NUREG/CR-5512, Vol. 3
SAND99-2148

Residual Radioactive Contamination From Decommissioning

Parameter Analysis

Draft Report for Comment

Sandia National Laboratories

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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NUREG/CR-5512, Vol. 3
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Manuscript Completed: August 1999
Date Published: October 1999

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NRC Job Code W6227

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Abstract

NUREG/CR-5512 is a multi-volume report describing a generic modeling analysis of the potential radiation dose from exposures to residual radioactive contamination after the decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission. Individual volumes describe the generic scenarios, models, and parameter values for screening calculations, and the software that implements these calculations. This third volume describes the analysis used to define default parameter values for the Building Occupancy and Residential scenarios and the results of that analysis. Different procedures are used to define default values for parameters that characterize the behavior of potential receptors (behavioral parameters) and parameters that characterize the physical features of the site (physical parameters). Both procedures start from a literature review which identifies current sources of data about the parameter, considering the way the parameter is defined and used in the screening model. Behavioral parameters represent the average member of the critical group. For screening calculations, a screening group has been defined for each scenario, and a distribution of parameter values was assigned that describes the variations among individuals in the screening group. The default value for behavioral parameters is the average value of this distribution. Values for physical parameters depend on the conditions existing at each site. Screening calculations are designed to support dose-based decisions without requiring information about specific site conditions. To provide this support, the range of conditions that might exist at licensed sites was used to develop distributions describing the variability in site-specific parameter values. These distributions were then used, along with the scenario models defined in Volume 2, to derive distributions of potential dose values for unit concentrations of individual source radionuclides. Parameter values were then identified which produce dose values in the upper quantiles of the distributions for all source radionuclides. The resulting parameter values define a generic screening calculation that has a limited risk of underestimating a site-specific dose calculation based on the generic scenarios, models, and screening group. The distributions that underlie these parameter values provide a basis for developing site-specific parameter values for the generic models.

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FOREWORD

This technical report, NUREG/CR-5512, Volume 3, was prepared by Sandia National Laboratory under their DOE Interagency Work Order (JCN W6227) with the Radiation Protection, Environmental Risk & Waste Management Branch, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. This report is the third volume to be published in the NUREG/CR-5512 series and provides detailed descriptions of the parameters used in the model, and the methodology and results of the parameter analysis that was performed to select a default parameter set for use in simple screening.

NUREG/CR-5512 technical report series includes Volume 1, which describes the scenarios and calculational approach for translating residual radioactivity to dose. Volume 2 is the User's guide for the DandD software, which automates the dose calculations described in Volume 1. Volume 2 also contains an appendix which describes the changes that have been made to the models and calculations since the publication of Volume 1. This series of reports is a part of the technical basis for the License Termination Rule (10 CFR 20, Subpart E), and was used to develop the implementation guidance for the Rule.

This NUREG/CR report is not a substitute for NRC regulations, and compliance is not required. The approaches and/or methods described in this NUREG/CR are provided for information only. Publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein. Use of product or trade names is for identification purposes only and does not constitute endorsement by the NRC or Sandia National Laboratory.

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Acknowledgments

This report was made possible through contributions of a number of individuals who have provided insightful analyses, thoughtful reviews, and technical supervision. The authors appreciated the opportunity to work with Christine Daily of the Nuclear Regulatory Commission, whose initiative, perseverence, and technical direction underlie this work. We would also like to thank Felicia Duran of Sandia National Laboratories for her direction of the project during its early phases, and her work on identifying appropriate data sources for defining behavioral parameter values. Elena Kalinina if GRAM Inc. reviewed and synthesized the extensive literature on partition coefficients for this analysis. David Gallegos and Paul Davis of SNL both provided critical programmatic and technical oversight. Steve Conrad of SNL developed and implemented the method used to define consistent soil characteristics for the Residential Scenario model. Sharon Wirth of IT Corporation contributed a thorough and thoughtful analysis of the literature on soil-to-plant concentration factors. Rick Haaker of AQ Safety, Inc. performed a detailed evaluation of the shielding properties of typical residences. Doug Brosseau of SNL analyzed a number of agricultural parameters, and help shepherd this document through the final stages of publication. We appreciate the time and thoughts of our numerous reviewers. Their insights helped us to improve our analysis, and to clarify our presentation of controversial points. Finally, the authors are indebted to Faith Puffer of Tech Reps, who oversaw the editing and preparation of this document, for her care and forbearance.

1.0 Overview

NUREG/CR-5512 is a multivolume report describing a generic modeling analysis of the potential radiation dose from exposures to residual radioactive contamination after the decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission (NRC). Individual volumes describe the generic models, scenarios, and parameter values for screening calculations of the potential dose, and the software that implements those calculations. Volume 1 of this report (Kennedy and Strenge, 1992 [hereafter referred to as "Volume 1"]) provides the technical basis for translating residual contamination levels to annual dose for decommissioned sites. Volume 1 describes four exposure scenarios, and defines default models for these scenarios. Volume 2 (Wernig et al., 1999) is a user's manual for DandD, the computer software that implements the models defined in Volume 1, which runs under Microsoft® Windows. This document, Volume 3 of the report, presents the procedures and results of the default parameter analysis. Volume 4 documents the comparison of DandD models to models developed for similar purposes.

In this volume, Section 2 summarizes the purpose of the dose modeling to provide a context for the default parameter analysis. Section 3 presents the theory and procedure underlying the parameter analysis. The primary input to this procedure is a set of probability distributions describing uncertainty in model parameter values. Section 4 discusses the interpretation and use of these distributions in the analysis, and some general considerations for defining the distributions.

The procedure described in Section 3 was applied separately to two exposure scenarios and associated dose models defined in Volume 1: the building occupancy scenario and residential scenario. Section 5 describes the parameter analysis of the building occupancy scenario, while Section 6 describes the parameter analysis for the residential scenario. Each section includes an overview of the scenario, the default model, and each parameter used in the model. Probability distributions are defined for most of the model parameters, and the bulk of each section is devoted to the literature reviews and analyses that underlie these distributions. For each uncertain parameter, the current relevant literature is identified, reviewed, and assessed and used to develop a probability distribution for the parameter. The results of the analysis include probability distributions of dose for each individual radionuclide that may be specified in the model source term, and a set of parameter values which, if used to calculate dose, produce a dose value at least as large as a specified quantile of the dose distributions for all source radionuclides. These results are summarized for both scenarios. A summary of the procedure and results is provided in Section 7.

2.0 Introduction

2.1 Overview of the NUREG/ CR-5512 Methodology

The NRC is responsible for evaluating requests from facility owner/operators for the partial or total termination of NRC operating licenses for their facilities. This evaluation is based on radiological criteria in defined in 10 CFR 20 Subpart E (NRC, 1997). These criteria establish limits on the annual total effective dose equivalent (TEDE) received during a year to an average member of the critical group (AMCG). The critical group is "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances" (10 CFR 20.1003).

An overall framework for decision making based on these criteria is defined in draft NUREG-1549 (NRC, 1998). This framework entails iterative dose assessments. Each assessment is designed to provide a defensible basis for terminating the license if the calculations meet the limits defined in the radiological criteria. If the limits are not met, the framework allows the licensee to evaluate a range of alternative strategies. Alternatives may include remedial action at the site, but may also include data collection designed to refine the dose assessment calculation. This framework allows the licensee to coordinate their data collection efforts, and other site management actions, to follow the most efficient path to license termination.

Implementing this framework requires a process for assessing dose that can be used with various amounts of information. To provide the greatest flexibility in tailoring data collection to site conditions, the initial dose assessment should require a minimum amount of site data. The decision framework optimizes the transition to more information-intensive site-specific assessments if such assessments are needed. The scenarios, models, and parameters defined in NUREG/CR-5512 are designed for the purpose of providing a defensible basis for calculating dose with minimal information requirements.

Volume 1 defines a Building Occupancy Scenario for assessing unrestricted release of buildings having residual contamination on building surfaces. For unrestricted release of land having soil contamination, Volume 1 defines a Residential Scenario which considers the residential use of the property, including the use of groundwater for drinking and irrigation of farm products. For each scenario, a set of potential exposure pathways have been identified based on the assumed location of residual contamination and receptor behavior. Mathematical models are also defined for each of these pathways in Volume 1, as well as provisional values for the model parameters.

2.2 Background and Previous Work

In 1987, Pacific Northeast Laboratories (PNL) began developing the NUREG/CR-5512 methodology to translate residual radioactive contamination levels into potential radiation doses to the public. A draft of NUREG/CR-5512, Vol. 1, was issued for comment in January 1990. During 1990 over 250 technical and policy comments were received on this draft. The technical approach was revised, and the final Volume 1 report was issued in 1992.

During 1993 Sandia National Laboratories (SNL) calculated dose conversion factors (DCFs) using the NUREG/CR-5512 methodology to support the NRC's draft regulatory guide NUREG-1500 (Daily et al., 1994) and the draft generic environmental impact study (dGEIS) on radiological criteria for decommissioning, NUREG-1496 (NRC, 1994). Four separate FORTRAN computer codes were developed to perform these calculations. These codes implemented the mathematical models defined in Volume 1 for four exposure scenarios: building occupancy, building renovation, drinking water, and residential. The codes were developed by SNL specifically for these calculations and were not designed for external release or use.

In 1994, SNL began developing DandD, a user-friendly software product that implements the NUREG/CR-5512 methodology. DandD integrates the scenario model codes originally developed by SNL with a graphical user interface. DandD is designed to run under Microsoft® Windows with a minimal hardware configuration. A beta version of DandD was released in August 1995. The code was modified based on comments on the beta version. Version 1.0 of DandD was released on July 1998. The user's manual for this program is Volume 2 of NUREG/CR-5512 (Wernig et al., 1999).

Throughout the process of supporting the NUREG-1500 and GEIS calculations, and implementing and testing the DandD software, SNL and the NRC staff continued to evaluate and improve the NUREG/CR-5512 methodology. Several changes and corrections were made to the original methodology described in Volume 1. These changes are documented in Volume 2 (Wernig et al., 1999).

All dose estimates are uncertain due to uncertainty about the processes and parameters that control exposure. The range of possible dose values given this uncertainty must be considered in order to support decisions based on dose. A tendency for a screening calculation to produce a dose value in the upper end of the range of possible doses allows that calculation to be used in decision making (see Section 3 of this document). The scenarios, models, and parameter values defined in Volume 1 were intended to have this tendency, but the supporting arguments were qualitative. NRC directed SNL to develop probability distribution functions (PDFs) for parameters, based on the information in Volume 1 and on any newer published studies, and to identify default values for those parameters suitable for screening calculations. This volume documents the process for defining PDFs and selecting default parameter values.

2.3 Scope and Purpose of the Parameter Analysis

The NRC has designed the scenarios and models described in Volume 1, to be an acceptable basis for evaluating compliance at a wide range of sites while requiring minimal information from the licensee. The parameter analysis described in this document supports this objective by defining values for the parameters of the Volume 1 models that require minimal site specific information and provide a defensible basis for evaluating compliance. In particular, the analysis defines parameter values which can be used in the Volume 1 models given only information about the site source term (in addition to any information required to defend the use of the Volume 1 models themselves).

Four scenarios are defined in Volume 1: building occupancy, building renovation, drinking water, and residential. Only the building occupancy and residential scenarios are used to assess compliance with 10 CFR 20 Subpart E. The models defined in Volume 1 for these two scenarios are considered in this document.

Unlike the provisional default values defined in Volume 1, parameter values defined in this document result from a formal quantitative analysis. This analysis is based on probability distributions for the model parameters which describe the variability in potential site-specific values over the current and future population of licensed sites. The parameter distributions developed in this analysis are based on the use of the parameter in the Volume 1 dose model. Although the information used to develop these distributions may be relevant in other applications, the resulting parameter distributions reflect specific model assumptions (such as the size of the region characterized by the parameter) and are not generally appropriate for other models.

3.0 Theory

3.1 Treatment of Uncertainty in Models and Parameters

Default models and parameter values are designed to allow license termination decisions to be made without requiring site data other than source concentrations. Like all dose assessments used to reach regulatory decisions, screening assessments should be reasonably conservative, meaning that the dose estimate is likely to decrease if more site information was included in the dose calculation. By designing the default models and parameter values so that they tend to overestimate the possible site-specific calculations, the screening dose assessment provides a defensible basis for decision-making without site-specific modeling. The purpose of the parameter analysis is to identify default values for the DandD model parameters that are consistent with this requirement.

A specific procedure for calculating dose can be defended by considering the range of possible calculations that might be made if more information was included in the calculation. Figure 3.1 shows the conceptual design of this procedure. A screening analysis is used to calculate dose using a limited amount of site information. This dose value is then compared to the value that would be calculated if additional site information was used. Because this additional information is not available for the screening calculation, a range of possibilities must be considered, leading to a range of possible site conditions. Each possible condition lends to a possible site-specific dose calculation. The tendency of the screening calculation to overestimate the *possible* calculations can then be assessed. The screening calculations can also be tailored to overestimate an acceptable fraction of the possible calculations.

This process provides a precise and objective characterization of the risk in using the screening calculation to make decisions, but it requires a specific set of alternative calculations to which the screening calculation will be compared. These alternative calculations depend on three factors:

1. The type and amount of additional information that would be available for the alternative calculations,
2. How this information would modify the dose assessment and
3. What range of possible values this information might have.

The conceptual approach illustrated in Figure 3.1 can be applied to manage uncertainty for a broad class of problems. Applying the approach to a specific problem requires definition of the possible site conditions, and corresponding dose calculations, using the three factors described above. The analysis described in this report is designed to control the risk of using the screening calculation to make decisions when the values of the parameters describing the site are unknown. Information added to the screening calculations includes any data that might limit or determine values for the dose model parameters. This information modifies the dose assessment by establishing the appropriate site-specific value for the parameter. The range of possible site conditions is defined by the range of possible parameter values that might be established from this information. The likelihood of obtaining different values for the parameters is described by defining probability distributions for each parameter. These probability distributions allow parameter values to be chosen in a way that quantitatively limits the risk associated with the screening calculation.

3.2 Overview of Procedures used to Define Default Parameter Values

The initial screening calculations are defined by the default parameter values used in place of site-specific values. The method used to establish default values depends on whether the parameter represents the behavior of potential receptors, the metabolic characteristics of potential receptors, or the physical characteristics of the site. The approaches for defining defaults for these distinct classes of parameters are summarized in this section.

Licensees may propose alternative values for physical and behavioral parameters based on site-specific features or conditions, or on site data, as discussed in NUREG/CR-1549 (NRC, 1998). The type of information used to support site specific parameter values depends on whether the parameter describes physical characteristics of the site, or behavioral characteristics of potential receptors.

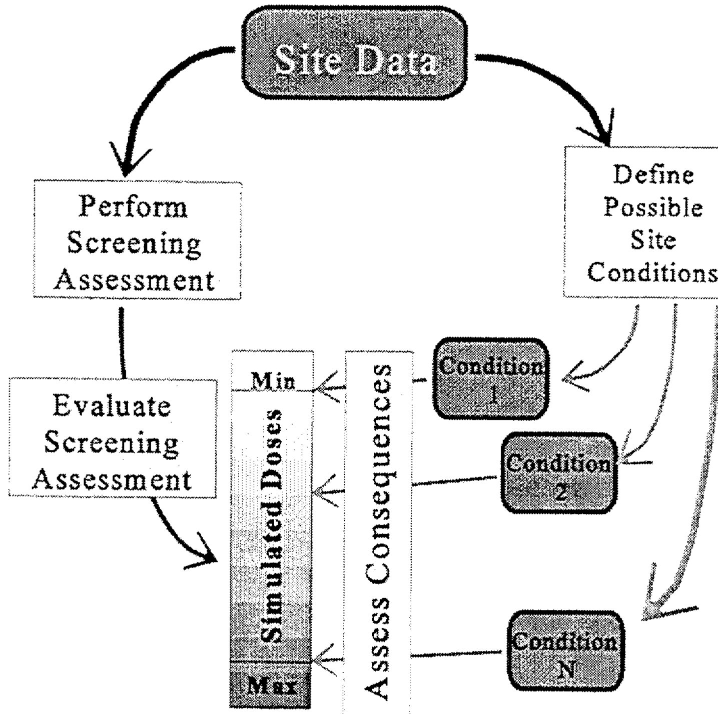

Figure 3.1 Conceptual design for assessing or designing screening calculations

3.2.1 Behavioral Parameters

In a site-specific analysis, behavioral parameters characterize the *AMCG* at the site. The critical group is the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances (10 CFR 20.1003). Default values for behavioral parameters are defined by stipulating a generic *screening group* for the scenario. The screening group is a site-independent population, appropriate for use at all sites, which is reasonably expected to receive the greatest exposure given the scenario definition (generic critical groups are defined in Volume 1). For the building occupancy scenario, the screening group consists of full-time adult male workers in light industry. For the residential scenario, the screening group consists of male resident farmers.

Default values for behavioral parameters were determined by:

1. Identifying the potential variability in the parameter value among individuals in the screening group;
2. Defining a probability distribution describing this variability;
3. Finding the average value from this distribution, which was used to estimate the value for the average member of the screening group (AMSG).

The average parameter value calculated in Step (3) is an estimate of the parameter for the AMSG because the average member is defined as the member receiving the average dose for the screening group, rather than the member with the average behavior. Using average parameter values produce the average dose provided the dose model is a linear function of each of the behavioral parameters. This provision is satisfied by the behavioral parameter values in the default models for the occupancy and residential scenarios.

3.2.2 Metabolic Parameters

Following the recommendation of International Commission on Radiological Protection (ICRP) 43 (ICRP, 1984), parameters representing metabolic characteristics are defined by average values for the general population. These values are not expected to be modified as part of a site-specific analysis. Breathing rates were the only metabolic parameters considered in the analysis.

3.2.3 Physical Parameters

Site-specific values for parameters describing physical characteristics of the site would generally be supported by collecting site-specific data, or by citing relevant literature data. Following the conceptual design shown in Figure 3.1, default values for these parameters were defined by considering the range of possible site-specific values that might be obtained at a site located anywhere in the United States. The remainder of Section 3 details the procedure used to establish default values for the physical parameters. In overview, this procedure consists of:

1. Identifying the potential variability in the parameter value considering the range of possible site conditions and locations;

2. Defining a probability distribution to describe this variability;

3. For each individual source radionuclide, finding the distribution of doses that might result from a site specific analysis. The dose distribution is based on the distributions of physical parameter values that might be used in such an analysis, defined in Step 2.

4. For each radionuclide, selecting a screening dose value from the dose distribution that is appropriate for decision making (e.g., a value that overestimates some acceptable fraction of the possible values);

5. Identifying parameter values which, when used with any source nuclide, reproduce, as closely as possible, the screening dose value selected from the dose distribution in Step 4.

In the absence of site data, the dose distributions defined in Step 3 describe the potential variability in site-specific dose values, and allow an appropriate dose value to be selected in Step 4 as a basis for making license termination decisions. These screening dose values are defined for unit amounts of individual source nuclides. The parameter values defined in Step 5 provide a way of reproducing these screening dose values for *all sources* using a single DandD calculation, rather than the multiple calculations that would be required to reproduce the complete dose distribution. This procedure produces *one* set of default parameter values that is applicable to all radionuclides.

3.3 Probabilistic Formulation

A screening dose assessment is a defensible basis for making decisions because the dose is likely to be overestimated rather than underestimated. The analysis described below uses a quantitative (probabilistic) definition of "likelihood" to insure that the physical parameter values satisfy this requirement. Demonstrating that a particular dose calculation satisfies this condition requires a probability value for each of the alternative conditions in Figure 3.1. These probabilities are then applied to the possible alternative dose calculations, which the screening calculation should tend to overestimate.

For a particular scenario, the default dose assessment model is denoted by the function *m*. The model calculates a TEDE value using a vector[1] of input parameters **x** and a vector source term specification **s**:

$$d_T = m(\mathbf{x},\mathbf{s}) \qquad (3.1)$$

The goal of the parameter analysis is to find some vector of default parameter values $\mathbf{x_d}$ that are appropriate when site-specific values are unknown. The unknown site-specific parameter values, and site-specific source term, are designated by the random variables **X** and **S**. To be appropriate for decision-making, the set of default parameters is designed to limit the risk of making an incorrect decision.

The default parameter values $\mathbf{x_d}$ can *potentially* lead to an incorrect decision if they underestimate the site-specific dose. This condition is termed an *inversion*, designated by the binary random variable I. Default parameter values are sought which limit the probability of inversion:

$$P(I) = P\big(m(\mathbf{x_d},\mathbf{S}) < m(\mathbf{X},\mathbf{S})\big) \le P_{crit} \qquad (3.2)$$

This equation defines a quantitative test following the conceptual design of Figure 3.1. The screening dose calculated with default parameters is required to overestimate all but a fraction P_{crit} of the dose calculations that follow from the possible site conditions. The possible site conditions are defined by the distributions assigned to the random variables **X** and **S**.

There is insufficient information to estimate a distribution for the source term **S**. Therefore a more restrictive condition is used: the probability of inversion conditional on a unit source is limited for each component of the source vector:

$$\begin{aligned} &P\big(I(\mathbf{s_i})\big) \equiv P\big(I|\mathbf{S} = \mathbf{s}_i\big) = \\ &P\big(m(\mathbf{x_d},\mathbf{s}_i) < m(\mathbf{X}(\mathbf{s}_i),\mathbf{s}_i) \le P_{crit}\big) \qquad (3.3) \\ &i = 1 \ldots n_s \end{aligned}$$

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[1]A *vector* is a quantity that is defined by an ordered set of numbers rather than by a single number. A location in a three-dimensional space, for example, is a vector defined by the values for the x, y, and z coordinates of the location.

where:

$$\mathbf{s}_i \equiv \{s_j\} \text{ with } s_j = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases} \qquad (3.4)$$

The n_s components of the source vector corresponds to the individual radionuclides that can occur in the source term. Table 3.1 lists these radionuclides.

As indicated in Equation 3.3, variability in site-specific parameter values is generally a function of the site source-term. This potential interdependence has been assumed to be insignificant in this analysis, so that:

$$\mathbf{X}(\mathbf{s}_i) = \mathbf{X} \qquad (3.5)$$

From Equation 3.1, the (random) site-specific parameters **X** produce a (random) TEDE value D_{Ti} for each of the n_s source terms:

$$D_{Ti} = m(\mathbf{X}, \mathbf{s}_i) \quad i = 1 \ldots n_s \qquad (3.6)$$

Each of these random dose values has an associated probability distribution F_{Di} that depends on the probability distribution assigned to the parameters. For each F_{Di}, there is an associated quantile d_{Ci} of order 1 − P_{crit} such that:

$$F_{Di}(d_{Ci}) \equiv P(D_{Ti} < d_{Ci}) = 1 - P_{crit} \qquad (3.7)$$

In order for Equation 3.3 to be satisfied, the TEDE value calculated using the default parameters, denoted d_{Di}, must be larger than the corresponding d_{Ci} for each source:

$$d_{Di} \equiv m(\mathbf{x_d}, s_i) \geq d_{Ci} \quad i = 1 \ldots n_s \qquad (3.8)$$

Equation 3.8 defines a set of n_s inequality constraints that must be satisfied by the default parameters. In words, the default values must produce dose values in the upper P_{crit} tail of the dose distribution for each source nuclide.

For both scenario models considered in this analysis, the number of constraints (i.e. source nuclides) is larger than the number of adjustable parameters (i.e. the dimension of $\mathbf{x}_d$)[2]. Solutions for $\mathbf{x}_d$ may not exist for over-constrained problems of this kind. Whether or not solutions can be found depends on the compatibility of the n_s constraints, that is, whether parameter values that tend to produce large doses for one source also tend to produce large doses for other sources.

Appendix B describes the procedure used to solve Equation 3.8. The algorithm generates sets of possible solutions for $\mathbf{x}_d$, which are then evaluated to determine whether they solve Equation 3.8. If no solution is found in the set, the algorithm creates a new set of candidate solutions based on the evaluation.

Multiple solutions to Equation 3.8 were identified for both scenario models. Two figures of merit, the average inversion probability (AIP) and the joint parameter exceedance probability (JPEP), were defined to help select among these solutions. The AIP measures how close a particular solution comes to solving Equation 3.8 as a strict equality, and JPEP measures how plausible the parameter values are.

3.4 Remarks on the Formulation

The screening dose assessment is required to over-estimate a specified fraction of the dose values that are consistent with the available information. This requirement is imposed in order to create a defensible basis for decision making according to the conceptual design described in Section 3.1. The resulting dose estimate is conservative in the sense that it is designed to over-estimate dose with a specified probability.

The formulation of the screening calculation introduces two additional sources of conservatism. First, the probability of an inversion is always larger than the probability of an incorrect dose-based decision, so that limiting the former is a conservative means of controlling the latter. Second, the requirement that the limit on inversion probability be satisfied for all source nuclides using a common set of deterministic parameters practically requires that the limit be surpassed for some source nuclides.

By definition, an inversion occurs whenever the default parameters underestimate the site-specific dose. The default parameters would lead to an inappropriate regulatory decision if the default dose was less than the regulatory limit of 25 mrem, and the site-specific dose was greater than the regulatory limit. Not all inversions lead to potentially inappropriate decisions: limiting the probability of inversion in Equation 3.2 is therefore more restrictive than limiting the probability of an inappropriate decision.

The dose values d_{Di} and d_{Ci} can be interpreted as factors that convert unit amounts each source nuclide i to dose

[2]Note that although the residential scenario model has 652 input parameters, many of these parameters (e.g. partition coefficients and plant uptake factors) are specified by chemical element, and therefore only affect the dose from particular radionuclides.

values which might be used to reach a regulatory decision. The dose conversion factor d_{Ci} is *the minimum dose factor that satisfies the specified risk tolerance* P_{crit}. The probability that a site-specific dose (for a unit source) would exceed d_{Ci} is exactly P_{crit}, given the assumptions underlying the dose model m. The default dose conversion factor d_{Di} must be at least as large as d_{Ci}, as indicated in equation (3.8). In addition to satisfying the specified risk tolerance P_{crit}, the d_{Di} values are further required to arise from a common set of parameter values for all sources.

