-01	0.00%	
	b parameter of Unsaturated zone	4.72E-01	4.72E-01	0.00%	
Occupancy	Inhalation rate	4.62E-01	4.83E-01	4.45%	
	Mass loading for inharation	4.46E-01	4.55E-01	1.91%	
	Indoor dust filtration factor	4.65E-01	4.88E-01	4.87%	
	External gamma shielding factor	4.59E-01	4.71E-01	2.54%	
	Indoor time factor	3.79E-01	5.49E-01	36.02%	
Ingestion Dietary	Fruit, vegetable and grain consumption	4.60E-01	6.94E-01	49.58%	
	Milk consumption	4.72E-01	4.72E-01	0.00%	
	Soil ingestion	3.87E-01	4.56E-01	14.62%	
	Drinking water intake	4.72E-01	4.72E-01	0.00%	
	Aquatic food	4.72E-01	4.72E-01	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	4.72E-01	4.72E-01	0.00%	
	Depth of roots	3.21E-01	4.72E-01	31.99%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Table A-13
Identification of Key Parameters in Probabilistic Dose Analysis (Cm-244)

Cm 244	Uncentainty analysis Input	Dose @ 5%	Dose @ 95%	Variability percentage	Key Parameters
Soil concentration	Kd in contaminated zone	2.43E-01	2.43E-01	0.00%	
	Kd in unsaturated zone	2.43E-01	2.43E-01	0.00%	
	Kd in saturated zone	2.43E-01	2.43E-01	0.00%	
	Plant transfer factor	1.06E-01	8.59E-01	309.88%	
	Meat transfer factor	2.43E-01	2.47E-01	1.65%	
	Milk transfer factor	2.43E-01	2.44E-01	0.41%	
	Fish transfer factor	2.43E-01	2.43E-01	0.00%	
cover/hydrau	Density of contaminated zone	2.43E-01	2.43E-01	0.00%	
	Contaminated zone erosion rate	2.43E-01	2.43E-01	0.00%	
	Contaminated zone total porosity	2.43E-01	2.43E-01	0.00%	
	Contaminated zone hydraulic conductivity	2.43E-01	2.43E-01	0.00%	
	Contaminated zone b parameter	2.43E-01	2.43E-01	0.00%	
	Evapotranspiration coefficient	2.43E-01	2.43E-01	0.00%	
	Wind speed	2.43E-01	2.43E-01	0.00%	
	Runoff coefficient	2.43E-01	2.43E-01	0.00%	
Saturated zone	Density of saturated zone	2.43E-01	2.43E-01	0.00%	
	Saturated zone total porosity	2.43E-01	2.43E-01	0.00%	
	Saturated zone effective porosity	2.43E-01	2.43E-01	0.00%	
	Saturated zone hydraulic conducitivity	2.43E-01	2.43E-01	0.00%	
	Saturated zone hydraulic gradient	2.43E-01	2.43E-01	0.00%	
	Saturated zone b parameter	2.43E-01	2.43E-01	0.00%	
	Well pump intake depth	2.43E-01	2.43E-01	0.00%	
unsaturated zone	Thickness of unsaturated zone	2.43E-01	2.43E-01	0.00%	
	Density of unsaturtaed zone	2.43E-01	2.43E-01	0.00%	
	Total porosity of Unsaturated zone	2.43E-01	2.43E-01	0.00%	
	Effective porosity of Unsaturated zone	2.43E-01	2.43E-01	0.00%	
	Hydraulic conductivity of Unsaturated zone	2.43E-01	2.43E-01	0.00%	
	b parameter of Unsaturated zone	2.43E-01	2.43E-01	0.00%	
Occupancy	Inhalation rate	2.43E-01	2.43E-01	0.00%	
	Mass loading for inharation	2.43E-01	2.43E-01	0.00%	
	Indoor dust filtration factor	2.40E-01	2.52E-01	4.94%	
	External gamma shielding factor	2.43E-01	2.43E-01	0.00%	
	Indoor time factor	2.43E-01	2.43E-01	0.00%	
Ingestion Dietary	Fruit, vegetable and grain consumption	2.43E-01	2.43E-01	0.00%	
	Milk consumption	2.43E-01	2.43E-01	0.00%	
	Soil ingestion	2.43E-01	2.43E-01	0.00%	
	Drinking water intake	2.43E-01	2.43E-01	0.00%	
	Aquatic food	2.43E-01	2.43E-01	0.00%	
Ingestion Non Dietary	Depth of soil mixing layer	2.43E-01	2.43E-01	0.00%	
	Depth of roots	2.43E-01	2.43E-01	0.00%	

V (variability) = (Dose@95% - Dose@5%) / Dose@Deterministic * 100%,
while V > 10%, we assume the parameter is key parameter;
if there are more than ten key parameters, we select the top ten to analyze uncertainty.

Target:
Nuclear Power

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

1006949

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com