An explicitly probabilistic screening calculation would use the dose conversion factor d_{Ci} directly as the dose (per unit source) that overestimates site-specific dose with a likelihood of $1 - P_{crit}$. By definition, the "real" dose (represented by the calculation using model m and site-specific parameters) is greater than this value with probability P_{crit}. The calculation using the default parameters is instead apparently deterministic, in that only a single calculation using $\mathbf{x}_d$ is required. The default parameters $\mathbf{x}_d$, however, are selected and justified through the underlying probabilistic analysis: the resulting "default" dose d_{Di} must be greater than (or equal to) the corresponding quantile of order $1 - P_{crit}$, d_{Ci}. The default parameters are simply a mechanism for producing doses that bound the appropriate quantiles for all sources.

The advantage of using default parameters to make screening decisions is that the deterministic defaults subsume the complexities of the underlying (probabilistic) justification. The disadvantage is that the "default" doses d_{Di} are more restrictive than the doses d_{Ci} (which exactly satisfy the specified tolerance for decision error) because the "default" doses are required to come from a common set of parameter values for all sources.

Table 3.1 Source nuclides used in the parameter analysis

Source ID	Source*	Source ID	Source	Source ID	Source
1	3H	87	126Sn+C	180	232Th
2	10Be	89	125Sb	181	232Th+C
3	14C	93	123mTe	183	231Pa
5	22Na	95	127mTe	184	231Pa+C
9	35S	106	129I	187	232U
10	36Cl	114	134Cs	188	232U+C
11	40K	115	135Cs	189	233U
12	41Ca	117	137Cs	190	233U+C
13	45Ca	128	144Ce	191	234U
14	46Sc	132	147Pm	192	235U
16	54Mn	137	147Sm	193	235U+C
18	55Fe	138	151Sm	194	236U
20	57Co	140	152Eu	196	238U
21	58Co	141	154Eu	197	238U+C
22	60Co	142	155Eu	199	237Np
23	59Ni	144	153Gd	200	237Np+C
24	63Ni	145	160Tb	203	236Pu
27	65Zn	146	166mHo	205	238Pu
31	75Se	147	181W	206	239Pu
32	79Se	148	185W	207	240Pu
41	90Sr	150	187Re	208	241Pu
48	93Zr	151	185Os	209	242Pu
49	93Zr+C	153	192Ir	211	244Pu
52	93mNb	156	210Pb	212	241Am
53	94Nb	160	210Po	213	242mAm
58	93Mo	165	226Ra	215	243Am
61	99Tc	166	226Ra+C	216	242Cm

Table 3.1 Source nuclides used in the parameter analysis (continued)

Source ID	Source*	Source ID	Source	Source ID	Source
65	106Ru	167	228Ra	217	243Cm
69	107Pd	169	227Ac	218	244Cm
71	110mAg	170	227Ac+C	219	245Cm
73	109Cd	173	228Th	220	246Cm
74	113mCd	174	228Th+C	221	247Cm
81	119mSn	175	229Th	222	248Cm
82	121mSn	176	229Th+C	223	252Cf
84	123Sn	177	230Th		
86	126Sn	178	230Th+C		

* "+C" denotes equilibrium initial activity assumption for progeny. Initial progeny activity is zero for all other radionuclides.

4.0 Use of Parameter Distributions in Dose Calculations

Although distributions are used to define defaults for both behavioral and physical parameters, distributions for behavioral and physical parameters describe different types of variability, and have different roles in the analysis:

- *Behavioral parameter distributions* describe variability over individuals in the screening group. These distributions serve two purposes: the average values define the default behavioral parameter values, and the range of values allows the range of doses to individual members of the screening group to be calculated. This calculation of the possible variability in dose to individuals provides assurance that the defined screening group is homogeneous.

- ICRP-46 proposes that the "critical group ... should be relatively homogeneous," while ICRP-43 suggests that "to satisfy the homogeneity requirement the ratio of maximum to minimum [dose] values should not exceed an order of magnitude."

- *Physical parameter distributions* describe variability in parameter values over sites. These distributions also represent uncertainty in the value at a particular site if no site-specific information is available about that parameter. Like the behavioral parameters, default values for physical parameters depend on the assigned distributions. Unlike the behavioral parameters (which are selected directly from their respective distributions), default values for the physical parameters must satisfy restrictions based on the dose distribution, as detailed in Section 3.3. The dose distribution is derived from the distributions for all physical parameters.

4.1 Considerations for Defining Parameter Distributions

As used in this analysis, both behavioral and physical parameter distributions describe the variability of values over a population. It is possible, in principle, to establish these distributions exactly using a large number of measurements from the defined population. In practice this is not possible because the number of available measurements is often quite small and the measured quantities often do not directly correspond to the model parameters. There is some uncertainty about the parameter distributions arising from the assumptions needed to develop these distributions from limited information.

In general there is less uncertainty about the distributions of behavioral parameters than about the distributions for physical parameters. This is because relevant human behavior has been extensively studied for risk assessment purposes, and the screening groups for both scenarios closely correspond to population groups used to summarize results from these studies. The main limitation of behavioral data is the difference in time scale between the data collection period (typically a single day) and the one-year model exposure period. This discrepancy can introduce uncertainty about the parameter distribution as a whole, yet the default values, which are defined as the mean values of the behavioral parameter distributions, are arguably unaffected. In contrast, the population of licensed sites has not been extensively characterized to define distributions of physical parameters. Assumptions are therefore required to relate data reported in the literature to this specialized population. As an example, licensed sites are assumed to be uniformly spatially distributed across the contiguous United States.

Uncertainty in parameter distributions themselves can be quantified by assigning probability values to the alternative parameter distributions that are consistent with available information. An embedded probabilistic analysis of this kind would provide a rigorous and formal treatment of uncertainty about the parameter distributions. The additional information, interpretation, and analysis that would be required, however, are beyond the scope of the current analysis. Uncertainty in parameter distributions was treated qualitatively by describing, for each parameter, the limitations of existing information in determining a distribution for the parameter. These qualitative descriptions of uncertainty could be the basis for assigning probabilities to alternative distributions, and therefore serve as the first step in any formal quantitative treatment of uncertainty in distributions.

4.1.1 Behavioral Parameters

Distributions for the behavioral parameters were developed using the definition of the screening group for each scenario. Large national population studies have been conducted to characterize human behavior, often for the specific purpose of providing data for exposure assessments (e.g., the studies cited in the Exposure

Factors Handbook (U.S. Environmental Protection Agency [EPA], 1996), the Nationwide Food Consumption Survey (U.S. Department of Agriculture [USDA] 1993)). Data from these studies provide a good basis for estimating the time that individuals spend in various activities and environments, and their rates of consumption of various goods and substances. Data are typically reported for population cohorts defined by age, race, sex, geography, as well as by other factors. Distributions describing the screening group were generally developed from these studies by identifying a cohort that most closely matched the definition of the screening group. As discussed above, data on activity and consumption are typically collected over a period of days or weeks, and are therefore more variable than the annual average values required by the scenario models. Discrepancies between the measurement time scale and the model time scale are discussed for each of the behavioral parameters (Sections 5.2 and 6.2).

4.1.2 Physical Parameters

Unlike the behavioral parameters, a large number of representative samples is usually not available for defining physical parameter distributions. Physical parameter distributions describe the variability of the physical parameters over the licensed sites. The population of licensed sites, unlike the general population of humans, is not a common subject of study. Distributions must often be assembled from separate studies of specialized situations. Constructing distributions in this way necessarily requires assumptions about the representativeness of the available information, that is, how well the existing studies cover the range of possible site conditions. Variations in experimental conditions among studies create uncertainty about whether and how their separate results can be pooled. As discussed above, these considerations create uncertainty about how accurately the parameter distributions describe variability over licensed sites. In developing the parameter distributions, the key assumptions are identified and discussed, however the resulting uncertainty is not quantified. The assigned distribution generally depends, to some extent, on judgements made in consideration of this uncertainty. The diversity in the amount, type, quality, and relevance of available data for the various physical parameters led to diverse procedures for defining distributions.

Measurements reported in the literature seldom correspond to the conditions defined for the scenario. To develop a parameter distribution, reported data must be interpreted in light of the use of the parameter in the model. Like the behavioral parameters, experimental data are typically collected at a smaller scale than the scale of the corresponding model parameter, which represents an annual average value over an extensive exposure area. Discrepancies in time scale are important for some parameters (such as dust loading), but are not important when the phenomenon characterized by the parameter is expected to be constant over time (e.g., soil density).

Discrepancies between the spatial scales of the model parameters and experimental data are common. Usually the experimental results cover a smaller area than the corresponding model parameter, and are collected over a much shorter period than the one year exposure period used in the scenario models. When this is true, the model parameter values are estimated by averaging some number of the experimental results to produce an effective value over the area and time period used in the model. The potential variability in model parameter values is therefore smaller than the potential variability in experimental values because of this averaging process.

Some parameters are supported by a large body of experimental data. In these cases the potential variability in experimental values is captured in the actual variability in reported results. In other cases very few relevant experimental results were identified. In these cases available data cannot be assumed to reflect the potential variability in experimental results because of the small sample size. In these cases, the assigned parameter distribution can extend beyond the range of reported experimental results.

4.2 Modifying Default Distributions with Site-specific Data

4.2.1 Behavioral Parameters

Behavioral parameter values are a function of the critical group used in the dose assessment. The defaults defined in this analysis reflect the generic screening group. Alternative distributions, leading to alternative mean values, can be supported by defining a site-specific critical group. NUREG/CR-1549 discusses the procedure for defining such a critical group. Once defined, the data sources and procedures used in this analysis (see Sections 5.2 and 6.2) should be reviewed to determine whether the site-specific screening group corresponds to one of the cohorts defined in the cited studies. If so, distributions for the screening group can be developed using data for the corresponding cohort. If not, distributions for the screening group might be developed using the raw survey data from a large national sample (e.g., the National Human Activity Pattern Survey) by selecting observations for individuals matching the critical group definition.

4.2.2 Physical Parameters

The physical parameter distributions defined in this analysis describe the variability of parameter values over all potential sites. As discussed above, these parameter distributions also describe uncertainty about the value at a particular site provided no additional information about that parameter is available. If additional parameter information is available for a site, this information reduces uncertainty about the parameter value. A site-specific parameter distribution is therefore expected to be narrower than the distribution defined in this analysis. The spread of the parameter distribution decreases as more information, or more accurate information, is included, ultimately converging on a single value if all uncertainty is eliminated.

Site specific information can be incorporated by updating the distributions defined in this analysis. There are two basic strategies for integrating site information with the information used to define the default distributions. Site information can be used to screen the data cited in this report by demonstrating that certain values or value ranges are not appropriate for the site, or new data specific to the site can be added to the data considered in this analysis, either supplementing or replacing the data used here. Whether site information is used to filter the default data set, or to supplement or replace the default data set, will depend on the type of information provided, the type of information in the default data set, and on other site-specific considerations.

The default parameter distributions describe the variability of parameter values over all sites. In the filtering approach, the effect of information about a particular site is to identify which subset of all sites the current site belongs to. For example, the initial distribution for the hydrologic parameters in the residential scenario model is based on the relative frequency of soil classifications across the United States. If the soil classification for a site can be determined, this information can be used to limit the ranges of values for a variety of hydrologic parameters (see Section 6.4.3 for the connection between soil classification and model parameters).

Measurements made at a site, or at a suitable analog location, might also be used to supplement or replace the data used to define default parameter distributions. The specific procedure for integrating new experimental information with the data cited in this analysis will depend on the amount, type, and quality of new data, and on the amount, type, and quality of data used to establish the default distributions. Specific procedures are not proposed because of the wide diversity of circumstances. There are several important factors that will need to be considered, however, when using any set of experimental data to establish parameter values, including:

- Differences between the experimental conditions and the conditions defined for the scenario;
- Differences between the temporal and spatial scales of the experimental results and the scenario model;
- Potential errors or bias in the experimental data.

These factors should be considered both for the data sets used in this analysis, and for any site specific data. The relative strengths of each data set, according to these factors, should be considered when developing a site-specific parameter distribution.

5.0 Building Occupancy Scenario in NUREG/CR-5512

The building occupancy scenario model, as defined in Volume 1 and implemented in Release 1.0 of DandD (Wernig et al., 1999), is based on the following assumptions:

- Radioactive dose results from exposure via three major exposure pathways:
  - (1) external exposure to penetrating radiation from surface sources,
  - (2) inhalation of resuspended surface contamination, and
  - (3) inadvertent ingestion of surface contamination
- Four other potential exposure pathways are not included in the analysis:
  - (1) external exposure during submersion in airborne radioactive dust,
  - (2) internal contamination from puncture wounds infected by contaminated surfaces,
  - (3) dermal absorption of radionuclides, and
  - (4) inhalation of indoor radon aerosol
- The building will be commercially used after decommissioning.
- The occupancy of the building will occur immediately after its release.
- The residual contamination will be represented by a thin surface layer left on the inner building surfaces.
- The exposure type will be a long-term chronic exposure to low level radioactive contamination since major contamination will be cleaned up prior to decommissioning.

The building occupancy scenario model includes eight parameters:

- External dose rate factor for exposure from contamination uniformly distributed on surfaces, $DFES_j$ (mrem/h per dpm/100 cm^2)
- Inhalation committed effective dose equivalent (CEDE) factor, DFH_j (mrem/pCi inhaled)
- Ingestion CEDE factor, DFG_j (mrem/pCi ingested)
- Length of the occupancy period, t_{to} (d)
- Time that exposure occurs during the occupancy period, t_o (d)
- Resuspension factor for surface contamination, RF_o (m^{-1})
- Volumetric breathing rate, V_o (m^3/h)
- Effective transfer rate for ingestion of removable surface contamination from surfaces to hands, from hands to mouth, GO (m^2/h)

The length of the occupancy period (t_{to}), the time that exposure occurs (t_o), and the effective transfer rate for ingestion (GO) are behavioral parameters. The volumetric breathing rate (V_o) is a metabolic parameter. The committed effective dose equivalent factors and the resuspension factor are physical parameters. As discussed below, the committed effective dose equivalent factors are classified as physical parameters because their values depend on the source geometry and contaminant solubility class.

The annual TEDE for a parent radionuclide in the building occupancy scenario $TEDEO_i$ is calculated as a sum of:

- external dose resulting from external exposure to penetrating radiation from the surface sources represented by the parent and daughter (if any) radionuclides, $DEXO_i$;
- CEDE for inhalation resulting from inhalation of resuspended surface contamination represented by the parent and daughter (if any) radionuclides, DHO_i; and
- CEDE for ingestion resulting from inadvertent ingestion of surface contamination represented by the parent and daughter (if any) radionuclides, DGO_Q.

The mathematical formulation of the above is (NUREG/CR-5512, Vol. 1, p. 3.14):

$$TEDEO_i = DEXO_i + DHO_i + DGO_i \qquad (5.1)$$

$DEXO_i$, DHO_i, and DGO_i are calculated using the average annual surface activity per unit area of the parent, C_i, and daughter radionuclides, C_j, during the first year of the building occupancy scenario. Although ingrowth of daughter nuclides may, in some cases, cause TEDE to increase with time, in the default scenario model the maximum TEDE is assumed to occur during the first year of the scenario to simplify the analysis.

The average annual activity is determined as an integral of the radionuclide activities during the first year after the building release over the length of the occupancy period, t_{t0}, divided by an averaging time, t_{av}, which is equal to one year (365.25 days). The release of the building is conservatively assumed to occur at time zero, and building occupancy is conservatively assumed to be at least one year. The default value for t_{to} is 365.25 days (see Section 5.2.1 below). The mathematical formulation is as follows:

$$C_{avj} = 1/t_{av} \int_{o}^{t_{to}} C_j(t)dt = \lambda_{rj} * \sum_{(n=1,j)} K_{jn} \left[\left(1 - exp\left(\lambda_{rn} * t_t o \right) / \lambda_{rn} \right) \right]$$
$$K_{jn(n=1 \text{ to } j-1)} = \sum_{(p=n,j-1)} \left[d_{pj} * \lambda_{rp} * K_{pn} \right] / \left(\lambda_{rj} - \lambda_{rn} \right) K_{jj} = C_j(0) / \lambda_{rj} - \sum_{(n=1,j-1)} K_{jn} \quad (5.2)$$

where λ_{rj} is the radioactive decay constant of radionuclide j, d_{pj} is the decay fraction, and $C_j(0)$ is the initial activity of radionuclide j. The external dose ($DEXO_i$), the inhalation CEDE (DHO_i), and the ingestion dose (DGO_i) are obtained as follows (NUREG/CR-5512, Vol. 1, pp. 3.12–3.14):

$$DEXO_i = 24 * t_o * \sum_{(j=1,Ji)} DFES_j * C_{avj} \quad (5.3)$$

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * \sum_{(j=1,Ji)} DFH_j * C_{avj} \quad (5.4)$$

$$DGO_i = 45.05 * 24 * t_o * GO * \sum_{(j=1,Ji)} DFG_j * C_{avj} \quad (5.5)$$

where J_i, RF_o, V_o, GO, $DFES_j$, DFH_j, and DFGj are, respectively: the number of radionuclides in chain i; the resuspension factor; the volumetric breathing rate; the effective transfer factor; the external dose rate factor; the inhalation CEDE factor; and the ingestion dose factor. Substituting Equations (5.3), (5.4), and (5.5) in (5.1), the annual TEDE can be expressed as:

$$TEDEO_i = 24/365.25 * t_o * \sum_{(j=1,Ji)} \left[C_{avj} * \left(DFES_j + 45.05 * RF_o * V_o * DFH_j + 45.05 * GO * DFG_j \right) \right] \quad (5.6)$$

As Equation (5.6) indicates, TEDE is directly proportional to the parameter t_o. The larger the time that exposure occurs during the building occupancy period, the higher the total dose.

The total dose is not in direct proportion to the other parameters. However, increasing these parameter values will result in a linear increase in the total dose. The sensitivity of dose to the parameters that are not radionuclide specific, such as RF_o, V_o, and GO, will be different for different radionuclides and will depend on the dose factors for each radionuclide in the chain. For example, if the external dose rate factor $DFES_j$ is significantly larger than the inhalation CEDE factor DFH_j and the ingestion dose factor DFG_j for all radionuclides in the chain, then $TEDEO_i$ will not be sensitive to RF_o, V_o, or GO.

5.1 Definition of Screening Group

The screening group is a site-independent population, appropriate for use at all sites, which is reasonably expected to receive the greatest exposure given the scenario definition. For the building occupancy scenario, the screening group consists of full-time adult male workers in light industry.

5.2 Behavioral Parameters

5.2.1 Length of the Occupancy Period, t_{to} (d)

5.2.1.1 Description of t_{to}

The time parameter t_{to} is used to determine the time integral of activity over the building occupancy period, which in turn is used to determine the mean activity level of each radionuclide. The value for this parameter defined in NUREG/CR-5512, Vol. 1, is 365.25 d or one year. Using 365.25 days in a year accounts for a leap year. This represents continuous use of a building for 100% of the calendar year so that, as stated in the regulatory criterion, annual TEDE is calculated. The RESRAD value for the same parameter is 365.0 d.

5.2.1.2 Use of t_{to} in Modeling

The longer the building occupancy period, the higher the total annual dose during the first year of the scenario.

This parameter is used to calculate the average annual surface activity of radionuclide j per unit area C_{avj} during the first year of the building occupancy scenario. The relationship between C_{avj} and t_{to} is given in Equation 5.2 above.

5.2.1.3 t_{to} Uncertainty

The value for this parameter is defined by the regulatory criterion to calculate annual TEDE.

5.2.1.4 Alternate t_{to} Values

This parameter would vary if the licensee defined a site-specific critical group which did not have year-round access to the building.

5.2.2 Time That Exposure Occurs During the One-Year Building Occupancy Period (Behavioral), t_o (d)

5.2.2.1 Description of t_o

The exposure time parameter, t_o, describes the actual time spent on the job during the one-year duration of the building occupancy scenario by the average member of the screening group.

5.2.2.2 Use of t_o in Modeling

The total dose is directly proportional to the time of exposure during the building occupancy period.

As a behavioral parameter, t_o represents the amount of time spent in a contaminated building by the average member of the screening group. This parameter is used to calculate the total dose, $TEDEO_i$, from parent radionuclide i and its daughters due to external exposure to surface contamination, inhalation of resuspended surface contamination, and inadvertent ingestion of surface contamination during the first year of the building occupancy scenario. The relationship between $TEDEO_i$ and t_o is described by the following formula:

$$TEDEO_i = 24/365.25 * t_{o(j=1,Ji)}\ C_{avj} * \left(DFES_j + 45.05 * RF_o * V_0 * DFH_j + 45.05 * GO * DFG_j\right) \quad (5.7)$$

where J_i is the number of radionuclides in chain i, C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario, RF_o is the resuspension factor, V_o is the volumetric breathing rate, GO is the effective transfer rate factor, $DFES_j$ is the external dose rate factor, DFH_j is the inhalation CEDE factor, and DFGj is the ingestion dose factor. An increase in the t_o value results in a proportional increase in the annual total dose value.

5.2.2.3 Information Reviewed to Define A PDF for t_o

The value for this parameter defined in NUREG/CR-5512, Vol. 1, is 83.33 effective 24-h days. This is calculated assuming that the actual time on the job is 100% of a work year during which a person spends 2000 h/y working in the building (40-h work week for 50 working weeks with two weeks of vacation/sick leave/any other leave).

The default assumption in the RESRAD code is that 50% of a person's time is spent indoors, while 25% is spent outdoors in the presence of contamination.

For this analysis, data on current work patterns was reviewed to establish a PDF for t_o describing variability among members of the screening group. Information reviewed included Bureau of Labor Statistics (BLS) data on hours worked (BLS, 1996a; BLS, 1996b; and BLS, 1997) and relevant references cited in the EPA Exposures Factors Handbook (1996) for human activity patterns. The following sections summarize the data and information available from these sources.

5.2.2.3.1 BLS Data on Hours Worked

In June, 1996, data from the BLS Current Population Survey (CPS) were obtained from the BLS website. The CPS is a monthly survey. During 1995, the CPS was sent out to approximately 50,000 households a month, and was used to obtain information for about 94,000 persons ages 16 years and older (BLS, 1996a). During 1996, approximately 56,000 household units were surveyed, and information was obtained for about 107,000 persons ages 16 and older (BLS, 1997). Annual averages from the CPS are also published in January issues of *Employment and Earnings* (BLS, 1996a; BLS 1997).

The CPS is used to determine "Characteristics of the Employed" statistics, including hours worked. Current data for "Characteristics of the Employed" can be accessed from the BLS home page for "Labor Force Statistics from the Current Population Survey" at the website http://stats.bls.gov/cpshome.htm. The specific page for the data listings on "Characteristics of the Employed" is located at http://stats.bls.gov:80/cpsaatab.h #charemp. and can be accessed from the CPS home page. In June 1996, the data for persons at work in agriculture and non-agricultural industries by hours of work for 1995 were downloaded and are presented in Table 5.1. These data are also published in the January 1996 issue of *Employment and Earnings*. The reported data range is from 1 to 4 h/wk of work to 60 h/wk and over. The 1995 overall annual average reported is 39.3

h/wk. In April 1997, the data from the 1996 Annual Average Tables (BLS, 1997) were also reviewed. The numbers were slightly different, but the percentages in any range did not differ by more than two tenths of a percent.

The other available BLS data are from the National Current Employment Statistics (CES). These statistics are determined from a industry survey of employers that report man hours, number of employees, and payroll information, but do not report anything about part-time or full-time employees. The website location for these statistics is http://stats.bls.gov:80/cgi-bin/surveymost?ee. In June 1996, several series of data related to national employment, hours, and earnings, were downloaded and reviewed, including the following:

- Total Private Average Weekly Hours of Production Workers - Seasonally Adjusted
- Total Private Indexes of Aggregate Weekly Hours - Seasonally Adjusted
- Total Private Average Weekly Hours of Production Workers - Not Seasonally Adjusted
- Goods-producing Average Weekly Hours of Production Workers - Seasonally Adjusted
- Goods-producing Indexes of Aggregate Weekly Hours - Seasonally Adjusted
- Mining Average Weekly Hours of Production Workers - Seasonally Adjusted
- Manufacturing Average Weekly Hours of Production Workers - Seasonally Adjusted
- Manufacturing Average Weekly Overtime of Production Workers - Seasonally Adjusted
- Manufacturing Indexes of Aggregate Weekly Hours - Seasonally Adjusted
- Private Service-producing Average Weekly Hours of Production Workers - Seasonally Adjusted
- Private Service-producing Indexes of Aggregate Weekly Hours - Seasonally Adjusted

Table 5.1 1995 data for "Persons at work in agriculture and nonagricultural industries by hours of work" (BLS, 1996a)

Hours of work	Thousands of persons			Percent distribution		
	All industries	Agriculture	Non-agricultural industries	All industries	Agriculture	Non-agricultural industries
Total Persons at Work, 16 years and over	119,318	3,247	116,071	100.0	100.0	100.0
1 to 34 hours	30,664	1,051	29,613	25.7	32.4	25.5
1 to 4 hours	1,297	83	1,214	1.1	2.6	1.0
5 to 14 hours	4,943	262	4,681	4.1	8.1	4.0
15 to 29 hours	15,120	476	14,644	12.7	14.7	12.6
30 to 34 hours	9,304	229	9,075	7.8	7.1	7.8
35 hours and over	88,654	2,196	86,458	74.3	67.6	74.5
35 to 39 hours	8,783	173	8,610	7.4	5.3	7.4
40 hours	42,228	635	41,592	35.4	19.6	35.8
41 hours and over	37,643	1,388	36,255	31.5	42.7	31.2
41 to 48 hours	13,958	250	13,708	11.7	7.7	11.8
49 to 59 hours	13,591	388	13,203	11.4	11.9	11.4
60 hours and over	10,094	750	9,344	8.5	23.1	8.1
Average hours, total at work	39.3	42.2	39.2	-	-	-
Average hours, persons who usually work full time	43.4	49.7	43.2	-	-	-

5.2.2.3.2 Data from Studies on Human Activity Patterns

The EPA Exposure Factors Handbook (EPA, 1996) includes a summary of several studies on human activity patterns, including some information relevant for estimating occupancy duration. The discussion for each cited study outlines the methodology and type of data collected, and discusses the strengths and limitations of each. The following is a discussion of four studies cited in the Handbook, and the data relevant to occupancy duration adapted from the Handbook summary.

In each of these studies, data on time use was recorded for either the preceding 24 hours, based on recall (telephone surveys) or for the succeeding 24 hours (based on diaries). In some studies (e.g., Hill, (1985)) the same respondents were polled periodically throughout the year. This follow-up aside, the data cited in these studies provides information on the variability over the sample population of time spent during a single day. The occupancy duration parameter instead describes average behavior of individuals over the year. This average is not the same as the average of daily behavior over a population of individuals. To estimate the former, information on the variability in daily activities for single individuals would also be required.

Robinson and Thomas (1991) report population averages for time spent performing various activities (e.g., "Paid Work," "Household Work") and in various micro-environments (e.g., "Restaurant/Bar," "Work/Study-nonresidence"). Data from Californians (1,762 respondents ages 12 and older collected between October 1987 and August 1988) and from a national sample (5,000 respondents across the United States ages 12 and older collected during January through December 1985) are categorized by activity and by gender. Separate statistics are also reported for "Doers" of an activity as distinct from the general population (for example, time spent cooking by people who actually cook). Population statistics are not reported, however, the standard error of the mean is given in some cases. The mean time spent in paid work for ages 18-64 years ranged from 190 min/d (34.31 effective 24-h d/y) for women in the national survey to 346 min/d (62.47 effective 24-h d/y) for men in the California study. These numbers correspond to 15.83 h/wk and 28.83 h/wk, respectively. (Effective 24-h d/y are calculated based on 52 wk/y; weekly hours are based on a five-day work week.) Given the age range for the survey, a significant portion of the survey population must be part-time workers, and therefore not representative of the screening group. The mean time for "doers" spent in the work/study-other micro-environment in the total population (ages 12 years and older) ranged from 383 to 450 min/d (69.15 to 81.25 effective 24-h d/y); during the weekday, from 401 to 415 min/d (72.40 to 74.93 effective 24-h d/y); and for ages 24-64 from 410 to 429 min/d (74.02 to 77.46 effective 24-h d/y), respectively. The range of all these values (383 to 450 min/d) corresponds to 31.92 to 37.50 h/wk.

Tsang and Klepeis (1996) contains information from the largest and most recent human activity pattern survey currently available. The survey was conducted by the EPA. Data from 9,386 respondents in the 48 contiguous states were collected via minute-by-minute 24-h diaries between October 1992 and September 1994. Distributions are reported for the number of minutes spent working for pay, the number of minutes spent in a "main job," the number of minutes spent indoors at work, the number of minutes spent in a plant/factory/warehouse, and the number of minutes spent in an office or factory. Distributions are provided for the entire sample populations, as well as subpopulations defined by gender, race, employment status, region, season, and other factors. The mean 24-h cumulative number of minutes in a main job for full-time employees is 504.350 min/d (standard deviation = 164.818), which corresponds to 91.06 effective 24-h d/y and 42.03 h/wk.

Robinson (1977) compares average time spent in "Work for Pay" in 1965 and 1975. Averages are reported by gender, employment status, age, race, and education. These data are not as current as the two previous sources. For four age categories spanning 25-65 years of age, these averages ranged from 29.2 to 35.9 h/wk in 1965 and 20.4 to 34.4 h/wk in 1975.

Hill (1985) reports average time spent at "Market Work" from data collected during the mid-1970s for subpopulations defined by gender, region, day of the week, and season. Distributions are not provided, however, sample standard deviations are given for some quantities. Mean hours per week, weighted to reflect the number of workdays and weekend days in a week (along with the reported standard deviation) for married men and women working full-time were 47.84 (16.54) and 38.55 (16.87), respectively. Data on seasonal variations were obtained by resampling the same population.

5.2.2.4 Distribution and Default Value for t_o

The data used to develop the PDF for t_o is based on the BLS CPS 1995 data (BLS, 1996a) for hours worked by full-time workers (those working 35 hours per week or more) at work in nonagricultural industries. These data are representative of annual estimates for the entire U.S. worker population and are determined from the largest sample of data that has been collected and processed in a standardized manner for almost 40 years. Limiting the data to full-time non-agricultural workers provides a more representative estimate for the screening group. Although the BLS reports statistics for a number of worker categories, no category directly corresponds to workers in light industry.

Table 5.2 shows the relative frequency of hours worked for persons working 35 hours or more per week in non-agricultural industries. These relative frequencies were calculated from the data in Table 5.1 by dividing the number of persons in each "Hours of Work" range by the total number of persons working 35 hours or more per week. Persons reported to work 40 hours were assumed to have worked between 39 and 41 hours. A histogram based on this data is presented in Figure 5.1. This histogram defines the PDF for members of the screening group. The cumulative distribution function based on this histogram is presented in Figure 5.2. In developing this distribution, the number of hours worked in each of the intervals reported by the BLS was assumed to be uniformly distributed across the interval.

Table 5.2 Relative frequency of hours worked by persons working 35 hours or more per week

Hours Worked per Week	Relative Frequency
35-39	9.96×10^{-2}
39-41	4.81×10^{-1}
41-48	1.59×10^{-1}
49-59	1.53×10^{-1}
60-65	1.08×10^{-1}

As indicated in Table 5.1, significant portions of the working population in nonagricultural industries work less than or more than 40 h/wk. Only 35.8% of workers in nonagricultural industries work 40 h/wk; 27.8% work 15 to 39 h/wk and 23.2% work 41 to 59 h/wk. From Table 5.1, the 1995 weekly average for persons who usually work full time for nonagricultural industries is 43.2 h/wk. The default value for t_0, determined by the expected value of the distribution shown in Figures 5.1 and 5.2, is 97.5 d/y, or 45 h/wk. The difference between the expected value of the distribution and the average value reported in Table 5.1 is due to the difference between the actual distribution of hours worked within each range, and the uniform distribution over each range assumed in constructing the PDF.

5.2.2.5 t_0 Uncertainty

In general, uncertainty about this parameter exists because of a lack of complete knowledge about the hours worked by workers in the screening group. The PDF proposed in Figure 5.2 represents the variability of individual worker hours across different industries and different regions of the country. Although the BLS provides data for a number of worker categories, no category directly corresponds to workers in light industry.

The BLS data used for the PDF are representative of annual estimates for the entire U.S. worker population and are determined from the largest sample of data available that has been collected and processed in a standardized manner for almost 40 years. The BLS CPS covers about 92% of the decennial census population. Also, a sample rotation scheme allows for 50% of the sample to be common from year to year. Thus, the

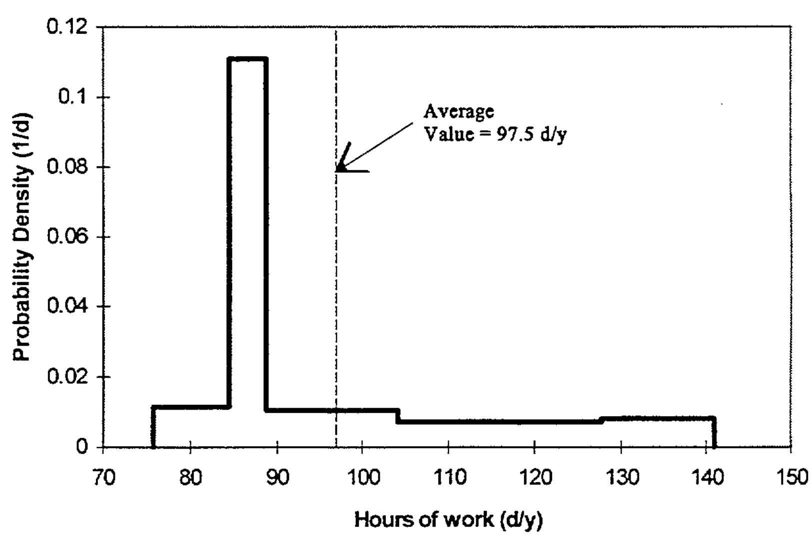

Figure 5.1 Probability Density Function for t_0

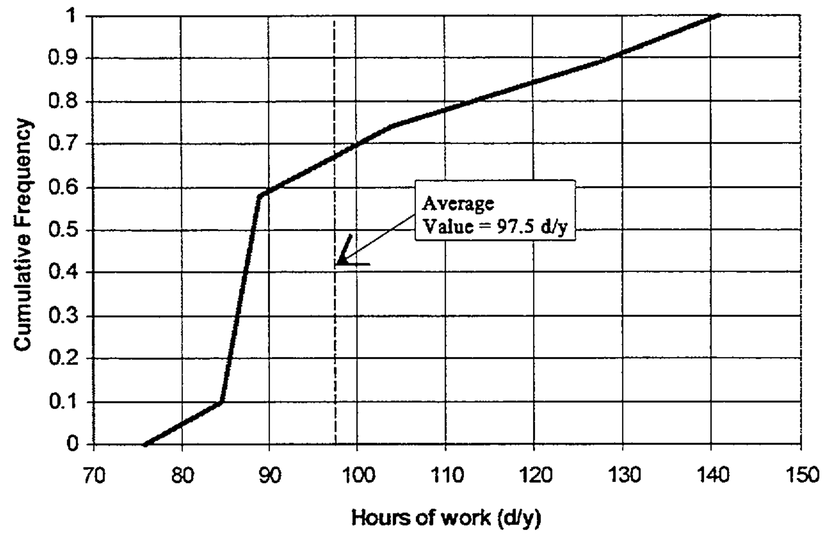

Figure 5.2 Cumulative Distribution Function for t_o

uncertainty due to sampling and non-sampling error and historical comparability is minimal and well-characterized (BLS, 1996a).

5.2.2.6 Alternative t_o Values

For this parameter, other BLS or similar data sets may provide the basis for a licensee to develop a different distribution of hours worked for a site-specific critical group. For example, a licensee may propose that the primary use of the building following license termination will be for manufacturing. Then, the licensee may use the BLS data to define the range of expected hours for the dose assessment. However, the licensee may need to provide the NRC with the assurance that the building will only be used for manufacturing over the regulated time period.

5.2.3 Effective Transfer Rate for Ingestion of Removable Surface Contamination from Surfaces to Hands, from hands to Mouth (Behavioral) GO (m^2/h)

5.2.3.1 Description of GO

Ingestion of removable surface contamination inside buildings that is transferred from contaminated surfaces via hands, food, and other items to the mouth is referred to as secondary ingestion. The parameter GO is defined as the effective transfer rate and provides a mechanism for calculating the quantity of secondary ingestion. The effective transfer rate is described as the surface area contacted per unit time, the contents of which are ultimately transferred to the mouth by inadvertent fingering of the mouth or placing contaminated objects, such as food, cigarettes, pencils, etc., that had been in contact with a contaminated surface, into the mouth.

The occupancy scenario definition does not include contaminated furniture such as desks and table tops. Only walls and floors are assumed to have residual contamination. The value of GO should reflect the rate of ingestion from contaminated surfaces (walls and floors) rather than the rate of ingestion from all surfaces.

5.2.3.2 Use of GO in Modeling

As described below, the dose for the ingestion pathway is directly proportional to GO. GO is therefore an important parameter for situations in which a significant proportion of the total dose is received through ingestion.

The parameter GO is used to calculate CEDE for internal ingestion dose (DGO_i) resulting from inadvertent ingestion of surface contamination. The relationship between GO and internal dose due to ingestion is defined by the following formula (NUREG/CR-5512, Vol. 1, p. 3.14):

$$DGO_i = 45.05 * 24 * t_o * GO * \sum_{(j=1,Ji)} DFG_j * C_{avj} \qquad (5.8)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during the first year of the building occupancy scenario, and DFG_j is the ingestion dose factor for radionuclide j. The resulting internal ingestion dose is directly proportional to the effective transfer rate.

As discussed above, GO measures the tendency for occupants to ingest surface contamination as a surface area per unit time. Ingestion is caused by touching contaminated walls and floors with the hands or other objects, and placing contaminated objects in the mouth. GO is a summary measure of chronic behavioral patterns for members of the screening group.

In Equation 5.8, all surface contamination is assumed to be available for ingestion by this mechanism, and the concentration of ingested material is assumed to be equal to the source concentration C_{avj}. The overall ingestion rate may be lower if the amount of "loose" contamination (i.e., contamination available for transport by this mechanism) is less than the total amount of contamination or if the ingested dust or soil is only partially composed of contaminated material. Equation 5.8 can be generalized to include the fraction of "loose" contamination and the fraction of contacted surfaces that are contaminated by scaling the available concentration:

$$DGO_i = 45.05 * 24 * t_o * GO * \sum_{(j=1,Ji)} DFG_j * F_S * F_l * C_{avj} \qquad (5.9)$$

where F_l is the fraction of "loose" contamination and F_S is the contaminated fraction of the total surface area contacted by the receptor. This scaling is equivalent to defining an effective secondary ingestion transfer factor as:

$$GO^* = F_S * F_l * GO \qquad (5.10)$$

and by replacing GO in Equation 5.8 by the effective rate GO^*. This decomposition preserves the definition of GO as a measure of behavior (the area accessed per unit time), and allows the ingestion rate to be modified to account for site-specific measurements of removable activity. This is the same approach as is used for resuspension (see Section 5.4.2 below). In Equation 5.10, GO represents an ingestion rate from all surfaces, while GO* represents ingestion of loose material from contaminated walls and floors.

5.2.3.3 Review of Information Related to Secondary Ingestion

The value for GO is defined in NUREG/CR-5512, Vol. 1, as 1×10^{-4} m²/h. This value was defined based on the literature analysis of surface-contamination ingestion data. Eight references are listed for this data (Dunster, 1962; Gibson and Wrixon, 1979; Healy, 1971; Kennedy et al., 1981; Sayre et al., 1974; Lepow et al., 1975; Walter et al., 1980; and Gallacher et al., 1984). Half of these studies focused on intake by children of surface contamination. These estimates tend to be larger than the corresponding estimates for adults (i.e., greater than 1×10^{-3} m²/h). The range of ingestion rates for the adult-worker/members of the public is 4×10^{-5} to 1×10^{-3} m²/h. The value of 1×10^{-4} m²/h is consistent with the range for adults.

Kennedy and Strenge (1992) (hereafter referred to as "Volume 1") summarize estimates of GO published prior to 1992. In general, these estimates derive from postulates about behavior or from measured rates of ingestion. Information on ingestion by adults is especially sparse, and no direct measurements of adult ingestion rates are cited as a basis for GO. In addition, most theoretical estimates cited for GO or for adult ingestion rates found in the literature (Dunster (1962), Gibson and Wrixon (1979), Hawley (1985)) derive from the supposition by Dunster that 10 cm² of surface area would be accessed by a typical adult in a typical day. Hawley (1985), in calculating adult ingestion rates, assumed that adults working outdoors would transfer contamination from the inside surface of the fingers twice during a typical day of outdoor work, implying a secondary ingestion transfer rate of 137 cm² in an eight-hour day. This estimate, however, is speculative, and was proposed in the absence of empirical data on adult ingestion or behavior.

Recent publications, including references cited in the EPA *Exposure Factors Handbook* (1996) were reviewed to identify and evaluate data related to secondary ingestion transfer rate. The goal of most studies was to estimate rates of soil ingestion as a mass per unit time, rather than to estimate a transfer factor analogous to GO. In addition, most of the recent literature continues to focus on children. Because they are not representative of the screening group, and because children are presumably exposed to higher densities of dust and soil, and to ingest dust and soil at greater rates for a given density, estimated ingestion rates for children are not considered to be directly relevant for estimating GO.

Several studies on soil ingestion have been published since 1990. Ingestion rates for adults have been measured or estimated by a number of techniques and under a variety of conditions. Sheppard (1995) summarized the literature and described a basic model for soil ingestion that included food consumption and other activities, such as mouthing and ingestion of non-food items, concentration enrichment, and the bio-availability of contaminants in soil. He recommended the use of simple models, rather than explicit use of empirical data, for estimating soil ingestion in humans. Reported values for soil ingestion rates by normal adults, summarized by Sheppard (1995) from other studies, range from 1 to 65 mg/d.

Soil ingestion rates in adults have been estimated by 1) analysis of selected tracer elements in human diets and comparing the dietary intake of tracer elements with tracer elements in feces and 2) observations of individual behavior patterns under a range of environmental conditions and activities. Recently, numerous studies on soil ingestion rates have been conducted using a tracer method (BTM) developed by Binder et al. (1986) (Stanek and Calabrese, 1995; Sedman and Mahmood, 1994; Stanek et al., 1997 and others). Stanek and Calabrese (1995) and Stanek et al. (1997) estimated soil ingestion rates in adults based on mass-balance studies in which intake rates were estimated from concentrations of several trace elements in foods, medicines, environmental dust and soil, and feces. Both studies collected data over multiple one-week periods, during which each subject ingested a controlled quantity of soil from their environment. This mass, along with soil mass ingested with food, was subtracted from the estimated mass in feces to estimate the daily amount of inadvertent ingestion. These studies are the only published measurements of adult ingestion found in the literature review, and are therefore the only empirical basis for defining a distribution for GO.

Two types of published data related to the secondary ingestion transfer factor were found: direct estimates of the area of skin surface (and therefore area of contaminated surface) contacted by mouth in a given time, and measurements or estimates of the rate of soil ingestion by adults. No studies report actual measurements of contacted area: the two primary sources for direct area estimates are Dunster's (1962) proposal that "in order to arrive at some indication of the magnitude of the problem, it is assumed here that a person may ingest all the contamination from 10 cm^2 of contaminated skin every day," and Hawley's (1985) assumption that adults working outdoors would transfer contamination from the inside surface of the fingers twice during a typical day of outdoor work, implying a secondary ingestion transfer rate of 137 cm^2 in an eight-hour day. Both estimates, while plausible, have no empirical support.

5.2.3.4 Inferring GO from Ingestion Rates

Estimates of inadvertent soil ingestion rates by adults provide indirect information on secondary ingestion transfer rates. The rate of soil ingestion by an individual can be related to the individual's behavior (reflected in the secondary ingestion transfer rate for the individual), and to the environmental conditions (reflected in the average dust or soil loading experienced by the individual) using the following simple model:

$$SI_{C,I} = GO_{C,I} * DL_{C,I} \qquad (5.11)$$

where SI is the inadvertent soil ingestion rate (mg/hr), GO is the transfer factor (m^2/hr), and DL is the average surface density of dust or soil in the environment in which ingestion was measured. The suffix C,I denotes chronic (annual average) values for individual subjects. Equation 5.11 is consistent with the exposure model used in dose assessment (Equation 5.8).

In the absence of direct measurements of transfer factor, this model was used to derive a distribution of individual transfer factor values from estimates of soil ingestion rate and soil densities. In making these estimates, measured soil ingestion rates are assumed to reflect the soil density in the subjects' environment, as well as mannerisms and behavior that are independent of the environment. The chronic behavior of individuals, characterized by $GO_{C,I}$, is assumed to be independent of their environment, characterized by $DL_{C,I}$, so that

$$E[\log(SI_{C,I})] = E[\log(GO_{C,I})] + E[\log(DL_{C,I})] \qquad (5.12)$$

and

$$\mathrm{Var}[\log(SI_{C,I})] = \mathrm{Var}[\log(GO_{C,I})] + \mathrm{Var}[\log(DL_{C,I})] \qquad (5.13)$$

where E(X) and Var(X) denote the expected value and variance over the population of individuals. Equations 5.12 and 5.13 allow distributional properties of $GO_{C,I}$ to be inferred from distributional properties of $SI_{C,L}$ and $DL_{C,L}$. This procedure requires a distribution for $SI_{C,I}$, describing the variability of soil ingestion rate over individuals, and a distribution for $DL_{C,I}$, describing the variability in the soil density on skin corresponding to the conditions under which SI was measured or estimated.

Defining a distribution for GO entails three main steps:

1. Estimating distributional properties for individual chronic soil ingestion rates ($SI_{C,I}$) from available literature. As discussed in Section 5.2.2, there are few published estimates of adult ingestion rates, and these rates were measured in residential settings. The summaries of acute (daily) individual ingestion rates provided by Stanek (1997) provide the most recent experimental basis for estimating adult soil ingestion. This study is therefore considered in some detail.
2. Estimating distributional properties for the individual chronic soil densities ($DL_{C,I}$) corres-ponding to

the experimental situation in which the ingestion rates were measured or estimated. Because the available ingestion rate measurements were made in residential settings, an estimate of dust density in residences is required in order to calculated the transfer rate corresponding to the measured rates of ingestion.

3. Deriving distributional properties for the individual chronic transfer factor ($GO_{C,I}$) from the distributional properties of soil ingestion rate and soil density, assuming that the variations in transfer factor and soil density among individuals are independent. This derivation assumes that the behavior characterized by GO would be the same in occupational and residential environments. Differences in mass ingestion rates in these two environments are therefore assumed to be due to differences in the surface density of dust and soil.

Section 5.2.2.3 below describes the application of this procedure to derive a distribution for GO. A number of intermediate assumptions and inferences are required, which create a large degree of uncertainty in the derived distribution. These assumptions are summarized below.

- By using this model to estimate transfer factors for individuals from measurements or estimates of soil ingestion rate, all inadvertent ingestion (i.e., excluding ingestion through food and medicine) is assumed to occur through transfer from surficial sources: other potential sources, such as swallowed wind-borne soil, are neglected.

- Measured inadvertent ingestion SI includes dust and soil ingestion from any surfaces in the subject's environment. In the occupancy scenario model, surface contamination is assumed to occur only on walls and floors. As a result, secondary ingestion transfer factors inferred from measured ingestion rates will overestimate transfer factors from the contaminated surfaces considered in the scenario. Using the effective transfer factor GO^* defined in Equation 5.9, $F_S = 1$ for all measured ingestion rates, while F_S is expected to be less than 1 based on the source location assumed in the scenario definition.

- The few available estimates of adult ingestion rates are for residential environments, while the parameter GO characterizes occupational environments. In Equation 5.10, ingestion rate is decomposed into a behavioral component $GO_{C,I}$ and an environmental component $DL_{C,I}$. Both components will differ between residential and occupational settings, although the size and direction of this difference is uncertain. *Transfer rates* based on soil ingestion in a residential setting are assumed to be representative of *transfer rates* in an occupational setting even though mass ingestion rates differ. Under this assumption, soil ingestion rates in residences would be higher than ingestion rates in occupational settings solely due to the higher soil density in residences.

- In deriving Equations 5.12 and 5.13, $GO_{C,I}$ and $DL_{C,I}$ are assumed to be independent. Individuals who tend to behave in ways leading to large (small) transfer factors are not preferentially exposed to environments with high (low) dust densities. This assumption is plausible, but cannot be tested with available information.

- The distribution of $GO_{C,I}$ describes the variability of transfer factors among individuals in the screening group. Due to the limited data available, no specific estimates for workers in light industry are available. Transfer factor estimates for adults in general are assumed to be appropriate for the screening group.

- The available information on adult soil ingestion rates is quite limited, and is not sufficient to determine the distribution of $SI_{C,I}$. Similarly, the distribution of $DL_{C,I}$ corresponding to the reported ingestion rates is highly uncertain. For both soil ingestion rate and soil density, the mean, minimum, and maximum values of these distributions were estimated as described in Section 5.2.2.3. Lacking specific information on the form of these distributions, distributions were assigned using the principle of maximum entropy. As stated by Jaynes (1982), this principle requires that "when we make inferences based on incomplete information, we should draw from them that probability distribution that has the maximum entropy permitted by the information we do have." In as much as the form of the secondary ingestion rate and dust loading distributions are unknown, the assumption of any specific distribution is arbitrary, and likely to be wrong. Given this uncertainty, the maximum entropy distribution was judged the most reasonable choice in that "most information theorists have considered it obvious that, in some sense, the possible distributions are concentrated strongly near the one of maximum entropy" (Jaynes, 1982). With a specified mean value, lower limit, and upper limit, the maximum entropy distribution corresponds to a truncated exponential distribution

5.2.3.5 Derivation of a Distribution for GO

The procedure described in Section 5.2.2.2 was used to develop a distribution for GO. Details and intermediate results are presented below.

5.2.3.5.1 Distributional Properties of Chronic Individual Ingestion Rate

Mean Individual Ingestion Rate

Sheppard (1995) provides a summary of current literature on soil ingestion, and cited soil ingestion rates by normal adults ranging from 1 to 65 mg/d. These estimates include the theoretical calculations by Hawley (1985), based on assumed transfer rates and soil densities, as well as the estimates based on tracer measurements reported by Calabrese (1989, 1990). Stanek (1997) describes a more recent application of the "best tracer" method to estimate adult soil ingestion, which drew from a larger number of subjects and a longer measurement period than the earlier work of Calabrese (1989). Individual ingestion rates reported by Stanek appear to be the strongest available experimental basis for estimating adult soil ingestion. This study is therefore considered in some detail.

Soil ingestion rates were estimated by Stanek et al. (1997) for each of 10 adult subjects on each of 28 days. The measurement period was divided into four periods of seven days each. During each period, a known mass of soil was ingested by each participant. This mass, along with the estimated soil mass ingested with food, was subtracted from the total estimated ingested mass, yielding 280 values for daily individual inadvertent ingestion. Total ingested mass on a given day was estimated as the mass of dust and soil in feces on the subsequent day. Soil and dust masses in meals and feces were in turn estimated from measured concentrations of eight trace elements found in soil and dust (Al, Ce, La, Nd, Si, Ti, Y, and Zr).

Resulting estimates of daily soil ingestion, and daily dust ingestion are summarized in Stanek et al. (1997). This summary describes the distribution of daily individual ingestion rate estimates over the entire study period, and over each of the four seven-day intervals. There is considerable variability in these estimates, as illustrated in Figure 5.3. Many negative values are reported, suggesting that a large amount of the variability in reported values is due to experimental error rather than to variability in ingestion rate among individuals, or to variability over time. Daily estimates for a single individual over a one-week period (Stanek et al., 1997 Table 8) suggest that estimates of *chronic* ingestion rate may be considerably more stable than daily values, however chronic rates cannot be derived for all individuals from the summaries presented in the report. Overall ingestion rates, averaged over both time and individuals, are provided, and have been used to estimate the potential variability in chronic dust ingestion over individuals.

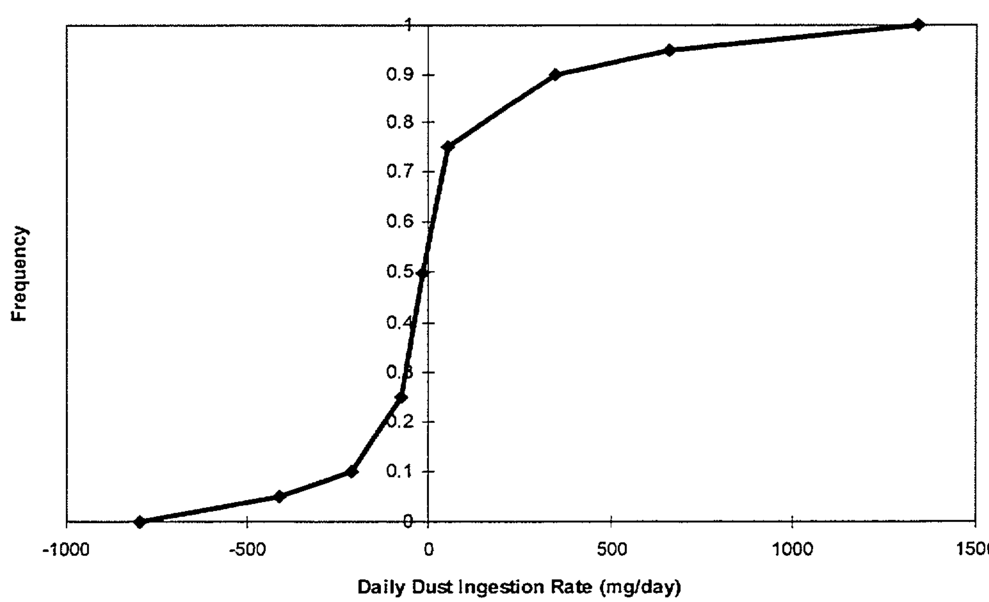

Figure 5.3 Distribution of estimated daily dust ingestion rates for 10 adults and 28 days based on the median value from four tracers (data from Stanek et al., 1997, Table 10)

Table 5.3 shows the average dust ingestion rate over the 10 subjects for the entire study duration, and for each of the four time periods. Standard errors for the average are also reported, calculated from the sample standard deviations provided in Stanek et al. (1997).

Table 5.3 Average estimated daily dust ingestion rates over 10 individuals and four one-week periods using median daily values from the four best tracer elements (from Stanek et al., 1997)

Period	Average dust ingestion rate (mg/d)	Standard error* (mg/d)
Week 1 (0 mg/day capsule ingestion)	139	52
Week 2 (20 mg/day capsule	73	22
Week 3 (100 mg/day capsule ingestion)	129	32
Week 4 (500 mg/day capsule ingestion)	-225	32
All 4 weeks	29	20

* Calculated from reported sample standard deviations.

The overall average ingestion rate of 29 mg/d is an estimate of the mean of the distribution of individual acute (daily) soil ingestion rates over time and over individuals. The mean of this distribution is identical to the mean of *chronic* ingestion rates over individuals, $SI_{C,L}$. Due to the large variation in individual daily values, there is considerable uncertainty in the estimate of the mean, as indicated by the large standard error. Using two standard errors as an indication of this uncertainty, the experimental results are consistent with a mean ingestion rate between 0 and 69 mg/d.

For comparison, Stanek and Calabrese (1995) reanalyzed results of their previous study of adult soil ingestion (Calabrese et al., 1990) using the best tracer method to rank the reliability of estimated rates based on individual tracers. The resulting average ingestion rate over six adults and three weeks was 64 mg/day.

Upper and Lower Limits for Individual Ingestion Rate

Available experimental data appear to be consistent with mean ingestion rates for adults between 0 and 70 mg/day. The large variability in estimates of daily ingestion rate (e.g., Figure 5.3) leads to large uncertainty in the estimate of average chronic ingestion rate. Ingestion rates typically recommended for adults (e.g., 50 mg/day in EPA (1996)) appear to reflect the detection limit associated with current experimental practice.

The minimum chronic individual soil ingestion rate is evidently 0. An upper limit for chronic adult soil ingestion rate is more difficult to establish, however the experimental results summarized in Table 5.3 can be used, along with other information, to assign a plausible upper bound. For a particular subject, the chronic soil ingestion rate (over the 250 day period relevant for the occupancy scenario) would be calculated as the average of 250 daily estimates for that subject. Average values for individual subjects are not available in Stanek et al. (1997), however the data in Table 5.3 indicate that the average ingestion rate over 210 subject-days (that is the average over 10 subjects and 21 days) can be as large as 114 mg/day, taking the average value over the three weekly periods having the largest weekly averages, or can be as small as 0 considering the three weeks having the lowest weekly averages.

Soil ingestion by children has been much more extensively studied than adult soil ingestion. Children's soil ingestion rates tend to be larger than reported adult ingestion rates, presumably due to their more frequent exposure to soil, and to a higher rate of hand-to-mouth transfer. Ingestion rates for children are therefore not appropriate as estimates for adults, but may provide information about reasonable upper limits for adults. A number of recent studies report measurements of soil ingestion rates for children using the tracer mass balance approach described above (Stanek and Calabrese, 1995, Binder et al., 1986, Clausing et al., 1987, van Wijnen et al., 1990, Davis et al., 1990). The EPA *Exposure Factors Handbook* (EPA, 1997) provides summaries and evaluations of these studies, leading to a recommended average ingestion rate for children of 100 mg/day. This rate represents an average over individuals and over the various study periods, however the study periods were typically short (days or weeks), and were typically conducted in the summer when ingestion rates are expected to be higher than during other times of the year. An upper percentile (unquantified) of 400 mg/day is also recommended in the EPA *Exposure Factors Handbook*, however low confidence is assigned to this estimate in view of the limited study period.

An upper limit for the individual chronic adult soil ingestion rate of 200 mg/day was adopted for this analysis based on the above information. This limit is consistent with the averages of daily rates from the limited sample reported by Stanek et al. (1997). The adopted upper limit for adults is larger than the average value recommended for children in the EPA *Exposure Factors Handbook*, however, the latter value represents an average over individuals, while the former represents limiting behavior of a single individual.

5.2.3.5.2 Distributional Properties of Chronic Dust Loading

Mean Dust Loading

Adult ingestion rates from Stanek et al. (1997) and Calabrese et al. (1990) were measured in a residential environment, and other published values for adult ingestion rate (e.g., Sheppard (1995)) typically describe residential conditions. As described in Section 5.2.2.2, estimating GO from measured ingestion rates requires an estimate of dust densities for the environment in which ingestion occurred. Dust densities used to infer secondary ingestion transfer rates from Equation 5.11, using ingestion rates measured or estimated for a residential environment, should therefore represent chronic values that may be encountered in this environment. In an occupational setting, dust densities, and therefore ingestion rates, are expected to be smaller than those observed in residences: the transfer factor GO, however, is assumed to be comparable in the two environments.

Hawley (1985) discusses ranges of dust densities found inside residences. Citing Solomon and Hartford (1976), he reports average dust densities for 239 floor dust samples taken from 12 homes of 320 mg/m^2 and 290 mg/m^2 based on concentrations of Pb and Cd, respectively. The larger number was adopted as an estimate of the average chronic dust concentration $DL_{C,I}$.

Upper and Lower Limits for Dust Loading

A lower limit on $DL_{C,I}$ was established based on the range of reported indoor dust-fall rates discussed in Hawley (1985), and assuming daily removal of accumulated dust. In a sample of suburban homes with closed windows, Shaefer et al. (1972, cited in Hawley, 1985) measured a mean dust fall rate of 20 mg/m^2/day. This dust-fall rate is the lowest cited by Hawley, and with the assumption of daily cleaning, corresponds to a chronic average density of 10 mg/m^2 as a lower limit in residential environments.

Ingestion rates in a residential setting may include ingestion while outdoors, where the subject's hands may become heavily soiled. The surface soil density to which the individual is exposed in outdoor settings is assumed to be limited by the density of soil retained on the hands. Sheppard and Evenden (1994) summarizes measured and estimated soil loads on hands for a variety of soil types and conditions, reproduced as Table 5.4. An upper limit of $DL_{C,I}$ of 0.5 mg/c^2 was assumed on the basis of these estimates. This density is generally consistent with reported densities for soiled hands, with the notable exception of Hawley's theoretical value of 3.5 mg/cm^2. Sheppard and Evenden (1994) propose that soil loads higher than 1 mg/cm^2 would prompt cleaning, and that higher densities would therefore not be associated with chronic ingestion.

5.2.3.5.3 Estimated Distribution for Chronic Individual Transfer Rate $GO_{C,I}$ and Default Value for GO

The variation among individuals in chronic values of soil ingestion, and of surface soil densities corresponding to the conditions in which that ingestion occurs, have been characterized by a mean value, an upper limit, and a lower limit. Without additional information to define the distributions for soil ingestion rate and surface soil density, a maximum entropy distribution was assigned for both variables. With a specified mean value, lower limit, and upper limit, the maximum entropy distribution corresponds to a truncated exponential distribution. Figures 5.4 and 5.5 show the assigned distributions for $SI_{C,I}$ and $DL_{C,I}$, respectively.

Table 5.4 Measurements and estimates of soil load on hands for freshly soiled or partially cleaned hands from Sheppard (1994), Table III

Reference	Load (mg/cm^2)	Conditions
Driver et al. (1989)	0.2 – 0.9	Dry whole soil, no cleaning
	0.8 – 2	Dry sieved soil, < 150 µm diameter
Hawley (1985)	3.5	Estimate assuming 50-µm-thick covering
Lepow et al. (1975)	0.5	Children, sampled with adhesive film
Que Hee et al. (1985)	0.5	House dust adhering to palm
Sheppard and Evenden (1994)	0.06 – 2	Dry soil, brushed clean, adhesive film sample
	0.3 – 0.5	Moist soil, brushed clean, adhesive film sample
	0.4 – 0.8	Wet soil, brushed clean, adhesive film sample
	<1	Visually clean, adhesive film sample

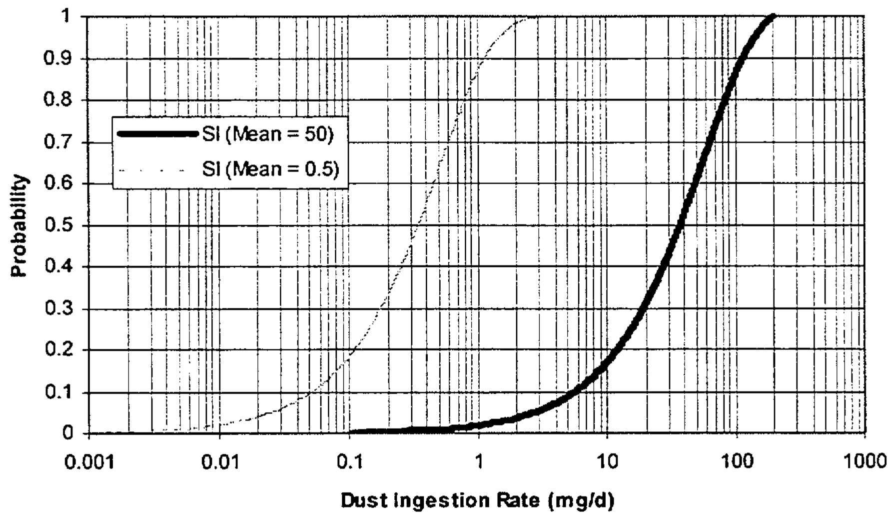

Figure 5.4 Estimated distribution of chronic dust ingestion rates based on two alternative mean ingestion rates

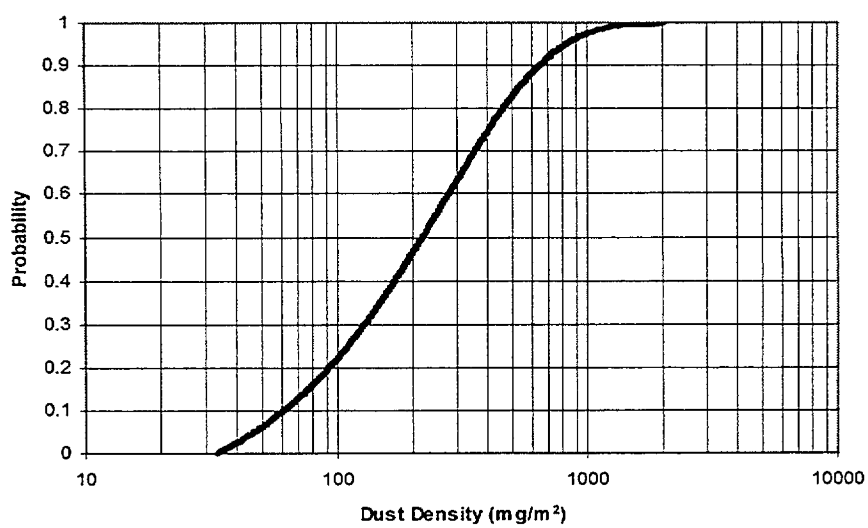

Figure 5.5 Estimated distributional of chronic individual dust densities corresponding to measured ingestion rates

As discussed above, there is considerable uncertainty in the estimate of mean ingestion rate due to the large variability in daily ingestion estimates. Available data are consistent with mean ingestion rates between 0 and 70 mg/day. To illustrate the effect of this uncertainty, two alternative distributions for $SI_{C,I}$, denoted $SI^L_{C,I}$ and $SI^U_{C,I}$, based on alternative mean ingestion rates of 0.5 mg/day and 50 mg/day, are shown in Figure 5.4.

The mean and variance of the logarithm of chronic individual transfer rate $GO_{C,I}$ was calculated using Equations 5.12 and 5.13 and given the mean and variance of the logarithms of $SI_{C,I}$ and $DL_{C,I}$. The alternative distributions for dust ingestion, SI^L_{CI} and $SI^U_{C,I}$, were each used to evaluate the effect of uncertainty in mean ingestion rate on the inferred distribution of transfer rate, producing the corresponding transfer rate distributions GO^L_{CI} and GO^U_{CI}. Table 5.5 summarizes the properties of these distributions. Loguniform distributions were then defined for $GO^L_{C,I}$ and $GO^U_{C,I}$ based on the calculated mean and variance of $\log(GO^L_{C,I})$ and $\log(GO^U_{C,I})$ from Table 5.5.

Figure 5.6 shows the derived distributions for $GO_{C,I}$. In converting the units of $GO_{C,I}$ from m^2/day to m^2/hr, measured dust ingestion was assumed to occur over a 16-hour period. This period corresponds to the period during which the reported soil ingestion rates, which were measured in a residential setting, would typically be operative.

Table 5.5 Distributional properties for chronic individual dust ingestion rate ($SI_{C,I}$), dust density ($DL_{C,I}$), and transfer factor ($GO_{C,I}$)

Parameter	Mean	Lower limit	Upper limit	Mean of $\log_{10}$	Variance of $\log_{10}$
$SI^{L}_{C,I}$ (mg/d)	0.50	0	200	-0.55	0.30
$SI^{U}_{C,I}$ (mg/d)	50	0	200	1.47	0.29
$DL_{C,I}$ (mg/m^2)	320	10	5000	2.29	0.22
$GO^{L}_{C,I}$ (m^2/d)	1.8E-3	4.4E-4	4.6E-3	-2.85	0.09
$GO^{U}_{C,I}$ (m^2/d)	1.8E-1	5.1E-2	4.3E-1	-0.82	0.07

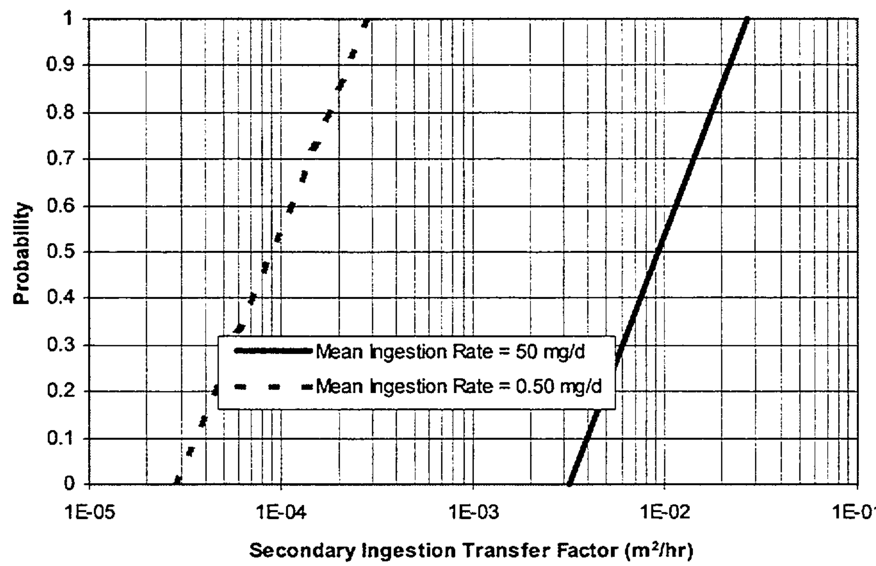

Figure 5.6 Estimated distribution of chronic individual secondary ingestion transfer factor $GO_{C,I}$ corresponding to alternative mean ingestion rates

Both distributions in Figure 5.6 are consistent with available data on adult ingestion, and the larger value is the approximate detection limit of current experimental procedures.

Uncertainty in the mean value of $SI_{C,I}$ creates large uncertainty in GO relative to the estimated variability of GO over individuals, as can be seen in Figure 5.6. Measurements of the frequency of various mouthing behaviors among adults might be used to estimate the surface area potentially accessed through such behavior, as well as the fraction of this surface area consisting of walls and floors. Such information might reduce uncertainty in the distribution of GO. No studies of this kind were identified in the literature review, however some transfer rates consistent with measured ingestion may be judged unrepresentative of adult behavior in an occupational setting.

A transfer rate of 10^{-2} m^2/hr, for example, implies mouthing an area equivalent to the inner surface of the hand once each hour. A rate of 10^{-3} m^2/hr implies transfer from an area roughly equivalent to two postage stamps each hour. The behavior implied by the latter rate is arguably a plausible upper limit for individuals in an occupational setting, and distributions having higher rates may be rejected on the basis of this judgment. The resulting distribution for GO would not be conservative with respect to uncertainty in the average ingestion rate given existing measurements, however the likelihood that additional information would lead to higher transfer rates would still be assumed to be small, in view of the behavior implied by these higher rates.

Among the possible distributions of GO consistent with measured ingestion rates, the lower distribution shown in Figure 5.6 was used in the parameter analysis. The distribution centered around 10^{-2} m^2/hr corresponds to a mean ingestion rate of 50 mg/day, which reflects the apparent detection limit of current experimental practice. The distribution centered around 10^{-4} m^2/hr (corresponding to a mean ingestion rate of 0.5 mg/day) includes plausible reductions from the higher distribution in consideration of two factors, each of which is assumed to reduce the transfer factor by an order of magnitude: the stipulation that an individual transfer rate of 10^{-2} corresponds to unreasonable behavior in an occupational setting; and the assumption that walls and floors are much less likely to be contacted than other surfaces, such as tables and desks. The average value of 1.1×10^{-4} m^2/hr represents the average member of the screening group, and defines the default value for this parameter.

As discussed in Section 5.2.2, the actual amount of contamination ingested will also depend on other factors, including the fraction F_I of the total source term that is "loose," and therefore available for ingestion. The fraction of loose contamination (F_I) is expected to be estimated or bounded using data collected prior to decommissioning.

5.2.3.6 Uncertainty of $GO_{C,I}$

The proposed distribution describing the variability of the secondary ingestion effective transfer rate rests on a number of assumptions, introducing a large amount of uncertainty in the assigned distribution.

(1) Empirical support for this parameter is very limited. The most recent measurements of soil ingestion in adults are subject to wide variability, and are consistent with average ingestion rates ranging from 0 to 70 mg/day. The upper limit represents the apparent detection limit of current experimental practice. The proposed value of 0.5 mg/day is consistent with available information. This value was established in consideration of judgments about 1) the plausibility of the behavior associated with higher rates, and 2) the fraction of the total contacted surface area consisting of contaminated walls and floors.

(2) Ingestion rates have been measured for adults in residential settings. Transfer factors in occupational settings, representing behavioral characteristics of individuals, are assumed to be similar to those in residential environments. Higher ingestion rates in residences are therefore assumed to be due to exposure to higher soil density, rather than to distinctive behavior.

(3) Surface dust and soil densities associated with available measurements of adult ingestion rates are unknown, and have been estimated from independent studies of dust densities and dust fall rates in residences, and soil densities on soiled hands.

5.2.3.7 Alternative Parameter Values

The value of the parameter used in the model can be modified based on site-specific survey data regarding removable activity, or with additional information on secondary ingestion.

5.3 Volumetric Breathing Rate (Metabolic), V_o (m^3/h)

5.3.1 Description of V_o

The breathing rate parameter (V_o), in conjunction with the resuspension factor and isotope-specific inhalation CEDE factors, is used to calculate the average annual dose due to inhalation. V_o is a metabolic parameter which represents the annual average breathing rate of adult males in the general population engaged in occupational activities.

The default value for this parameter defined in NUREG/CR-5512, Vol. 1, is 1.2 m^3/h. This value corresponds to breathing rates characteristic of light activity as defined in ICRP Publication 23 (1975). The RESRAD value for the same parameter is 0.96 m^3/h.

5.3.2 Use of V_o in Modeling

Inhalation dose is linearly proportional to V_o, as described below. The overall importance of V_o to total dose depends on the relative contribution of inhalation dose to total dose.

V_o is used to calculate the CEDE for the internal dose due to inhalation (DHO_i) resulting from inhalation of resuspended surface contamination. The relationship between V_o and internal dose due to inhalation is described by the following formula (NUREG/CR-5512, p 3.31):

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * \Sigma_{(j=1,Ji)} DFH_j * C_{avj} \quad (5.14)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period (d), C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario(dpm-d/100 cm^2), DFH_j is the inhalation CEDE factor (mrem per pCi inhaled), and RF_o is the resuspension factor (m^{-1}). The resulting internal inhalation dose is directly proportional to the volumetric breathing rate.

5.3.3 Information Reviewed to Define Breathing Rate Distributions

The literature review conducted to support the EPA Exposure Factors Handbook (EPA, 1996) was adopted for this study as the most current compilation of relevant literature. Eleven studies are reviewed and summarized in the Handbook. Five are identified as "key studies," and form the basis for inhalation values recommended there. The six remaining studies are considered "relevant," and contain supporting information relating to inhalation rate. Breathing rate estimates are not specifically reported in any study for general workers, although Linn et al. (1992) studied breathing rates for a small sample of construction workers. In several studies, daily average values are reported, as well as breathing rates for individuals engaged in various levels of activity. These activity levels are descriptively defined, for example as "rest," "sedentary," "light," "moderate," and "heavy."

Reported average daily values include a range and relative weighting of activities typical of an entire day, including sleep: this range and weighting of activities is not representative of activities specifically conducted by workers. For this reason, reported average daily values are not appropriate for V_o. Instead, breathing rates for adult male workers were based on the range of activities that would occur in an occupational setting, and the reported average values for the corresponding activity levels (see Section 5.3.3.1).

The summaries in the Handbook were used to evaluate the five "key" studies for the purpose of defining breathing rates for adult male workers. Each of these studies, and the resulting breathing rates that reflect adult male workers, are summarized below.

Layton (1993) presents a method for estimating breathing rate based on metabolic information:

$$V_E = E \times H \times VQ \qquad (5.15)$$

where:

V_E = the ventilation rate
E = the energy expenditure rate
H = the volume of oxygen consumed in the production of 1 KJ of energy, and
VQ = the ratio of intake volume to oxygen uptake

Three approaches are used to estimate the energy expenditure rate: annual caloric intake (corrected for reporting bias), elevation above basal metabolic rate (BMR) with BMR values estimated from body weight using a fitted regression model, and elevations above BMR using activity-specific elevation factors and time allocation data. These methods are used to estimate average inhalation rates over various population subsets defined by age and gender. This study draws from comparatively large data sets, and provides information on the relative contributions of the diverse factors influencing inhalation rate, including general health, body weight, diet, activity level, age, and gender. The first two methods provide estimates of long-term average breathing rate, which is not specific to occupational settings. The third method provides estimates of breathing rate for different levels of activity. Average inhalation rates for adult males for five activity levels, estimated by the third method, are summarized in Table 5.6. Estimates for two sets of activity classifications are reported. For each set, activity level is characterized by a qualitative description as well as by a BMR value or range. Different sets of BMR values were used for each set.

Linn et al. (1992) estimates inhalation rates for "high-risk" subpopulations, including outdoor workers, elementary school students, high school students, asthmatic adults, young asthmatics, and construction workers. Of these subpopulations, construction workers are most representative of adult male workers. The average breathing rate for construction workers, consisting of seven men between the ages of 26 and 34, is 1.50 m^3/hr. Activity-dependent breathing rates are also reported for three activity levels, as shown in Table 5.7.

Linn et al (1993) reports breathing rates for 19 construction workers who perform heavy outdoor labor both before and during a typical work shift. Spier et al. (1992) reports breathing rates for elementary and high-school students. Although considered "key" studies in the Handbook, these subpopulations do not correspond to adult male workers in light industry. Results of these two studies were not used to establish a default breathing rate value.

The California Air Resources Board (CARB) (1993) reports breathing rates in routine daily activities for children and adults at various activity level classifications. The study included a laboratory protocol, in which ventilation rate, heart rate, breathing frequency, and oxygen consumption were measured during treadmill tests. Heart rate, ventilation rate, and breathing frequency were also measured during a "field" protocol, which included (for adult males) driving and riding in cars, yard work, and mowing. Average breathing rates during the laboratory protocol are reported for five activity classifications. Average values during the field protocol are reported for three activity classifications. Table 5.8 summarizes the reported values for adult males.

Table 5.6 Estimated breathing rates for males from Layton (1993) for two sets of five activity levels (m^3/hr)

Inhalation rates for short-term exposures[1]					
Age (years)	Activity level				
	Rest BMR: 1	Sedentary BMR:1.2	Light BMR: 1.5 -2.5	Moderate BMR: 3 - 5	Heavy BMR: >5 - 20
18 - < 30	0.43	0.52	0.84	1.74	4.32
30 - < 60	0.42	0.50	0.84	1.68	4.20

Activity-dependent inhalation rates used to estimate daily inhalation rate[2]					
Age (years)	Activity level				
	Sleep BMR: 1	Light BMR: 1.5	Moderate BMR: 4	Hard BMR: 6	Very Hard BMR: 10
20 – 34	0.4	0.7	1.7	2.6	4.3
35 – 49	0.4	0.6	1.7	2.5	4.2
50 – 64	0.4	0.6	1.7	2.5	4.2

[1] Source: EPA(1996) Table 5-5
[2] Source: EPA(1996) Table 5-6

Table 5.7 Estimated breathing rates from Linn (1992) for two panels of healthy adult subjects[1] (m^3/hr)

Subject Group	Mean self-estimated breathing bates		
	Slow	Medium	Fast
Construction Workers	1.26	1.50	1.68

[1] Source: EPA(1996) Table 5-7

Table 5.8 Average inhalation rates for adult males from CARB (1993) (m^3/hr)

	Activity level				
	Resting	Sedentary	Light	Moderate	Heavy
Laboratory protocols[1]	0.54	0.60	1.45	1.93	3.63
Field protocols[2]		0.62	1.40	1.78	

[1] Source: EPA(1996) Table 5-13
[2] Source: EPA(1996) Table 5-14

The six studies classified as "Relevant" provide supporting information, such as assessments of the quality of individual's subjective judgments of their breathing rate and activity level. However, they do not provide information directly related to estimating breathing rates.

Three literature surveys are also classified as "Relevant." The EPA (1985) provides a summary of inhalation rates by age, gender, and activity level. This study compiles results of earlier investigations, and does not present information on the accuracy and methods used in these investigations. Reported breathing rates range from 0.7 to 4.8 m^3/hr for adult males depending on activity level. The ICRP (1981) presents ventilation estimates for reference adult males and females at two activity levels ("Resting" and "Light Activity") as well as daily inhalation rates based on an assumed activity pattern during the day. For adult males, the respective rates are given as 0.45 m^3/hr, 1.2 m^3/hr, and 22.8 m^3/day (0.95 m^3/hr). The value for V_o defined in Volume 1 of NUREG/CR-5512 was based on the "Light Activity" breathing rate for males from this study. It was not considered a sufficient basis for defining the default value for this parameter because of the availability of more extensive empirical data in three of the five "key" studies discussed above. The AIHC (1994) Exposure Factors Sourcebook recommends an average adult inhalation rate of 18 m^3/day based on data presented in other studies. This report draws from information presented elsewhere, and does not provide primary information on breathing rate.

5.3.4 Breathing Rates for the Average Member of the Screening Group

Breathing rates for adult male workers were estimated from the activity-dependent average breathing rates for adults summarized in Section 5.3.3. Activities of workers in an occupational setting include desk work, operating machinery, sweeping, and carrying items. Such activities correspond to the "Sedentary," "Light," and "Moderate" level classifications used by Layton (1993) and CARB (1993), and to the "Slow" and "Medium" subjective breathing rate classifications used in Linn's studies of construction workers. Although some types of work entail more strenuous activities characterized as "hard" or "very hard," sustained (year long) activity of this type was assumed not to be typical of the screening group.

The reported average breathing rates for the activity levels typical of adult male workers were selected from the values reported in Section 5.3.3. Table 5.9 summarizes the reported breathing rate values for occupational activity levels. (For each of the two sets of values reported by Layton (1993), the median breathing rate over the individual age groups was selected as typical of adult males.) Estimated breathing rates cover a range of values due to differences among the studies, and to differences in activity levels. An estimate of overall average breathing rate would require information on time allocation among these activity levels. Because detailed time allocation information is not available, the median reported value of 1.4 m^3/hr was selected as typical of males in the normal population.

Table 5.9 Reported average breathing rates corresponding to activity levels typical of workers in light industry

Breathing rate	Reference study and activity level
0.5	Layton (1993), Set 1: Median of "Sedentary" values over adult age groups
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.6	CARB (1993): "Sedentary" value from laboratory protocol
0.6	CARB (1993): "Sedentary" value from field protocol
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.3	Linn et al. (1992): "Slow" value for construction workers
1.4	CARB (1993): "Light" value from field protocol
1.4	CARB (1993): "Light" value from laboratory protocol
1.5	Linn et al. (1992): "Medium" value for construction workers
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	CARB (1993): "Moderate" value from laboratory protocol

5.4 Physical Parameters

5.4.1 External Dose Rate Factor for Exposure From Contamination Uniformly Distributed on Surfaces, $DFES_j$ (mrem/h per dpm/100 cm^2)

5.4.1.1 Parameter Description

The radionuclide-specific external dose rates conversion factors are defined as suggested in EPA Federal Guidance report No. 12 (Eckerman and Ryman, 1992). These factors provide the external effective dose equivalent by summing the product of individual organ doses and organ weighting factors over the body organs. For the building occupancy scenario, these factors are defined for an infinite surface (thin-layer) source condition. This source condition approximates the non-uniform residual contamination on building walls, ceilings, and floors by a uniform concentration over a floor having infinite area. This assumption is based on the earlier sensitivity study by Kennedy and Peloquin (1990). Relative dose rates obtained for rooms of different volumes with uniform and selected non-uniform sources of contamination were compared with the dose rates obtained using an infinite flat uniform source. The infinite flat uniform source provides a conservative estimate for the small rooms (less than 200 m^3) and reasonably conservative estimate (about 15% lower than the rate due to a non-uniform source) for the larger rooms. However, the sensitivity study was performed using one radionuclide only (Co-60). A constant distance between floor and ceiling (3 m) was assumed.

Although a number of assumptions underlie the values defined for the external dose conversion factors, these values have been obtained from a standardized dosimetry data base and have been determined to be appropriate for use in the NUREG/CR-5512 modeling. Uncertainty in these values was not evaluated in the parameter analysis.

5.4.1.2 Use of $DFES_j$ in Modeling

Radionuclide specific, the sensitivity of this parameter will depend on values of DFH_j, DFG_j, RF_o, V_o, and GO. The higher the value of $DFES_j$ for each of the radionuclides in the chain, the higher the total dose.

This parameter is used to calculate the external dose, $DEXO_i$, resulting from external exposure to penetrating radiation from an infinite surface source. The relationship between $DFES_j$ and external dose is described by the following formula (NUREG/CR-5512, Vol. 1, p. 3.12):

$$DEXO_i = 24 * t_o * \sum_{(j=1,Ji)} DFES_j * C_{avj} \quad (5.16)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, and C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario. The higher the value of $DFES_j$ for each of the radionuclides in the chain, the higher the resulting external dose.

5.4.1.3 Uncertainty in $DFES_j$

Dose conversion factors reflect the biological effects induced by exposure to a unit radionuclide activity density. The conversion from activity to a common measure of biological impact requires a number of simplifying assumptions, including assumptions regarding source geometry and spatial variability, the age and physiology of the receptor, and the circumstances of exposure (Eckerman and Ryman, 1992). These assumptions introduce a large amount of uncertainty about the appropriate value for dose conversion factors. Sources of uncertainty are identified in EPA Federal Guidance Report No. 12 (Eckerman and Ryman, 1992), however, this uncertainty is not quantified as distributions for the dose conversion factors recommended in the report. Uncertainty in dose conversion factors has therefore not been explicitly incorporated in this analysis.

5.4.1.4 Alternative Values for $DFES_j$

Variability in dose conversion factors may be related to differences in contaminant distribution on building surfaces. Different types of industrial activities at different buildings/sites could result in different contaminant distributions. In some cases (predominantly gaseous releases of condensible materials), contaminants could be distributed uniformly over all surfaces while liquid contaminants would be on the floor. The licensee may substitute different values from Report 12 based on a site-specific source geometry different from an infinite plane.

5.4.2 Inhalation CEDE Factor, DFH_j (mrem/pCi Inhaled)

5.4.2.1 Description of DFH_j

The radionuclide-specific internal inhalation dose rate conversion factors are defined as suggested in the EPA Federal Guidance report No. 11 (Eckerman et al., 1988). These factors are intended for general use in assessing average individual committed doses for inhalation of radioactive materials in any population that can be characterized by Reference Man.

Although a number of assumptions underlie the values defined for the inhalation dose conversion factors, these values have been obtained from a standardized dosimetry data base and have been determined to be appropriate for use in the NUREG/CR-5512 modeling. Uncertainty in these values was not evaluated in the parameter analysis.

5.4.2.2 Use of DFH_j in Modeling

Radionuclide specific, the sensitivity of this parameter will depend on values of $DFES_j$, DFG_j, RF_o, V_o, and GO. The higher the value of DFH_j for each of the radionuclides in the chain, the higher the total dose.

This parameter is used to calculate CEDE for inhalation (DHO_i) resulting from inhalation of resuspended surface contamination. The relationship between DFH_j and internal dose due to inhalation is described by the following formula (NUREG/CR-5512, Vol. 1, p. 3.13):

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * \sum(j=1,Ji)\ DFH_j * C_{avj} \quad (5.17)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during the first year of the building occupancy scenario, RF_o is the resuspension factor, and V_o is the volumetric breathing rate. The higher the value of DFH_j for each of the radionuclides in the chain, the higher the resulting inhalation dose.

5.4.2.3 Uncertainty in DFH_j

As with $DFES_j$, DFH_j is uncertain due to the underlying simplifying assumptions, including assumptions about residence time in the body and the spatial distribution of nuclides among and within various organs. This uncertainty has not been incorporated in this analysis.

5.4.2.4 Alternative DFH_j Values

Inhalation dose conversion factors may vary due to variations in the chemical properties of the contaminant. The licensee may propose a different value from Report 11 based on solubility class.

5.4.3 Ingestion CEDE Factor, DFG_j (mrem/pCi Ingested)

5.4.3.1 Parameter Description

The radionuclide-specific internal ingestion dose rate conversion factors are defined as suggested in the EPA Federal Guidance report No. 11 (Eckerman et al., 1988). These factors are intended for general use in assessing average individual committed doses for inhalation of radioactive materials in any population that can be characterized by Reference Man.

Although a number of assumptions underlie the values defined for the internal ingestion dose conversion factors, these values have been obtained from a standardized dosimetry database and have been determined to be appropriate for use in the NUREG/CR-5512 modeling. Uncertainties in these values were not evaluated in the parameter analysis.

5.4.3.2 Use of DFG_j in Modeling

Radionuclide specific, the sensitivity of this parameter will depend on values of $DFES_j$, DFH_j, RF_o, V_o, and GO. The higher the value of DFG_j for each of the radionuclides in the chain, the higher the total dose.

This parameter is used to calculate CEDE for ingestion (DGO_i) resulting from inadvertent ingestion of surface contamination. The relationship between DFG_j and internal dose due to ingestion is described by the following formula (NUREG/CR-5512, Vol. 1, p. 3.14):

$$DGO_i = 45.05 * 24 * t_o * GO \sum_{(j=1,Ji)} DFG_j * C_{avj} \quad (5.18)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario, and GO is the effective transfer factor. The higher the value of DFG_j for each of the radionuclides in the chain, the higher the resulting ingestion dose.

5.4.3.3 Uncertainty in DFG_j

DFG_j, like DFH_j, is uncertain due to the underlying simplifying assumptions (see Section 5.4.2.3). This uncertainty was not incorporated in this analysis.

5.4.3.4 Alternative Values for DFG_j

Ingestion dose conversion factors are radionuclide specific and are not likely to vary from site to site. However, licensees may propose updated dose conversion factors or uptake (f1) factors based on more recent dosimetry information.

5.4.4 Resuspension Factor for Surface Contamination (Physical), RF_o (m^{-1})

5.4.4.1 Parameter Description

The resuspension factor, RF_o, defines the ratio of contaminant concentration in inhaled air to surface contamination concentrations in the default NUREG/CR-5512 dose model. The model uses a single, constant (time-invariant) value. This value should therefore represent the effective value for the average member of the critical group over the one-year duration of the building occupancy scenario.

5.4.4.2 Use of RF_o in Modeling

Resuspension is important to dose because inhalation dose is directly proportional to RF_o, as discussed below.

This parameter is used to calculate CEDE for inhalation (DHO_i) resulting from inhalation of resuspended surface contamination. The relationship between RF_o and internal dose due to inhalation is described by (NUREG/CR-5512, Vol. 1, p. 3.13):

$$DHO_i = 45.05 * 24 * t_o * RF_o * V_o * 3_{(j=1,Ji)} DFH_j * C_{avj} \quad (5.19)$$

where J_i is the number of radionuclides in chain i, t_o is the time that exposure occurs during the building occupancy period, C_{avj} is the average annual activity of the radionuclide j during first year of the building occupancy scenario, DFHj is the inhalation CEDE factor, and V_o is the volumetric breathing rate. The resulting internal inhalation dose is directly proportional to the resuspension factor.

5.4.4.3 Information Reviewed to Define A PDF for RF_o

The value for the resuspension factor recommended in NUREG/CR-5512, Vol. 1, is 1×10^{-6} m^{-1}, based on a literature analysis of studies published from 1964 through 1990. The overall range of values obtained from these literature sources is 2×10^{-11} to 4×10^{-2} m^{-1}. However, most data referenced are not for indoor conditions. Only two of the references cited in Volume 1 provide data for indoor resuspension. The first of these, an IAEA technical report (1970), reports a value of 5×10^{-5} m^{-1} which has been obtained for operating nuclear facilities. The second of these two references, a review by Sehmel (1980), provides different resuspension factors depending on the type of activity conducted within the rooms of the building (walking, vigorous sweeping, and fan). The overall range cited by Sehmel is from 1×10^{-6} to 4×10^{-2} m^{-1}. The lower end of this range is suggested as a default based on the fact that surfaces are assumed to be cleaned of easily removable contamination at the time of license termination.

The parameter analysis requires a distribution describing the variability of site-specific values for this parameter over licensed sites. To define this distribution, a licensee is assumed to have detailed information about (or control over) factors effecting resuspension at their site, such as the activities of occupants. This information would be used to define a critical group for the site by selecting a subset of occupants exposed to a relatively high concentration of resuspended contaminants. RF_o would then be defined as the time-weighted average resuspension factor for this group over the one-year scenario duration.

A literature review was conducted to identify any developments in the understanding of the resuspension process since the review reported in NUREG/CR-5512 in 1992, and to identify data or approaches that could be used to develop a probability distribution function for the indoor resuspension factor. Older publications that were not referenced in NUREG/CR-5512, Vol. 1, were also reviewed for the same purpose.

Resuspension factor values are reported in a number of studies published between 1964 and 1997. Reported values vary over a wide range, from approximately 10^{-11} m^{-1} to approximately 10^{-2} m^{-1}. The review of some older publications indicated that a value of 1×10^{-6} m^{-1} was used in the development of general guidelines. This value has been seen as a general value having a reasonable factor of safety for hazard evaluation and design purposes (Brodsky, 1980). This value was also recommended by the IAEA (1982; 1986) and suggested as an average for Europe in Garland (1982). These sources support (but were not cited to justify) the parameter value adopted for RF_o in NUREG/CR-5512, Vol. 1. Most studies, and all but one study not included in the review reported in NUREG/CR-5512, Vol. 1, provide data on outdoor resuspension factors. These values are not directly relevant for the occupancy scenario model. Additionally, most reported resuspension factor values were measured or inferred under conditions that would not reasonably be sustained during the one-year exposure period. The different time scales of the experimental conditions and the scenario model must be considered in determining site-specific values for RF_o.

Published estimates of resuspension factors and resuspension rates under indoor conditions, identified during the literature review, are summarized in Table 5.10. The reported values from these sources range from 2×10^{-8} to 4×10^{-2} m^{-1}. With one exception (Thatcher and Layton, 1995), no recent information on indoor resuspension was found. This most recent study provides estimates of resuspension *rates* of aerosols measured in a California residence under controlled indoor conditions. However, these rates cannot be directly translated into resuspension factor values.

Various factors affecting resuspension, underlying the range of reported values, have been proposed in the literature. The effects of some factors are quantified in some studies, while other effects are discussed qualitatively. Although many studies consider the factors affecting outdoor resuspension, these factors have analogs in indoor conditions. Such studies are therefore relevant for understanding potential *variations* in RF_o across sites. Sources of variability in reported resuspension factor values are described in more detail below.

The common measurement techniques for determining indoor resuspension factors are:

- direct measurement of contaminant concentrations on surfaces and in the air (Jones and Pond, 1964; Glauberman et al., 1964; Brunskill, 1964; Mitchell, and Eutsler, 1964)
- redispersion of settled particulates (Fish et al., 1964)
- recoil of "hot-atoms" during decay of radionuclides (Leonard, 1995)

In addition to differences in experimental technique, measured values of resuspension factor may vary due to

Table 5.10 Reported information for indoor resuspension

Condition/reference	Range	Comments
Wind stress and mechanical disturbances, (Jones and Pond, 1964)	2×10^{-8} – 5×10^{-5} m^{-1}	Resuspension of loose Pu-nitrate particles deposited on various surfaces
Wind stress and vehicular and mechanical disturbances, (Glauberman et al., 1964)	1×10^{-5} – 1.5×10^{-2} m^{-1}	Resuspension from Pu-contaminated surfaces; 0.2% to 10% removable by smear sampling
Wind stress (Brunskill, 1964)	2.5×10^{-4} – 3.9×10^{-3} m^{-1}	Resuspension of radionuclide contaminants from clothing in change room
Vigorous mechanical disturbance (sweeping) (Mitchell and Eutsler, 1964)	1×10^{-2} – 4×10^{-2} m^{-1}	Resuspension of BeO on contaminated wood floor; ~4% removable by smear sampling
Vigorous mechanical disturbance (sweeping) (Fish et al., 1964)	9.4×10^{-6} – 7.1×10^{-4} m^{-1}	Redistribution of loose thorium oxide and thorium metal aerosol particles, ZnS and CuO particles on stainless steel surfaces
Indoor Residence (Thatcher and Layton, 1995)	1.2×10^{-10} – 1.0×10^{-7} sec^{-1} m^{-1}	Resuspension rate in a California residence (Note: These values cannot be directly translated to resuspension factors).

spatial variability of surface contaminant concentrations, variability of concentrations in air with location and with elevation, and spatial variations in surface texture leading to location-dependent resuspension. These variations can create uncertainty in the effective value of resuspension factor as estimated by the ratio of concentrations measured in air and on the contaminated surface.

A large number of physical factors can affect resuspension. According to IAEA (1992), the major factors are the following:

- time since disposal
- type of disturbance (air flow or mechanical)
- intensity of disturbance (air flow speed, traffic intensity)
- nature of surface (texture, composition, surface area)
- surface moisture
- particle size distribution
- climatic conditions (temperature, humidity, wind)
- type of deposition process (wet or dry)
- chemical properties of the contaminant
- surface chemistry
- topographic features

The potential effects of some of these factors on resuspension have been quantified, while only qualitative characterizations are available for others. As discussed above, some studies discuss the effects of these factors on outdoor resuspension factors. While values of outdoor resuspension factors are not appropriate for the occupancy scenario model, reported effects of variations in physical conditions (e.g., air flow) on relative resuspension factor values do provide useful information about potential variations in indoor resuspension factor values due to variations in the occupant's behavior or environment. Surface moisture and climatic conditions are factors that may influence resuspension in outdoor conditions but are assumed to be irrelevant for indoor resuspension. These factors are therefore not considered in the following discussion. For the other factors listed above, the studies cited in NUREG/CR-5512, Vol. 1, and Fish et al. (1964), Jones and Pond (1964), Brunskill (1964), Glauberman et al. (1964), and Mitchell and Eutsler (1964) were reviewed to better understand the factors controlling resuspension factors. The following discussion considers both outdoor and indoor conditions, but indoor conditions are emphasized.

5.4.4.3.1 Time Since Disposal

The parameter RF_0 is constant with time, however several studies model variations of resuspension factor with time, including Kathren (1968), Langham (1969), NRC (1975), IAEA (1982, 1986), Garland (1982), and Nair et al. (1997). All of these models produce a decrease in resuspension factor with time, reflecting the experimentally observed decrease in contaminant air concentrations with time over contaminated areas. Rather than a decrease in resuspension factor per se, this observed decrease in air concentrations may instead be due to overall depletion of surface contamination (e.g., downward migration of contaminants, downwind transport of resuspended contaminants, and other removal processes). The observed decrease might also be due to preferential depletion of easily-suspended contaminants.

All discussions of reduction of resuspension factor with time found in the literature survey pertain to outdoor resuspension. No information on the potential time-variation of indoor resuspension factors was found.

5.4.4.3.2 Type of Disturbance (air flow or mechanical)

Resuspension factors determined under conditions of mechanical disturbance can be at least one order of magnitude higher than resuspension factors determined under conditions where only wind resuspension occurred (Nair et al., 1997; Stewart, 1964; Thatcher and Layton, 1995; and IAEA, 1992).

Among studies reporting indoor resuspension factors, the higher resuspension factors provided in Brunskill (1964), Glauberman et al. (1964), and Mitchell and Eutsler (1964) were measured when disturbances significantly more severe than in normal operating conditions were applied to obtain measurable contaminant concentrations and when most of the surface contamination was a loose, easily removable, contamination (spills on the floor). Fish et al. (1964) reports a difference in resuspension factor of 1.5 orders of magnitude due to the type of activities in the room.

5.4.4.3.3 Intensity of Disturbance (air flow speed, traffic intensity)

Anspaugh et al. (1975) suggests that contaminant concentra-tions in the air are proportional to the power of the friction velocity which is, in turn, proportional to the horizontal wind velocity. Consequently, the difference of 1 order in magnitude between the wind speed may result in a difference of a few orders of magnitude in resuspension factors. The power law relationship between the wind speed and resuspension factor is also demonstrated by Hollander (1994).

Among studies of indoor resuspension, Fish et al. (1964) observed a power law relationship between the resuspension factor and the air velocity in the room, and Jones and Pond (1964) reports variations in resuspension factor due to different walking speeds.

5.4.4.3.4 Nature of Surface (texture, composition, surface area)

The magnitude of the influence of this factor on resuspension was not quantified in the literature. In a study of indoor resuspension, Glauberman et al. (1964) attributes a difference in resuspension factors of one order of magnitude to differences in room size.

5.4.4.3.5 Particle Size Distribution

Hinton et al. (1995) suggests that resuspension is greatest for particles with diameter smaller than 125 microns and the IAEA (1992) suggests that resuspension factor increases with particle diameter in the range from 1 to 5 microns. In Sehmel (1980), however, it is suggested that further studies are needed. In a study of indoor resuspension, Fish et al. (1964) reports a strong correlation with particle diameter and Thatcher and Layton (1995) report no indoor resuspension of particles less than 5 μm in diameter.

5.4.4.3.6 Chemical Properties of the Contaminant

The difference between resuspension factors determined in the same conditions for different radionuclides is one order of magnitude, but could be significantly smaller as discussed by Hartmann et al. (1989) and the IAEA (1992). Among studies reporting indoor resuspension factors, Jones and Pond (1964) reports variation of the resuspension factor within one order of magnitude depending on the contaminant.

5.4.4.3.7 Surface Chemistry

Although cited by the IAEA (1992) as a factor influencing resuspension, no specific information on the effect of surface chemistry on resuspension factor was found in the literature.

5.4.4.3.8 Topographic Features

No specific information on the effect of topography on resuspension factor was found in the literature. For outdoor resuspension, topographic variations would presumably create variations in near-surface wind speed, leading to variations in the effective resuspension factor. An analogous effect might occur for indoor resuspension due to the placement of ventilation ductwork and furniture.

The main conclusions of this literature review are:

- the new data on resuspension factors falls into the same range that was noted in NUREG/CR-5512, Vol. 1; however, the low end of the range is three orders of magnitude higher (2×10^{-8} vs. 2×10^{-11} m^{-1});
- no significantly new models of resuspension and methods of resuspension measurement were proposed since 1990;

- additional information is available on resuspension factors determined under indoor conditions

- the resuspension factor value of $1 \times 10^{-6}\ m^{-1}$ is the most frequently suggested and appears to represent some average of the experimental data;

- data on probability distribution functions that could be used to reflect uncertainty and variability in resuspension factors is very limited; however, it is possible to derive a distribution for RF_0 from experimental data on resuspension; and

- the range of the resuspension factor values measured under indoor conditions is around four orders of magnitude (Jones and Pond, 1964)

5.4.4.4 Estimating RF_0 from Site Information

For a particular site applying the building occupancy scenario model, a licensee might seek to defend a specific value for RF_0 based on the physical features of the site that influence resuspension directly, or based on expectations about, or restrictions on, the behavior of occupants which may affect resuspension. In view of the reported decrease in resuspension factor with time discussed above, a constant value of RF_0 reflecting the *initial* resuspension factor at the time of license termination is assumed to be appropriate for assessing regulatory compliance.

It is useful to express the resuspension factor used for the building occupancy dose calculation as the product of two separate parameters: the resuspension factor for "loose" contamination, and the fraction of the total contaminant that is "loose." "Loose" contamination refers to contamination that is available for transport via resuspension, and excludes any contamination that adheres to, is absorbed into, or is covered by exposed surfaces. This decomposition allows a more direct use of many reported values of resuspension factor given the underlying experimental conditions, and provides a physically plausible mechanism for linking the values of resuspension factor and secondary ingestion rate used in the dose calculation.

Based on the analysis of the literature data, the initial resuspension factor values can differ at least by a few orders of magnitude depending on site specific conditions which depend on the use of the property (i.e., the nature and intensity of mechanical disturbance associated with activities of the critical group), by an order of magnitude depending on radionuclide, and an order of magnitude depending on modeling approach used. Variations due to differences in radionuclides, topography, type of deposition, particle size, surface chemistry, and the nature of the surface are assumed to be uncontrollable by the licensee, but may be evaluated on a site-specific basis to support alternative values for resuspension factor.

Several of the physical factors discussed in Section 5.4.2.3 influencing resuspension may be plausibly bounded by characteristics of the site, or controlled by the licensee in an effort to support a site-specific value for RF_0. Other factors do not appear amenable to characterization or control. Site-to-site variations in these factors create variations among site-specific values of RF_0, but would presumably not be controllable by the licensee. Considerations of these factors follow.

5.4.4.4.1 Time Since Disposal

Because RF_0 is constant with time, the potential for resuspension factor to decrease with time is disregarded, as discussed above.

5.4.4.4.2 Type of Disturbance

Mechanical disturbance significantly increases the observed resuspension factor. Lower values of RF_0 may be appropriate if surface contamination is undisturbed by sweeping or walking. In addition, the effective (time averaged) resuspension factor may be reduced if the contaminated area is subject to brief intermittent disturbance rather than continuous disturbance.

5.4.4.4.3 Intensity of Disturbance

Large air-flow rates and vigorous mechanical disturbance lead to increased resuspension factors. Demonstration of limits on intensity, or of intermittence of periods of intense disturbance, may affect the value of RF_0, which reflects average annual conditions.

5.4.4.4.4 Nature of Surface

Little quantitative information on the effect of this factor was found in the literature. Available information is therefore assumed to be insufficient to support alternative values for RF_0 based on site-specific information about this factor.

5.4.4.4.5 Particle Size Distribution

Particle size is generally regarded as influencing resuspension factor.

5.4.4.4.6 Type of Deposition Process

Reported resuspension factor values are higher for loose, easily removable contamination than for contamination that is bound to, or absorbed into, the surface. Licensees are assumed to have removed most loose contamination prior to decommissioning. This assumption can be reflected in the occupancy scenario calculations in two ways: measured resuspension values for loose contamination may be excluded in defining RF_0, or RF_0 may be initially defined for loose contamination, and the licensee may later reduce this value based on the fraction of loose contamination at their site.

Excluding measurements on loose contamination in defining RF_0 assumes that *all* loose contamination has been removed, and that no mechanism will loosen contamination during the occupancy period. This assumption does not appear to be justifiable in all cases. The second approach, which decomposes the resuspension factor used in the occupancy scenario model into a resuspension factor for loose contamination, and a fraction of contamination that is loose (i.e., available for resuspension) allows uncertainty in the fraction of loose contamination to be explicitly addressed. This approach also provides a convenient mechanism for connecting the values for resuspension factor and secondary ingestion rate by using a common value for the fraction of loose contamination.

The parameter RF_0 is therefore assumed to describe loose (resuspendable) contamination, and the licensee can reduce this value by demonstrating that the fraction of loose contamination at their facility is less than a specified fraction of total contamination (see NUREG-1549).

5.4.4.4.7 Chemical Properties of the Contaminant

The potential effect of chemical properties on resuspension factor is estimated to be one order of magnitude or less. Because it is a source of site-to-site variability in RF_0, licensees may base site-specific values for RF_0 on chemical property arguments, however the size of this effect may be small.

5.4.4.4.8 Topography

No quantitative information on the effect of this factor was found in the literature. Available information is therefore assumed to be insufficient to support alternative values for RF_0 based on site-specific topographic information.

Of the factors influencing resuspension discussed above, site-specific values for RF_0 might be supported by information about the nature and intensity of disturbances likely to occur during the occupancy period. The effect of the remaining factors on resuspension is either relatively small (an order of magnitude or less), or is insufficiently defined in the literature for the licensee to defensibly derive a site-specific value of RF_0 from information about these factors. Variations in these factors from site to site introduce variations in RF_0 which are not expected be controllable by the licensee by restricting the use of the property (see NUREG-1549 for more information).

In addition to the nature and intensity of disturbance, the fraction of loose contamination will also control resuspension, and may be estimated from site data. As discussed above, any site-specific estimate for this fraction is assumed to be used to scale RF_0, while RF_0 is assumed to describe resuspension of loose contamination.

Variations in the site-specific values for RF_0 were estimated using published experimental data that were measured under a variety of activities and conditions. The procedure is summarized below, followed by a description of the application and results.

(1) Reported values for resuspension factor were categorized according to similarity in the descriptions of the experimental conditions regarding the nature and intensity of disturbance. As discussed above, variations in resuspension factor due to variations in mechanical disturbance may be plausibly controlled by the behavior of the critical group.

(2) For each category defined in Step 1, a range of acute (short term) resuspension factors was defined based on the reported values in each category. Within each category, variations in reported values are assumed to reflect variations due to factors other than the nature and intensity of surface disturbance, such as surface chemistry, surface topography, and particle size distribution. Variability in these factors among sites will also produce variability in site-specific values for RF_0, however, the effects of these factors on resuspension would not depend on the activities of occupants. Instead, such variations are modeled as random variations among sites, independent of the use of the property.

(3) For each category, a range of chronic (annual average) resuspension factors was defined using the range of reported resuspension factor values for that category. In general, the reported values for resuspension factor correspond to activities that

would be performed at intervals in an occupational setting, and performed only for a limited period of time. RF_0 represents a chronic (year-long) effective value, and should therefore reflect the mixture and duration of activities performed by members of the critical group during a typical year. The range of chronic resuspension factor values is based on the observed range in reported resuspension factor values in consideration of uncertainties in time allocation estimates and in the estimated range of acute resuspension factor values.

(4) For a range of possible property uses, the occupation of the critical group at these properties was associated with one of the categories defined by the nature and intensity of disturbance in Step (1). This assignment reflects the occupational conditions to which a member of the critical group is expected to be exposed at such properties. Due to the limited number of measurements, only two categories were used to describe the potential occupational environments for members of the critical group. These categories are distinguished by the presence or absence of high air-flow rates.

(5) A distribution describing the variability of RF_0 over sites was constructed based on: the estimated fraction of sites whose critical group is associated with each surface disturbance category defined in Step (4); and the distribution of chronic resuspension factor values associated with each category, defined in Step (3). In estimating the fraction of sites in each category, both the current use of the property, and the potential conversion of the property to other uses were considered.

Grouping of Reported Resuspension Factors based on Experimental Conditions

Table 5.11 summarizes the resuspension factors reported for experimental studies for various conditions (Jones and Pond, 1964; Glauberman et al., 1964; Mitchell and Eutsler, 1964; and Fish et al., 1964). Brunskill (1964) studied resuspension from contaminated clothing in the high air-flow conditions typical of a change room. In the occupancy scenario, contamination is assumed to occur on building surfaces. Resuspension from clothing was assumed to be unrepresentative of resuspension from these surfaces: values reported by Brunskill were therefore not considered in defining a distribution for RF_0.

The experiments by Jones and Pond (1964) provide resuspension factors for a range of activities that are common in occupational settings. The measured resuspension factors reported by Jones and Pond (1964) are for four levels of activities using PuO2-contaminated particles (0.4 - 60 microns diameter) and particulate air samplers positioned at 14-175 cm above the surface.

Glauberman et al. (1964) provides resuspension factors for a range of air-flow rates and mechanical disturbances that may occur in occupational settings. The values for this study reported in Table 5.11 show the relatively narrow range of resuspension factors observed for four experimental conditions. Glauberman measured occupational exposure to airborne particulates in a operating facility by measuring the concentrations of particles in air (high efficiency particulate sampler) and particles on surfaces (smear sampling), and reporting the ratio as a resuspension factor. Airborne particle contaminants in this experiment may have originated from sources other than surfaces (e.g., processing equipment, etc), which would tend to increase estimated resuspension factor values. The reported values from Glauberman et al. (1964) are included in Table 5.11 for comparison with the distribution for RF_0, but were judged to be highly uncertain and to overestimate the resuspension factor associated with the conditions described. These values were not used in developing the distribution. Mitchell and Eutsler (1964) measured resuspension factors during vigorous mechanical disturbance of contamination on a wood floor. The experimental conditions were contrived to deliberately suspend loose contamination in order to produce measurable values of resuspension factor. These conditions are not considered to be representative of conditions that would occur in an occupational setting. The reported values were therefore not included in defining a distribution for RF_0.

Fish et al. (1964) provides resuspension factors for a range of vigorous mechanical disturbances of contamination on a tile floor, and for high air-flow rates. The values in Table 5.11 for this study are reported for four types of disturbance.

In order to separate the effects of occupation-related factors from uncontrollable factors on resuspension, the resuspension factor values reported in Table 5.11 were grouped according to the nature and extent of surface disturbance. The presence or absence of high air-flow rates was first used to define two groups. For measurements made in the absence of high air flow, the descriptions of mechanical disturbance of the surface were used to classify each reported value in to one of two sub-groups based on the presence or absence of mechanical disturbance. For high air-flow conditions, too few values are available to support a distinction based on mechanical disturbance. Table 5.12 shows the values assigned to each of the three resulting categories.

Table 5.11 Resuspension factors measured under various conditions

Experimental condition	RF_o (m^{-1})
Reported by Jones and Pond (1964)	
Normal room ventilation	3.3×10^{-8}
Walking (14 steps/min)	9.1×10^{-6}
Walking (36 steps/min)	6.9×10^{-5}
Walking (100 steps/min) with wind stress (hair dryer directed toward floor)	1.5×10^{-4}
Reported by Glauberman et al. (1964)*	
Undisturbed	1.5×10^{-5} to 3.6×10^{-4}
Fans on	3.4×10^{-5} to 1.6×10^{-3}
Vibration (dolly)	1.2×10^{-4} to 1.9×10^{-4}
Fans + vibration	1.2×10^{-4} to 1.5×10^{-2}
Reported by Mitchell and Eutsler (1964)**	
Vigorous sweeping by two workmen	1.02×10^{-2} to 4.2×10^{-2}
Reported by Fish et al. (1964)	
Vigorous work activity, including sweeping	1.9×10^{-4}
Vigorous walking	3.9×10^{-5}
Light work activity	9.4×10^{-6}
Rapid air circulation	7.1×10^{-4}

* Values not used due to experimental error (see text)
** Values not used due to unrepresentative conditions (see text)

Table 5.12 Reported resuspension factor values grouped by experimental conditions

Air flow	Mechanical stress	Reference	RF_o (m^{-1})
Low/none	Absent	**Jones and Pond (1964):** Normal room ventilation	3.3×10^{-8}
Low/none	**Present**	**Jones and Pond (1964):** Walking (14 steps/min)	9.1×10^{-6}
		Fish et al. (1964): Light work activity	9.4×10^{-6}
		Jones and Pond (1964): Walking (36 steps/min)	6.9×10^{-5}
		Fish et al. (1964): Vigorous work activity, including sweeping	1.9×10^{-4}
		Fish et al. (1964): Vigorous walking	3.9×10^{-5}
High		**Fish et al. (1964):** Rapid air circulation	7.1×10^{-4}
		Jones and Pond (1964): Walking (100 steps/min) with wind stress (hair dryer directed toward floor)	1.5×10^{-4}

As discussed above, values reported by Glauberman et al. (1964) are assumed to overestimate resuspension by at least an order of magnitude, and were not included.

Trends among categories in Table 5.12 are generally consistent with expectations about resuspension: values tend to increase when mechanical disturbance or high air flow rates are present. Within each category, however, the range of reported values is generally large. This range is assumed to reflect variability in factors other than the nature and intensity of disturbance, such as surface chemistry, topography, and particle size.

Ranges of Resuspension Factors for Various Stress Conditions

Ranges of resuspension factor values were defined using the information in Table 5.12. Table 5.13 defines the ranges of resuspension factor values corresponding to each category. Estimates of the upper and lower limits, along with the source of these estimates, are provided for each category.

The values in Table 5.13 are based on the range of reported acute resuspension factor values for distinct conditions of surface disturbance. The particular activities of occupants at a given site will entail characteristic disturbance conditions, and therefore control the effective resuspension factor values appropriate for those occupants. Within each category, the range of reported values is assumed to reflect the effects of factors specific to the site but unrelated to occupation, such as surface topography and chemistry, and particle size.

The value for RF_0 used in the dose calculation should reflect the time-averaged value of condition-specific resuspension factors over the one year duration of the occupancy scenario. This time average (chronic) value will generally differ from the acute values in Table 5.13 due to variations in the occupant's behavior over time. In addition, the larger resuspension factor values given in Table 5.13 for high air-flow conditions imply significant depletion of the source over the one year period of the scenario. The effects of these two factors on the proposed distribution for RF_0 are described in the following sections.

Acute vs. Chronic Resuspension Factor Values

For a given individual, the resuspension factor will vary with time because their activities vary with time. Ideally, an estimate of the chronic (time averaged) resuspension factor value would be based on an estimate of the time spent in activities corresponding to each category. The chronic resuspension factors would then be calculated as the sum of the acute resuspension factors for each category, weighted by the amount of time spent in each category. As a result of this averaging process, the range of chronic values for occupants who tend to spend their time in activities in a given category will be narrower than the range of acute values experienced by the occupant over time.

A formal estimate of chronic resuspension factor values would require estimates of the time spent on each category, and of the acute resuspension factor for each category. For this analysis, the results of such a process would be subject to two important and counteracting sources of uncertainty.

First, estimates of time allocation for particular occupations that might occur at licensed properties would be highly uncertain. Although, as discussed above, the range of chronic values for occupants would be narrower than the range of acute values due to the effect of time averaging, the location of the range of chronic values within the larger range of acute values would be subject to considerable uncertainty due to uncertainty in the estimated time allocation.

Second, the ranges of possible acute resuspension factor values corresponding to distinct stress conditions is uncertain. Although ranges for the categories defined in Table 5.13 were defined by the limits of reported values, very few observations are available for each category. As a result, the potential range of acute resuspension factor values corresponding to distinct stress conditions is expected to be wider than the range in reported values due to limited sampling of these conditions by published experimental results. In order to formally calculate chronic resuspension factor values, estimates of the true range of acute resuspension factors, developed in consideration of the limited number of samples available in each category, would be required. These estimates would also be subject to considerable uncertainty.

Table 5.13 Ranges of potential resuspension factor values for categories of surface stress conditions

Category	Air flow	Mechanical stress	Limit	Value (m^{-1})	Source
A	**Low/ none**	**Absent**	Lower	3.3×10^{-8}	**Jones and Pond (1964):** Normal room ventilation
			Upper	3.3×10^{-8}	**Jones and Pond (1964):** Normal room ventilation
B	**Low/ none**	**Present**	Lower	9.1×10^{-6}	**Jones and Pond (1964):**Walking (14 steps/min)
			Upper	1.9×10^{-4}	**Fish et al. (1964):** Vigorous work activity, including sweeping
C	**High**		Lower	1.5×10^{-4}	**Jones and Pond (1964):** Walking with wind stress
			Upper	7.1×10^{-4}	**Fish et al. (1964):** Rapid air circulation

Rather than attempting a formal calculation of chronic resuspension factor values, the ranges of values in Table 5.13 were directly adopted as estimates of the ranges of potential chronic values for occupants typically exposed to conditions defined by each category. This approach does not require assumptions regarding time allocation for various occupations nor assumptions about the actual range of potential acute values given the range in reported measurements. As discussed above, these assumptions would introduce considerable uncertainty in the calculated chronic values. The ranges in Table 5.13 are also uncertain as estimates of chronic resuspension factors, however the two primary sources of uncertainty discussed above tend to have counteracting effects: time averaging of acute values would result in chronic values that are narrower than the range of acute values, however the actual range of acute values is wider than the range of observed values due to the limited number of samples.

Source Mass Conservation

Based on the above considerations, the ranges of reported acute resuspension factor values in Table 5.13 were assumed to define the ranges in potential annual average resuspension factor values. For high air-flow conditions, however, the annual average resuspension factor value may also be limited by the total source mass. Because the occupancy scenario model does not include source mass loss via resuspension, resuspension factor values which imply substantial depletion of source contaminants will lead to overestimates of dose.

The effect of source depletion by resuspension in the presence of high air flow can be included in one of two ways: the occupancy scenario model can be revised to include source mass conservation, or an effective resuspension factor can be derived which includes the effect of source mass loss during the one-year scenario period. The latter approach was adopted, as described below, to calculate an *effective* chronic resuspension factor value from the *potential* chronic values in Table 5.13. This effective value incorporates the influence of source depletion, which is not modeled in the default occupancy scenario model as defined in NUREG/CR-5512, Vol. 1. *The resulting resuspension factor values are not appropriate for models which explicitly include source mass loss via resuspension.*

Under conditions of high air-flow, any resuspended material is assumed to be removed as a potential source. Under this assumption, the rate of source depletion is equal to the resuspension rate:

$$\frac{dC_s(t)}{dt} = -\lambda_{res} C_s(t) \qquad (5.20)$$

where $C_s(t)$ is the source concentration, and λ_{res} is the resuspension rate. In Equation (5.20), all source mass loss is assumed to occur through resuspension, and mass loss due to other process is assumed to be negligible over the one-year dose assessment period. During this period, the amount of resuspended material is calculated from a constant specified source $C_s(0)$ and the specified resuspension factor value RF_{eff}. Mass depletion implied by Equation 5.20 may be approximately included via RF_{eff} by requiring that the resuspended mass, calculated using RF_{eff} and $C_s(0)$, is equal to the average resuspended mass calculated using the potential chronic resuspension factor RF_c and the depleting source $C_s(t)$:

$$RF_{eff} C_s(0) = \frac{1}{T}\int_0^T RF_c C_s(t)\,dt = \frac{1}{T}\int_0^T RF_c C_s(0) e^{-\lambda_{res} t}\,dt = RF_c C_s(0)\left(\frac{1-e^{-\lambda_{res}T}}{\lambda_{res}T}\right) \qquad (5.21)$$

so that the effective and potential resuspension factors are related by:

$$RF_{eff} = RF_c\left(\frac{1-e^{-\lambda_{res}T}}{\lambda_{res}T}\right) \qquad (5.22)$$

In Equation 5.22, T is the length of time during which source mass loss occurs, which was assumed to correspond to a standard working year of 250 eight-hour days (50 five-day weeks). The resuspension rate can be estimated from the room geometry, the ventilation rate, and the resuspension factor:

$$\lambda_{res} = \left(\frac{V}{A}\right)_{room} RF_c\, \lambda_V \qquad (5\text{-}23)$$

where V is the room volume, A is the room area, and λ_V is the ventilation rate. The ratio $\frac{V}{A}$ typically ranges from approximately 0.5 m for small rooms to approximately 1 m for large rooms. Ventilation rates corresponding to "high" air-flow rates were estimated using the Versar (1990) *Database of PFT Ventilation Measurements*, as summarized in the EPA Exposure Factors Handbook. The database compiles results from a number of separate studies, each study reporting a number of measurements taken at different residences or during different seasons. These measurements were made in residential rather than occupational settings, and cannot be used directly to estimate ventilation rates for high air-flow conditions. Across the summarized studies, the 90th percentile ventilation rates range from 0.38 to 5.89 h^{-1}. A ventilation rate of 5 h^{-1} was therefore chosen to represent high air-flow conditions in an occupational setting.

5.4.4.5 Proposed Distribution for RF_0

For a given site, a site-specific value for RF_0 should reflect conditions experienced by the average member of the critical group. The critical group at a given site is in turn assumed to be defined by the occupation associated with the upper end of the range of effective resuspension factor values.

A distribution function describing the variability of site-specific values for RF_0 was calculated as the weighted sum of the distributions for the surface stress categories defined in Table 5.13. Weights for each category represent the fraction of sites having critical groups which are chronically exposed to the type of surface disturbance characterizing each category.

Within each category, site-to-site variability in topography, chemistry, particle size, and other factors unrelated to occupation were assumed to produce values between the lower and upper limits for that category. Because no information is available on the potential distribution of values within these limits, the logarithm of RF_0 was assumed to be uniformly distributed between them. For resuspension in the presence of high air-flow, effective resuspension factor values were calculated from the potential resuspension factor values (Category C of Table 5.13) using Equations 5.22 and 5.23.

Assuming that any property might be devoted, at some future time, to light industry, no licensee would be able to exclude the possibility of mechanical disturbance chronically occurring at their site. The fraction of sites having critical groups exposed to Category A is therefore assumed to be 0. Many licensees would, however, be able to exclude the possibility of high air-flow rates, as such rates seem likely to be associated with customized ventilation systems, large openings such as bay doors, or other structural features which the building may lack. The fraction of sites containing such features was estimated as the fraction of non-service enterprises devoted to manufacturing in 1993 (approximately 9.8%), as reported by the U.S. Census Bureau. The remaining sites (90.2%) are assumed to have resuspension factor values from Category B.

In summary, 90.2% of sites are assumed to have resuspension factor values between 9.1×10^{-6} and 1.9×10^{-4} m^{-1}, with a log-uniform distribution assumed between these limits. The remaining 9.8% of sites are assumed to have structural features that might create high air-flow conditions, and therefore have potential resuspension factor values ranging from 1.5×10^{-4} to 7.1×10^{-4} m^{-1}, with a log-uniform distribution assumed between these limits. High resuspension factor values, however, in conjunction with high air-flow conditions, imply substantial depletion of source mass during the one-year performance period. This depletion is included in the resuspension factor value by calculating an effective annual average value from the potential resuspension factor value using Equations 5.22 and 5.23. In this calculation, the ventilation rate was assumed to be 5 h^{-1}, while the volume/area ratio was assumed to be uniformly distributed between 0.5 m and 1.0 m.

Figure 5.7 shows the resulting cumulative distribution functions for RF_0, while Figure 5.8 shows the corresponding probability density function. The proposed distribution for RF_0 ranges from 9.1×10^{-6} m^{-1} to 1.9×10^{-4} m^{-1}, with a median value of 5.0×10^{-5} m^{-1}. Although the resuspension factors for various experimental conditions ranges over several orders of magnitude, values of resuspension factor for the screening group are biased towards the upper end of reported values based on the range of surface stress conditions assumed for the workers in light industry. This distribution reflects resuspension of loose contamination, and should be scaled to reflect the fraction of the total contamination which is available for resuspension.

5.4.4.6 Parameter Uncertainty

The proposed distribution describing the variability in the resuspension factor is based on several assumptions, leading to uncertainty in this distribution as an estimate of the potential variability of RF_0 over sites:

(1) Resuspension of loose particles in a building occurs by a combination of wind stress from normal building ventilation and mechanical disturbances from walking and vehicular traffic. Other than in manufacturing establishments, persistent high air-flow conditions are assumed to be unlikely.

(2) Resuspension factor values are reported to depend to some extent on a number of other factors, including surface texture and topography, particle size distribution, type of deposition, and chemical properties of the contaminant and surface. These factors are assumed to produce site-to-site variations in resuspension factor values which are unrelated to the occupation of the critical group.

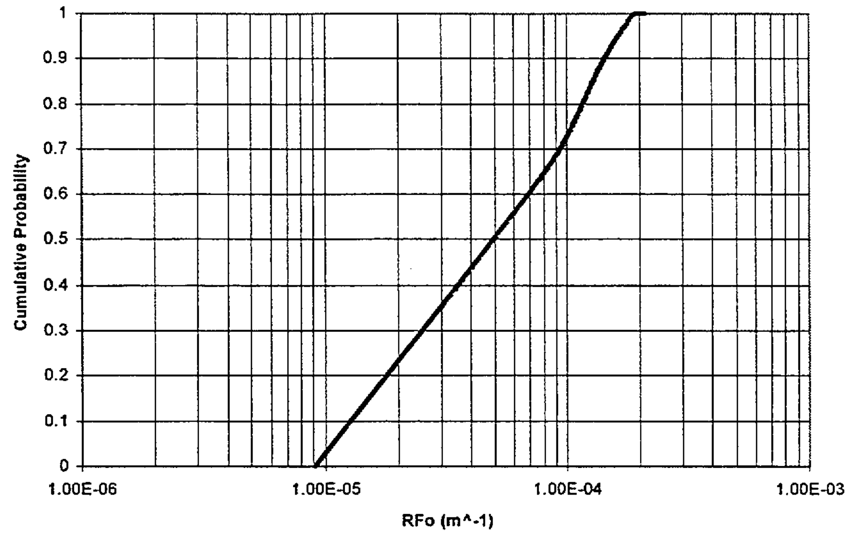

Figure 5.7 Cumulative probability function for RF_o

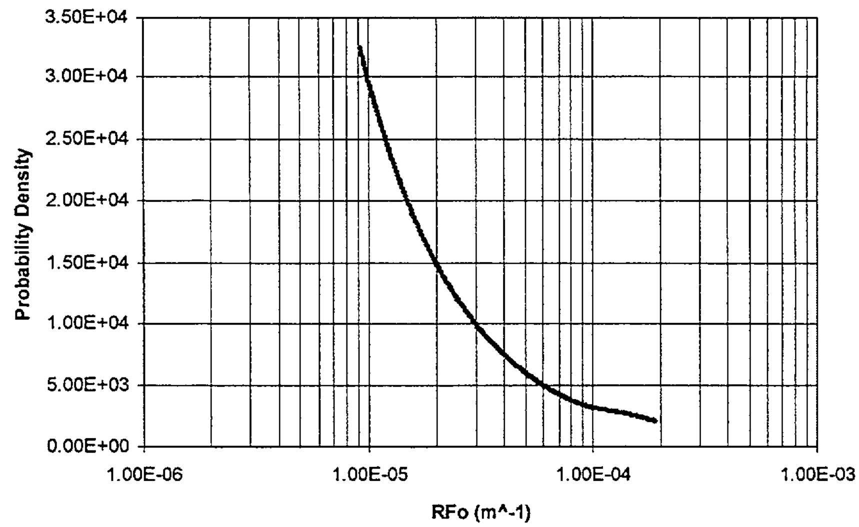

Figure 5.8 Proposed probability density function for RF_o

(3) The reported ranges of resuspension factors, measured under experimental conditions corresponding to episodic occupational activities, were adopted as the range of possible chronic resuspension factor values for occupants typically engaged in these activities. This assumption was made in consideration of the uncertainties associated with estimated time allocations for occupations, the tendency for time-averaged values to have lower variability than the true acute values, and the expectation that the limited number of measurements of resuspension underestimate the true variability in acute resuspension factor values.

(4) The combination of high resuspension factor values with high air flow conditions implies substantial depletion of source mass during the one year dose assessment period. Because the default occupancy scenario model does not include source mass loss through resuspension, effective (annual average) resuspension factor values, which approximate the effect of source depletion, were developed for these conditions. This approximation assumes that resuspension is the primary mechanism of source depletion, and that mass loss through other processes are comparatively small during the performance period. *These effective resuspension factor values are not suitable for use in models that explicitly include source mass loss by resuspension.*

(5) The data on resuspension reported by Glauberman (1964) are regarded as uncertain over-estimates.

(6) U.S. Census data on the numbers and types of industrial divisions in the United States reflect the variability in property uses over the licensed sites.

(7) Alternative future property uses would be considered in establishing a site-specific resuspension factor value. Such uses might increase or decrease mechanical surface disturbance. Increases in air flow are assumed to require extensive modifications to existing structures.

5.4.4.7 Alternative Parameter Values

The resuspension factor will vary across sites due to differences in the use of the properties, and due to factors unrelated to the use of the property such as surface chemistry and topography. A licensee may attempt to support limits on RF_o based on the intended use of the property or provide site-specific data regarding fixed vs. removable contamination. Physical properties of the building, existing zoning requirements, and site survey results may be used to support site-specific values.

5.5 Results

Parameter distributions defined in Section 5.4 were used to derive dose distributions for unit concentrations of each of the 106 potential source radionuclides having half-lives greater than 65 days (see Table 5.14). Screening dose values, corresponding to specified quantiles of the dose distributions, were then identified. Because the resuspension factor RF_o is the only variable physical parameter, the quantile values of the dose distributions correspond to the quantile values of the distribution for RF_o. The default value for RF_o, corresponding to a specified inversion tolerance P_{crit}, is simply the $1 - P_{crit}$ quantile value of the RF_o distribution. The general procedure for establishing these dose values is described in Section 3.0. The application of this procedure to the default Occupancy Scenario, and the resulting screening dose values and default RF_o values, are summarized below.

Table 5.14 Source nuclides used in the parameter analysis

Source ID	Source	Source ID	Source	Source ID	Source
1	3H	87	126Sn+C	180	232Th
2	10Be	89	125Sb	181	232Th+C
3	14C	93	123mTe	183	231Pa
5	22Na	95	127mTe	184	231Pa+C
9	35S	106	129I	187	232U
10	36Cl	114	134Cs	188	232U+C
11	40K	115	135Cs	189	233U
12	41Ca	117	137Cs	190	233U+C
13	45Ca	128	144Ce	191	234U
14	46Sc	132	147Pm	192	235U
16	54Mn	137	147Sm	193	235U+C
18	55Fe	138	151Sm	194	236U
20	57Co	140	152Eu	196	238U
21	58Co	141	154Eu	197	238U+C
22	60Co	142	155Eu	199	237Np
23	59Ni	144	153Gd	200	237Np+C
24	63Ni	145	160Tb	203	236Pu
27	65Zn	146	166mHo	205	238Pu
31	75Se	147	181W	206	239Pu
32	79Se	148	185W	207	240Pu
41	90Sr	150	187Re	208	241Pu
48	93Zr	151	185Os	209	242Pu
49	93Zr+C	153	192Ir	211	244Pu
52	93mNb	156	210Pb	212	241Am
53	94Nb	160	210Po	213	242mAm

Table 5.14 Source nuclides used in the parameter analysis (continued)

Source ID	Source	Source ID	Source	Source ID	Source
58	93Mo	165	226Ra	215	243Am
61	99Tc	166	226Ra+C	216	242Cm
65	106Ru	167	228Ra	217	243Cm
69	107Pd	169	227Ac	218	244Cm
71	110mAg	170	227Ac+C	219	245Cm
73	109Cd	173	228Th	220	246Cm
74	113mCd	174	228Th+C	221	247Cm
81	119mSn	175	229Th	222	248Cm
82	121mSn	176	229Th+C	223	252Cf
84	123Sn	177	230Th		
86	126Sn	178	230Th+C		

5.5.1 Assumed Fraction of Removable Contamination

As discussed in Sections 5.4.2 and 5.2.2, the resuspension factor and secondary ingestion transfer factor parameters describe the uptake of removable contamination. The distributions defined for these parameters describe the resuspension and transfer of loose contamination. In calculating the screening dose values, 10% of the measured source concentration was assumed to be removable.

5.5.2 Definition of the Screening Group for the Occupancy Scenario

The Screening Group is a generic Critical Group suitable for making decisions at any site without site specific information on potential occupant behavior. For the Occupancy Scenario, the Screening Group is defined as workers in light industry. The behavioral parameter values for the AMSG are defined by the mean values of their respective parameter distributions, described in Sections 5.2.1 and 5.2.2. Table 5.15 (see end of this section) lists the values for the behavioral and metabolic parameters of the occupancy scenario model: the time the AMSG spends in the building (T_o), the breathing rate for the AMSG (V_o), and the secondary ingestion rate for the AMSG (GO).

Table 5.15 Behavioral parameters for the average member of the screening group

Parameter	Value
TO (d/y)	97.46
VO (m^3/h)	1.4
GO (m^2/h)	1.11×10^{-5}

5.5.3 Calculation of Screening Dose Values

As described in Section 3.0, screening dose values are calculated by deriving the distribution of possible dose values over all sites (given the behavioral parameter values defining the AMSG), and selecting, for each source nuclide, a dose value near the upper end of the resulting distribution. In general, this calculation entails: sampling the distributions for the scenario parameters characterizing the physical properties of the sites; using the scenario model to calculate the dose to the AMSG for each set of sampled values of the physical parameters; assembling the dose distribution from the resulting individual dose calculations; and identifying the dose value at the selected quantile of this distribution.

The Occupancy Scenario model has one parameter, resuspension factor (RF_o), characterizing the physical properties of the site. The three remaining input parameters describe occupant behavior, and are established by the definition of the AMSG as described in Section 5.5.2. One thousand samples from the distribution for RF_o were generated using stratified Monte-Carlo (LHS) sampling (Iman and Shortencarier, 1984). For each sample, dose to the AMSG was then calculated for unit concentrations of each of the 106 possible source nuclides. For each source, the distribution describing possible doses to the AMSG was then constructed from these calculated doses.

Possible screening dose values were selected from these distributions by stipulating a tolerance for underestimating dose (i.e., P_{crit}). For three alternative values of P_{crit}, and for each source nuclide, a screening dose value was identified such that the fraction of doses larger than the screening dose was equal to P_{crit}. These values correspond to the ($1 - P_{crit}$) quantiles of the calculated dose distributions.

Table 5.16 lists these screening dose values for each of the source nuclides, and for three alternative values for P_{crit}. As a measure of the spread of the dose distributions, Table 5.16 also shows the ratio of dose at the 95th percentile to the median dose. Figures 5.9 through 5.15 show the calculated dose distributions for seven of the 106 individual sources: Co-60, Sr-90, Cs-137, Ra-226, Th-230, Th-232, and U-238. A P_{crit} value of 0.10 was used to define the screening calculations for DandD interim release 1.0.

Many source nuclides, such as Co-60 and Cs-137, have very narrow dose distributions: the ratio of the 95th percentile dose to the median dose is very close to 1. Dose due to these nuclides is not strongly dependent on resuspension, and presumably is dominated by non-inhalation pathways. Other nuclides, such as Sr-90 and Th-230 have broader (although still compact) distributions. The ratio of the 95th percentile dose to the median dose is greater than three for many nuclides, indicating that dose is strongly controlled by the resuspension factor, and therefore occurs primarily through the inhalation pathway.

5.5.4 Values of Physical Parameters Associated with Screening Doses

Because there is only one physical parameter (RF_o) in the Occupancy Scenario model, and because dose is a monotonically increasing function of resuspension factor, a given quantile of the dose distribution corresponds to the same quantile of the input distribution for RF_o. For example, the 95th percentile of dose for all sources can be directly calculated using the value of RF_o at the 95th percentile of it's distribution, in conjunction with the AMSG behavioral parameters. Table 5.17 lists the resuspension factor values corresponding to the alternative quantiles considered in Table 5.16.

The derived dose distribution functions can also be used to test or formulate more complex decision criteria. As an example, the dose value at the 95th percentile of the dose distribution can be identified by stipulating the dose value at some other quantile of the dose distribution. Table 5.18 lists, for each of the three P_{crit} values, the dose value at the 95th percentile, given that the dose at the (1 - P_{crit}) quantile is 25 mrem/year.

Dose values at the selected quantiles can also be used to calculate the source concentration equivalent to a dose of 25 mrem/year. Table 5.19 summarizes these concentration values.

Table 5.16 Quantile values of unit-source dose distributions(mrem/year per dpm/100 cm^2)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Dose @ P_{crit} = 0.05/ Dose @ P_{crit} = 0.50
3H	1.68E-07	2.02E-07	2.19E-07	1.87
10Be	5.50E-04	7.43E-04	8.37E-04	3.23
14C	5.66E-06	6.80E-06	7.36E-06	1.86
22Na	2.62E-03	2.62E-03	2.62E-03	1.00
35S	1.53E-06	1.97E-06	2.18E-06	2.53
36Cl	3.81E-05	5.01E-05	5.59E-05	2.78
40K	2.45E-04	2.52E-04	2.55E-04	1.09
41Ca	3.56E-06	4.29E-06	4.65E-06	1.90
45Ca	7.07E-06	8.90E-06	9.80E-06	2.27
46Sc	8.66E-04	8.71E-04	8.73E-04	1.02
54Mn	7.90E-04	7.93E-04	7.94E-04	1.01
55Fe	4.26E-06	5.55E-06	6.18E-06	2.67
57Co	1.15E-04	1.18E-04	1.20E-04	1.09
58Co	3.68E-04	3.69E-04	3.70E-04	1.01
60Co	3.43E-03	3.55E-03	3.60E-03	1.10
59Ni	4.40E-06	5.87E-06	6.59E-06	3.03
63Ni	1.03E-05	1.37E-05	1.54E-05	2.99
65Zn	5.13E-04	5.20E-04	5.23E-04	1.04

Table 5.16 Quantile values of unit-source dose distributions (mrem/year per dpm/100 cm^2) (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Dose @ P_{crit} = 0.05/ Dose @ P_{crit} = 0.50
75Se	2.31E-04	2.33E-04	2.34E-04	1.03
79Se	2.53E-05	3.07E-05	3.33E-05	1.93
90Sr	2.17E-03	2.87E-03	3.21E-03	2.90
93Zr	4.95E-04	6.71E-04	7.56E-04	3.27
93Zr+C	5.41E-04	7.32E-04	8.25E-04	3.25
93mNb	4.56E-05	6.12E-05	6.87E-05	3.09
94Nb	2.79E-03	3.01E-03	3.12E-03	1.28
93Mo	5.38E-05	6.97E-05	7.75E-05	2.59
99Tc	1.46E-05	1.91E-05	2.13E-05	2.75
106Ru	7.68E-04	9.56E-04	1.05E-03	2.16
107Pd	1.98E-05	2.67E-05	3.01E-05	3.24
110mAg	2.42E-03	2.45E-03	2.47E-03	1.03
109Cd	1.71E-04	2.19E-04	2.43E-04	2.45
113mCd	2.47E-03	3.28E-03	3.68E-03	2.95
119mSn	1.73E-05	1.96E-05	2.07E-05	1.49
121mSn	2.77E-05	3.41E-05	3.73E-05	2.07
123Sn	3.13E-05	3.91E-05	4.28E-05	2.19
126Sn	2.90E-03	2.96E-03	2.99E-03	1.06
126Sn+C	2.93E-03	2.99E-03	3.01E-03	1.06
125Sb	5.57E-04	5.64E-04	5.67E-04	1.04
123mTe	9.27E-05	9.51E-05	9.63E-05	1.08
127mTe	2.59E-05	3.06E-05	3.28E-05	1.73
129I	6.25E-04	7.20E-04	7.66E-04	1.59
134Cs	1.94E-03	1.96E-03	1.97E-03	1.03
135Cs	1.53E-05	1.78E-05	1.90E-05	1.64
137Cs	8.75E-04	8.92E-04	9.01E-04	1.06
144Ce	4.50E-04	5.85E-04	6.51E-04	2.63
147Pm	5.40E-05	7.28E-05	8.20E-05	3.19
147Sm	1.15E-01	1.56E-01	1.76E-01	3.28
151Sm	4.63E-05	6.26E-05	7.05E-05	3.24
152Eu	1.85E-03	1.96E-03	2.02E-03	1.21
154Eu	2.03E-03	2.18E-03	2.25E-03	1.25
155Eu	1.38E-04	1.59E-04	1.70E-04	1.59
153Gd	1.15E-04	1.23E-04	1.27E-04	1.23
160Tb	4.32E-04	4.36E-04	4.38E-04	1.03
166mHo	3.58E-03	4.00E-03	4.21E-03	1.43
181W	2.33E-05	2.34E-05	2.34E-05	1.00
185W	1.07E-06	1.19E-06	1.25E-06	1.39
187Re	9.46E-08	1.24E-07	1.39E-07	2.78
185Os	3.48E-04	3.50E-04	3.51E-04	1.02
192Ir	3.32E-04	3.37E-04	3.39E-04	1.04
210Pb	3.56E-02	4.57E-02	5.06E-02	2.47
210Po	7.62E-03	9.97E-03	1.11E-02	2.72
226Ra	1.75E-02	2.24E-02	2.47E-02	2.41
226Ra+C	6.18E-02	7.93E-02	8.78E-02	2.48

Table 5.16 Quantile values of unit-source dose distributions (mrem/year per dpm/100 cm^2) (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Dose @ P_{crit} = 0.05/ Dose @ P_{crit} = 0.50
228Ra	9.24E-02	1.24E-01	1.40E-01	3.12
227Ac	1.02E+01	1.38E+01	1.55E+01	3.28
227Ac+C	1.02E+01	1.38E+01	1.55E+01	3.28
228Th	4.46E-01	6.04E-01	6.81E-01	3.26
228Th+C	4.46E-01	6.04E-01	6.81E-01	3.26
229Th	3.32E+00	4.50E+00	5.08E+00	3.28
229Th+C	3.33E+00	4.51E+00	5.08E+00	3.28
230Th	5.00E-01	6.78E-01	7.64E-01	3.28
230Th+C	5.63E-01	7.58E-01	8.53E-01	3.17
232Th	2.52E+00	3.42E+00	3.85E+00	3.28
232Th+C	3.06E+00	4.15E+00	4.67E+00	3.27
231Pa	2.14E+00	2.90E+00	3.27E+00	3.26
231Pa+C	1.23E+01	1.67E+01	1.88E+01	3.27
232U	1.09E+00	1.48E+00	1.67E+00	3.28
232U+C	1.55E+00	2.10E+00	2.37E+00	3.27
233U	2.08E-01	2.82E-01	3.18E-01	3.28
233U+C	3.70E+00	5.01E+00	5.65E+00	3.28
234U	2.04E-01	2.76E-01	3.11E-01	3.28
235U	1.89E-01	2.56E-01	2.89E-01	3.27
235U+C	1.25E+01	1.69E+01	1.91E+01	3.27
236U	1.93E-01	2.61E-01	2.95E-01	3.28
238U	1.82E-01	2.47E-01	2.78E-01	3.28
238U+C	9.47E-01	1.28E+00	1.44E+00	3.22
237Np	8.34E-01	1.13E+00	1.27E+00	3.25
237Np+C	4.66E+00	6.32E+00	7.12E+00	3.27
236Pu	2.03E-01	2.75E-01	3.10E-01	3.26
238Pu	6.03E-01	8.16E-01	9.20E-01	3.25
239Pu	6.63E-01	8.97E-01	1.01E+00	3.25
240Pu	6.63E-01	8.97E-01	1.01E+00	3.25
241Pu	1.30E-02	1.76E-02	1.98E-02	3.25
242Pu	6.34E-01	8.58E-01	9.67E-01	3.25
244Pu	6.23E-01	8.43E-01	9.50E-01	3.25
241Am	6.85E-01	9.27E-01	1.04E+00	3.25
242mAm	6.67E-01	9.03E-01	1.02E+00	3.25
243Am	6.80E-01	9.20E-01	1.04E+00	3.25
242Cm	1.50E-02	2.04E-02	2.30E-02	3.26
243Cm	4.69E-01	6.34E-01	7.15E-01	3.25
244Cm	3.75E-01	5.08E-01	5.73E-01	3.26
245Cm	7.03E-01	9.52E-01	1.07E+00	3.25
246Cm	6.97E-01	9.43E-01	1.06E+00	3.25
247Cm	6.40E-01	8.66E-01	9.77E-01	3.25
248Cm	2.55E+00	3.46E+00	3.90E+00	3.25
252Cf	2.13E-01	2.88E-01	3.25E-01	3.26

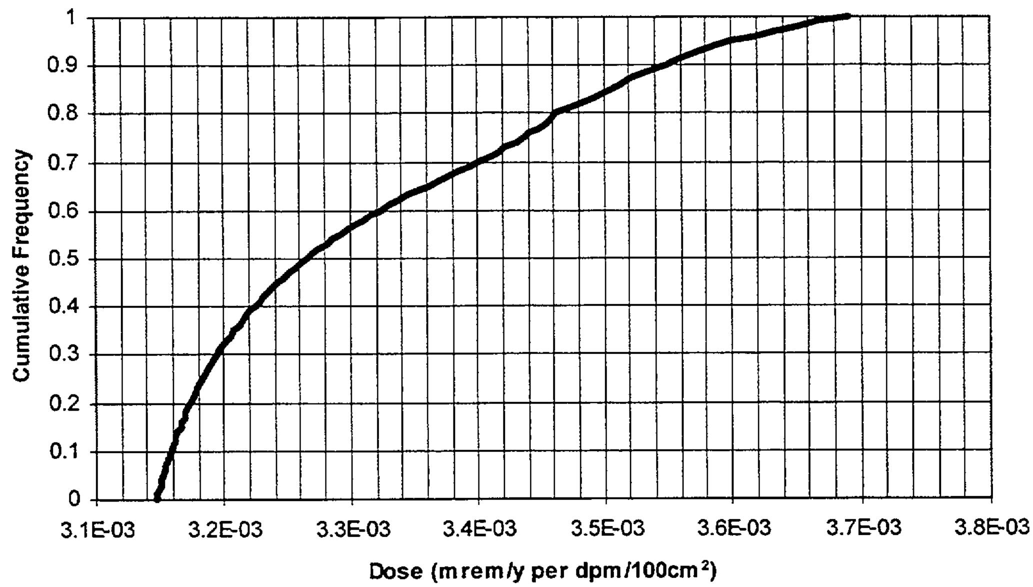

Figure 5.9 Calculated distribution of dose to the average member of the screening group due to a unit source of Co-60

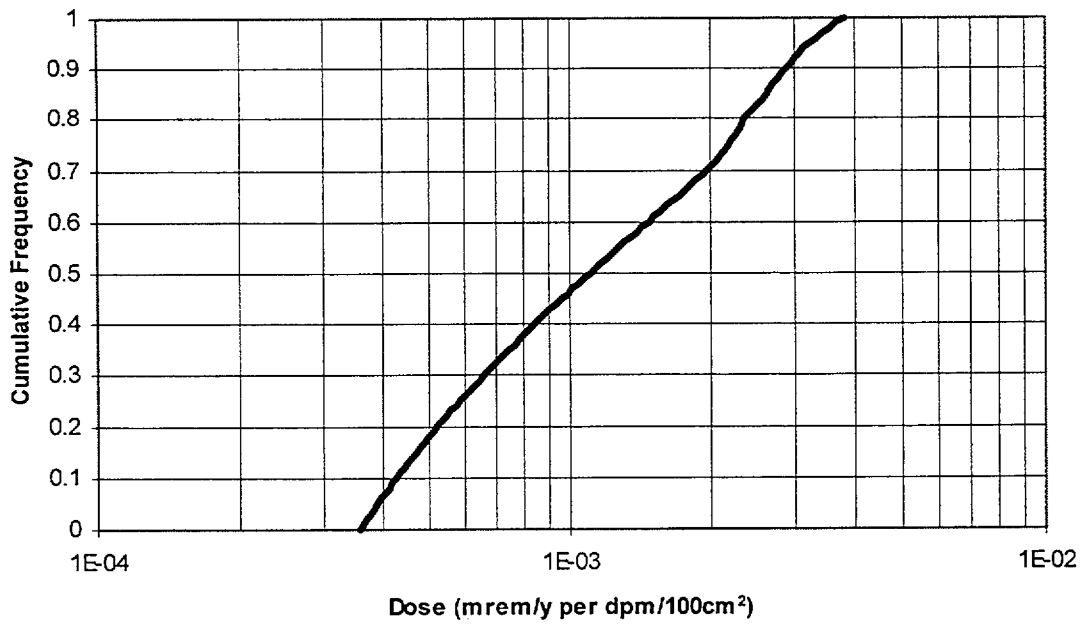

Figure 5.10 Calculated distribution of dose to the average member of the screening group due to a unit source of Sr-90

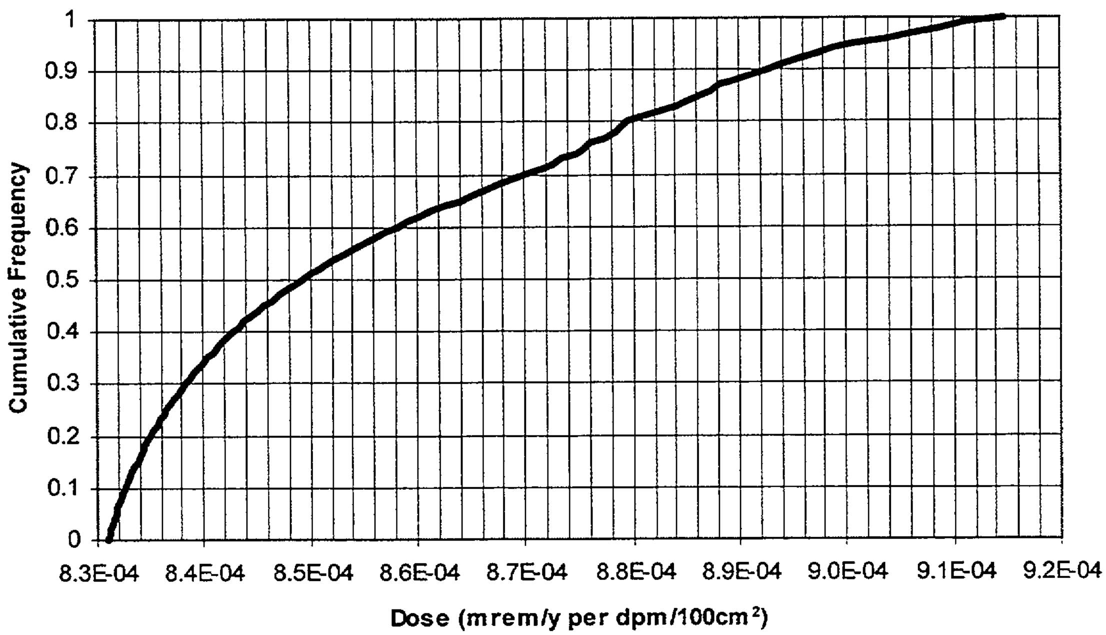

Figure 5.11 Calculated distribution of dose to the average member of the screening group due to a unit source of Cs-137

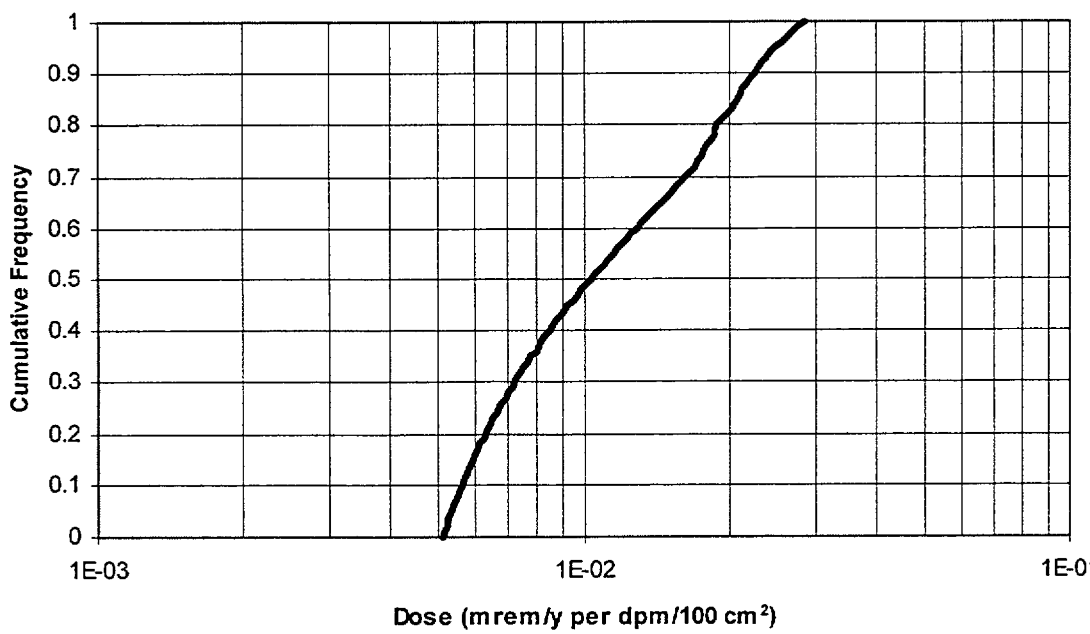

Figure 5.12 Calculated distribution of dose to the average member of the screening group due to a unit source of Ra-226

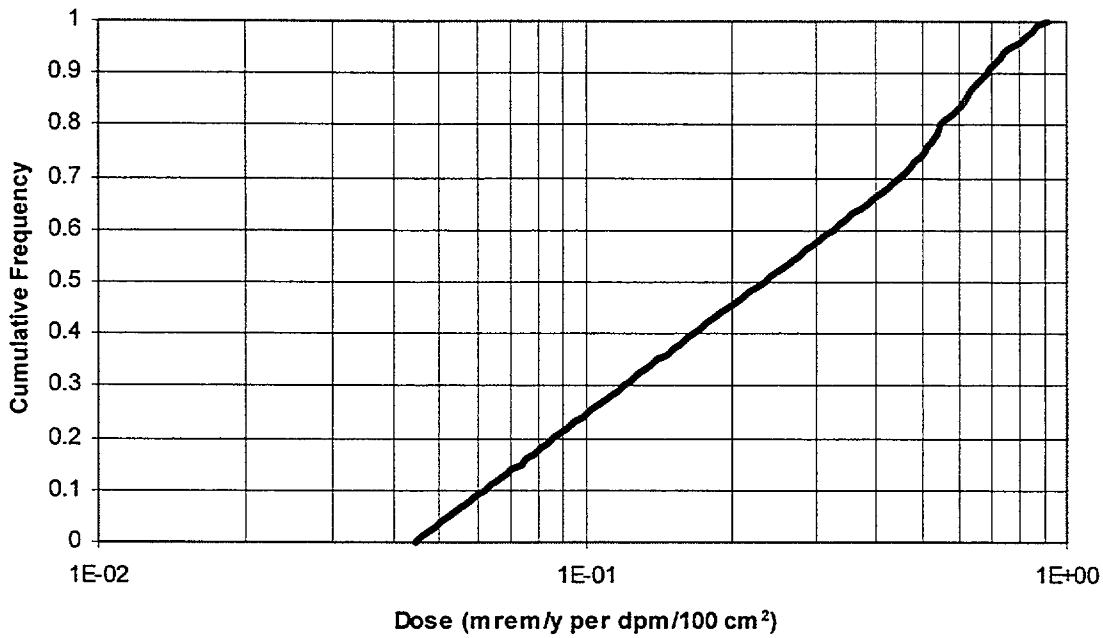

Figure 5.13 Calculated distribution of dose to the average member of the screening group due to a unit source of Th-230

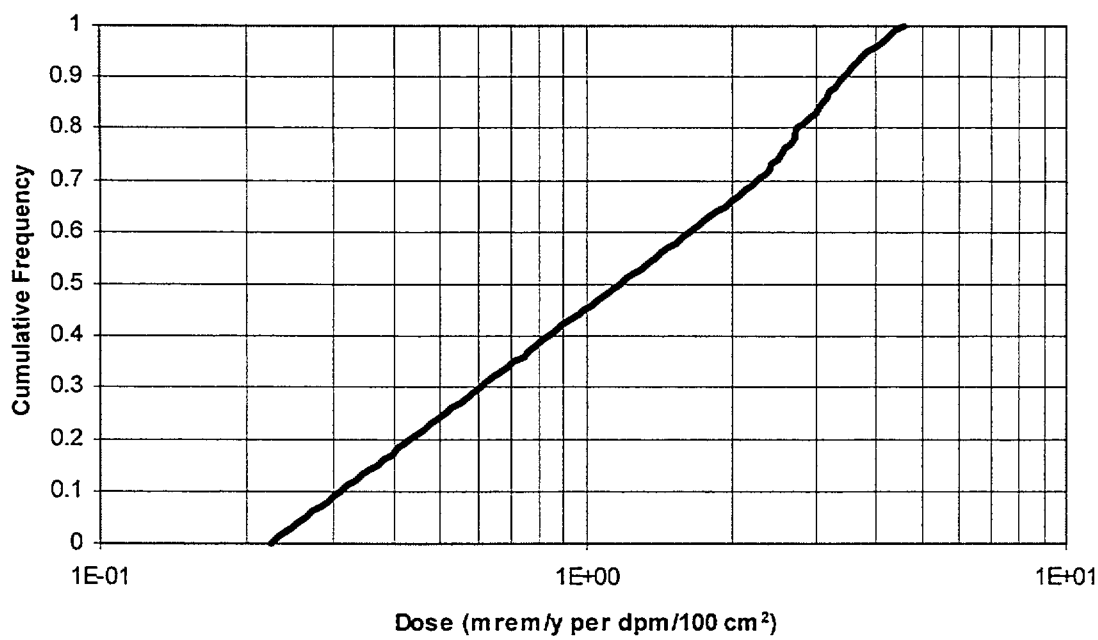

Figure 5.14 Calculated distribution of dose to the average member of the screening group due to a unit source of Th-232

Table 5.17 Resuspension factor values at five quantile levels

	Parameter quantile level				
	0.50	**0.75**	**0.90**	**0.95**	**0.99**
RF_o (m^{-1})	4.97×10^{-5}	1.06×10^{-4}	1.42×10^{-4}	1.62×10^{-4}	1.84×10^{-4}

Table 5.18 95th percentile dose values for 25 mrem/year dose values at P_{crit} (mrem/year)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05
3H	32.5	27.0	25
10Be	38.1	28.2	25
14C	32.5	27.0	25
22Na	25.1	25.0	25
35S	35.7	27.7	25
36Cl	36.7	27.9	25
40K	26.0	25.3	25
41Ca	32.7	27.1	25
45Ca	34.6	27.5	25
46Sc	25.2	25.1	25
54Mn	25.1	25.0	25
55Fe	36.3	27.8	25
57Co	26.0	25.3	25
58Co	25.2	25.1	25
60Co	26.2	25.4	25
59Ni	37.5	28.1	25
63Ni	37.4	28.0	25
65Zn	25.5	25.2	25
75Se	25.3	25.1	25
79Se	32.9	27.1	25
90Sr	37.1	28.0	25
93Zr	38.2	28.2	25
93Zr+C	38.1	28.2	25
93mNb	37.7	28.1	25
94Nb	28.0	25.9	25
93Mo	36.0	27.8	25
99Tc	36.6	27.9	25
106Ru	34.1	27.4	25
107Pd	38.1	28.2	25
110mAg	25.4	25.1	25
109Cd	35.4	27.7	25
113mCd	37.2	28.0	25
119mSn	29.9	26.4	25
121mSn	33.7	27.3	25
123Sn	34.2	27.4	25
126Sn	25.7	25.2	25
126Sn+C	25.7	25.2	25
125Sb	25.4	25.1	25
123mTe	26.0	25.3	25
127mTe	31.6	26.8	25

Table 5.18 95th percentile dose values for 25 mrem/year dose values at P_{crit} (mrem/year) (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05
129I	30.6	26.6	25
134Cs	25.4	25.1	25
135Cs	31.0	26.7	25
137Cs	25.7	25.2	25
144Ce	36.1	27.8	25
147Pm	37.9	28.1	25
147Sm	38.2	28.2	25
151Sm	38.1	28.2	25
152Eu	27.4	25.7	25
154Eu	27.8	25.8	25
155Eu	30.7	26.6	25
153Gd	27.6	25.8	25
160Tb	25.3	25.1	25
166mHo	29.4	26.3	25
181W	25.1	25.0	25
185W	29.1	26.2	25
187Re	36.7	27.9	25
185Os	25.2	25.1	25
192Ir	25.5	25.2	25
210Pb	35.5	27.7	25
210Po	36.5	27.9	25
226Ra	35.2	27.6	25
226Ra+C	35.5	27.7	25
228Ra	37.8	28.1	25
227Ac	38.2	28.2	25
227Ac+C	38.2	28.2	25
228Th	38.1	28.2	25
228Th+C	38.1	28.2	25
229Th	38.2	28.2	25
229Th+C	38.2	28.2	25
230Th	38.2	28.2	25
230Th+C	37.9	28.1	25
232Th	38.2	28.2	25
232Th+C	38.2	28.2	25
231Pa	38.1	28.2	25
231Pa+C	38.2	28.2	25
232U	38.2	28.2	25
232U+C	38.2	28.2	25
233U	38.2	28.2	25
233U+C	38.2	28.2	25
234U	38.2	28.2	25
235U	38.2	28.2	25

Table 5.18 95th percentile dose values for 25 mrem/year dose values at P_{crit} (mrem/year) (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05
235U+C	38.2	28.2	25
236U	38.2	28.2	25
238U	38.2	28.2	25
238U+C	38.0	28.2	25
237Np	38.1	28.2	25
237Np+C	38.2	28.2	25
236Pu	38.1	28.2	25
238Pu	38.1	28.2	25
239Pu	38.1	28.2	25
240Pu	38.1	28.2	25
241Pu	38.1	28.2	25
242Pu	38.1	28.2	25
244Pu	38.1	28.2	25
241Am	38.1	28.2	25
242mAm	38.1	28.2	25
243Am	38.1	28.2	25
242Cm	38.2	28.2	25
243Cm	38.1	28.2	25
244Cm	38.1	28.2	25
245Cm	38.1	28.2	25
246Cm	38.1	28.2	25
247Cm	38.1	28.2	25
248Cm	38.1	28.2	25
252Cf	38.2	28.2	25

Table 5.19 Concentration (dpm/100 cm^2) equivalent to 25 mrem/y for the specified value of P_{crit}

Source	P_{crit} = 0.75	P_{crit} 0 .90	P_{crit} 0 .95
3H	1.49E+08	1.24E+08	1.14E+08
10Be	4.55E+04	3.36E+04	2.99E+04
14C	4.41E+06	3.67E+06	3.40E+06
22Na	9.55E+03	9.54E+03	9.53E+03
35S	1.64E+07	1.27E+07	1.15E+07
36Cl	6.55E+05	4.99E+05	4.47E+05
40K	1.02E+05	9.92E+04	9.79E+04
41Ca	7.03E+06	5.83E+06	5.38E+06
45Ca	3.54E+06	2.81E+06	2.55E+06
46Sc	2.89E+04	2.87E+04	2.86E+04
54Mn	3.16E+04	3.15E+04	3.15E+04
55Fe	5.87E+06	4.50E+06	4.04E+06
57Co	2.17E+05	2.11E+05	2.08E+05

Table 5.19 Concentration (dpm/100 cm^2) equivalent to 25 mrem/y for the specified value of P_{crit} (continued)

Source	P_{crit} = 0.75	P_{crit} 0 .90	P_{crit} 0 .95
58Co	6.80E+04	6.77E+04	6.75E+04
60Co	7.28E+03	7.05E+03	6.94E+03
59Ni	5.69E+06	4.26E+06	3.79E+06
63Ni	2.43E+06	1.82E+06	1.63E+06
65Zn	4.87E+04	4.81E+04	4.78E+04
75Se	1.08E+05	1.07E+05	1.07E+05
79Se	9.88E+05	8.15E+05	7.51E+05
90Sr	1.15E+04	8.71E+03	7.78E+03
93Zr	5.05E+04	3.73E+04	3.31E+04
93Zr+C	4.62E+04	3.42E+04	3.03E+04
93mNb	5.48E+05	4.09E+05	3.64E+05
94Nb	8.97E+03	8.29E+03	8.00E+03
93Mo	4.64E+05	3.59E+05	3.23E+05
99Tc	1.71E+06	1.31E+06	1.17E+06
106Ru	3.26E+04	2.62E+04	2.39E+04
107Pd	1.27E+06	9.35E+05	8.30E+05
110mAg	1.03E+04	1.02E+04	1.01E+04
109Cd	1.46E+05	1.14E+05	1.03E+05
113mCd	1.01E+04	7.62E+03	6.80E+03
119mSn	1.44E+06	1.28E+06	1.21E+06
121mSn	9.03E+05	7.32E+05	6.71E+05
123Sn	7.99E+05	6.40E+05	5.83E+05
126Sn	8.61E+03	8.45E+03	8.37E+03
126Sn+C	8.53E+03	8.37E+03	8.30E+03
125Sb	4.49E+04	4.43E+04	4.41E+04
123mTe	2.70E+05	2.63E+05	2.60E+05
127mTe	9.64E+05	8.18E+05	7.62E+05
129I	4.00E+04	3.47E+04	3.26E+04
134Cs	1.29E+04	1.27E+04	1.27E+04
135Cs	1.63E+06	1.41E+06	1.32E+06
137Cs	2.86E+04	2.80E+04	2.78E+04
144Ce	5.56E+04	4.27E+04	3.84E+04
147Pm	4.63E+05	3.43E+05	3.05E+05
147Sm	2.18E+02	1.61E+02	1.42E+02
151Sm	5.40E+05	4.00E+05	3.55E+05
152Eu	1.35E+04	1.27E+04	1.24E+04
154Eu	1.23E+04	1.15E+04	1.11E+04
155Eu	1.81E+05	1.57E+05	1.47E+05
153Gd	2.17E+05	2.02E+05	1.96E+05
160Tb	5.79E+04	5.74E+04	5.71E+04
166mHo	6.98E+03	6.24E+03	5.94E+03
181W	1.07E+06	1.07E+06	1.07E+06

Table 5.19 Concentration (dpm/100 cm^2) equivalent to 25 mrem/y for the specified value of P_{crit} (continued)

Source	P_{crit} = 0.75	P_{crit} 0 .90	P_{crit} 0 .95
185W	2.33E+07	2.10E+07	2.01E+07
187Re	2.64E+08	2.01E+08	1.80E+08
185Os	7.19E+04	7.15E+04	7.13E+04
192Ir	7.52E+04	7.42E+04	7.38E+04
210Pb	7.01E+02	5.47E+02	4.94E+02
210Po	3.28E+03	2.51E+03	2.25E+03
226Ra	1.43E+03	1.12E+03	1.01E+03
226Ra+C	4.05E+02	3.15E+02	2.85E+02
228Ra	2.71E+02	2.01E+02	1.79E+02
227Ac	2.46E+00	1.82E+00	1.61E+00
227Ac+C	2.46E+00	1.81E+00	1.61E+00
228Th	5.60E+01	4.14E+01	3.67E+01
228Th+C	5.60E+01	4.14E+01	3.67E+01
229Th	7.52E+00	5.55E+00	4.92E+00
229Th+C	7.52E+00	5.55E+00	4.92E+00
230Th	5.00E+01	3.69E+01	3.27E+01
230Th+C	4.44E+01	3.30E+01	2.93E+01
232Th	9.91E+00	7.31E+00	6.49E+00
232Th+C	8.17E+00	6.03E+00	5.35E+00
231Pa	1.17E+01	8.61E+00	7.64E+00
231Pa+C	2.03E+00	1.50E+00	1.33E+00
232U	2.29E+01	1.69E+01	1.50E+01
232U+C	1.61E+01	1.19E+01	1.06E+01
233U	1.20E+02	8.86E+01	7.86E+01
233U+C	6.76E+00	4.99E+00	4.43E+00
234U	1.23E+02	9.06E+01	8.04E+01
235U	1.32E+02	9.76E+01	8.66E+01
235U+C	2.00E+00	1.48E+00	1.31E+00
236U	1.30E+02	9.57E+01	8.49E+01
238U	1.37E+02	1.01E+02	8.99E+01
238U+C	2.64E+01	1.95E+01	1.74E+01
237Np	3.00E+01	2.21E+01	1.96E+01
237Np+C	5.36E+00	3.96E+00	3.51E+00
236Pu	1.23E+02	9.10E+01	8.07E+01
238Pu	4.15E+01	3.06E+01	2.72E+01
239Pu	3.77E+01	2.79E+01	2.47E+01
240Pu	3.77E+01	2.79E+01	2.47E+01
241Pu	1.93E+03	1.42E+03	1.26E+03
242Pu	3.94E+01	2.91E+01	2.58E+01
244Pu	4.01E+01	2.96E+01	2.63E+01
241Am	3.65E+01	2.70E+01	2.39E+01
242mAm	3.75E+01	2.77E+01	2.46E+01

Table 5.19 Concentration (dpm/100 cm²) equivalent to 25 mrem/y for the specified value of P_{crit} (continued)

Source	P_{crit} = 0.75	P_{crit} 0 .90	P_{crit} 0 .95
243Am	3.68E+01	2.72E+01	2.41E+01
242Cm	1.66E+03	1.23E+03	1.09E+03
243Cm	5.34E+01	3.94E+01	3.50E+01
244Cm	6.66E+01	4.92E+01	4.36E+01
245Cm	3.56E+01	2.63E+01	2.33E+01
246Cm	3.59E+01	2.65E+01	2.35E+01
247Cm	3.90E+01	2.89E+01	2.56E+01
248Cm	9.79E+00	7.23E+00	6.42E+00
252Cf	1.17E+02	8.68E+01	7.70E+01

6.0 Residential Scenario in NUREG/CR-5512

The residential scenario model, as defined in Volume 1 and implemented in Release 1.0 of DandD (Wernig et al., 1999), is based on the following assumptions:

- Radioactive contamination occurs in a surface soil layer,
- The property can be used for residential and light farming activities,
- Residency can occur immediately after release of the property.
- Radioactive dose results from exposure via external exposure, inhalation, and ingestion. The model includes twelve exposure pathways created by the activities considered in the scenario:

  (1) external exposure to penetrating radiation from volume soil sources while outdoors,

  (2) external exposure to penetrating radiation from volume soil sources while indoors,

  (3) inhalation exposure to resuspended soil while outdoors,

  (4) inhalation exposure to resuspended soil while indoors,

  (5) inhalation exposure to resuspended surface sources of soil tracked indoors,

  (6) direct ingestion of soil,

  (7) inadvertent ingestion of soil tracked indoors,

  (8) ingestion of drinking water from a ground-water source,

  (9) ingestion of plant products grown in contaminated soil,

  (10) ingestion of plant products irrigated with contaminated groundwater

  (11) ingestion of animal products grown onsite, and

  (12) ingestion of fish from a contaminated surface-water source.

- Eight other potential exposure pathways are not included in the analysis:

  (1) external exposure to soil tracked indoors,

  (2) external exposure to penetrating radiation from submersion in airborne radioactive soil,

  (3) external exposure from swimming and shoreline activities,

  (4) inhalation of indoor radon aerosol,

  (5) inhalation of outdoor radon aerosol,

  (6) ingestion of drinking water from a surface-water source,

  (7) internal contamination from puncture wounds, and

  (8) dermal absorption of radionuclides

The residential scenario model includes 652 parameters in addition to external dose rate factors, and inhalation and ingestion CEDE factors. The partition coefficients and plant uptake factors can be independently specified for each chemical element. Other parameters, such as ingestion rates, are defined for each of the major food categories considered in the model.

These parameters are described in detail in Sections 6.2 through 6.4. These descriptions include the way the parameter is used in the model and a summary of the information used to establish default values for the parameters. Table 6.1 summarizes the major parameter groups along with the classification of these parameters as either physical, metabolic, or behavioral. Parameters that were not evaluated in this study, and were given the default values defined in Volume 1, are indicated in the right-hand column of Table 6.1.

The annual TEDE for a parent radionuclide in the residential scenario, $TEDER_i$, is calculated as the sum of:

- external dose resulting from external exposure to penetrating radiation from soil sources, $DEXR_i$;
- CEDE for inhalation resulting from inhalation of dust and resuspended contamination tracked indoors, DHR_i;
- CEDE for ingestion resulting from inadvertent ingestion of soil, DSR_i;

Table 6.1 Summary of residential scenario model input parameters

Parameter	Description	Units	Report section	Type: physical/ behavioral/ metabolic	Vol. 1
TI	Exposure period: indoors	d/y	6.2.3	B	
TX	Exposure period: outdoors	d/y	6.2.3	B	
TG	Exposure period: gardening	d/y	6.2.3	B	
TTR	Total time in the 1-year exposure period	d	6.2.1	B	x
SFI	Indoor shielding factor	-	6.2.4	B	
SFO	Outdoor shielding factor	-	6.4.1	P	x
PD	Floor dust-loading	g/m^2	6.4.4	P	
RFR	Resuspension factor for indoor dust	1/m	6.4.4	P	
CDI	Air dust-loading indoors	g/m^3	6.4.4	P	
CDO	Air dust-loading outdoors	g/m^3	6.4.4	P	
CDG	Air dust-loading gardening	g/m^3	6.4.4	P	
VR	Breathing rate: indoors	m^3/h	6.3	M	
VX	Breathing rate: outdoors	m^3/h	6.3	M	
VG	Breathing rate: gardening	m^3/h	6.3	M	
GR	Soil ingestion transfer rate	g/d	6.2.5	B	
UW	Drinking water ingestion rate	L/d	6.2.6	B	
H1	Thickness of surface-soil layer	m	6.4.1	P	x
H2	Thickness of unsaturated zone	m	6.4.2	P	
N1	Porosity of surface-soil	-	6.4.3	P	
N2	Porosity of unsaturated zone	-	6.4.3	P	
F1	Saturation ratio for the surface-soil layer	-	6.4.3	P	
F2	Saturation ratio for the unsaturated-soil layer	-	6.4.3	P	
VDR	Volume of water for domestic uses	L	6.2.8	B	
VSW	Volume of water in surface-water pond	L	6.4.1	P	x
I	Infiltration rate	m/y	6.4.3	P	
AR	Area of land cultivated	m^2	6.2.2	B	
IR	Irrigation rate	L/m^2-d	6.2.7	B	
PS	Soil areal density of surface plow layer	kg/m^2	6.4.3	P	
DIET	Fraction of annual diet derived from home-grown foods	-	6.2.1	B	
UV	Human diet of plant products	kg-wet/y	6.2.9	B	
UA	Human diet of animal products	kg/y	6.2.9	B	
UF	Human diet of fish	kg/y	6.2.9	B	
TCV(1)	Food consumption periods for plant products	d	6.2.1	B	x
TCA(1)	Food consumption periods for animal products	d	6.2.1	B	x
THV(1)	Holdup periods for plant products	d	6.2.1	B	x
THA(1)	Holdup periods for animal products	d	6.2.1	B	x
TGV(1)	Minimum growing periods for plant products	d	6.4.1	P	x
TGF, TGG, TGH	Minimum growing periods for forage, grain, and hay consumed by farm animals	d	6.4.1	P	x

Table 6.1 Summary of residential scenario model input parameters (continued)

Parameter	Description	Units	Report section	Type: physical/ behavioral/ metabolic	Vol. 1
RV(1)	Interception fractions for food crops	-	6.4.8	P	
RF, RG, RH	Interception fractions for forage, grain, and hay consumed by farm animals	-	6.4.8	P	
TV	Translocation factors for food crops	-	6.4.1	P	x
TF, TG, TH	Translocation factor for forage, grain, and hay consumed by farm animals	-	6.4.1	P	x
XF, XG, XH	Contaminated fractions of forage, grain, and hay consumed by farm animals	-	6.2.1	B	x
XW(1)	Contaminated fractions of water consumed by farm animals	-	6.2.1	B	x
YV(1)	Crop yields for food crops	kg-wet/m^2	6.4.5	P	
YF, YG, YH	Crop yields for forage, grain, and hay consumed by farm animals	kg-wet/m^2	6.4.5	P	
WV(1)	Wet/dry conversion factors for food crops	-	6.4.9	P	
WF, WH	Wet/dry conversion factors for forage and hay consumed by farm animals	-	6.4.9	P	
WG	Wet/dry conversion factors for grain consumed by farm animals	-	6.4.1	P	
QF, QG, QH	Farm animal Ingestion rates of forage, grain, and hay	kg-wet/d	6.4.6	P	
QW	Farm animal Ingestion rates of water	L/d	6.4.1	P	
QD	Soil intake fractions for farm animals	-	6.4.1	P	x
MLV	Mass-loading factors for food crops	g/g	6.4.1	P	x
LAMBDW	Weathering rate for activity removal from plants	1/d	6.4.1	P	x
FA	Animal product transfer factor	d/kg, d/L	6.4.1	P	x
BA	Fish bioaccumulation factor	pCi/kg-wet per pCi/L	6.4.1	P	x
RHO1	Surface Soil Density	g/mL	6.4.3	P	
RHO2	Unsaturated Zone Soil Density	g/mL	6.4.3	P	
TTG	Total time in gardening period	d	6.2.1	B	x
TF	Fish consumption period	d	6.2.1	B	x
TD	Drinking-water consumption period	d	6.2.1	B	x
MLF, MLG, MLH	Mass-loading factors for forage, grain, and hay consumed by farm animals	g/g	6.4.1	P	x
TFF, TFG, TFH, TFW	Feeding periods for forage, grain, hay, and water consumed by farm animals	d	6.4.1	P	x
Kd	Partition coefficients for the Surface Soil and Unsaturated Layers	mL/g	6.4.10	P	
fca	Carbon fractions for farm animals	-	6.4.1	P	
fcf, fch, fcg	Carbon fraction for forage, hay, and grain consumed by farm animals	-	6.4.1	P	
fcd05	Fraction of carbon in soil	-	6.4.1	P	x

Table 6.1 Summary of residential scenario model input parameters (continued)

Parameter	Description	Units	Report section	Type: physical/ behavioral/ metabolic	Vol. 1
satac	Specific activity equivalence for livestock	-	6.4.1	P	x
fha	Hydrogen fractions for farm animals	-	6.4.1	P	x
fhv	Hydrogen fractions for food crops	-	6.4.1	P	x
fhf, fhh, fhg	Hydrogen fractions for forage, hay, and grain consumed by farm animals	-	6.4.1	P	x
fhd016	Fraction of hydrogen in soil	-	6.4.1	P	x
sasvh	Tritium equivalence: plant/soil	-	6.4.1	P	x
sawvh	Tritium equivalence: plant/water	-	6.4.1	P	x
satah	Tritium equivalence: animal product/intake	-	6.4.1	P	x
sh	Moisture content of soil	L/m^3	6.4.1	P	x
B1,B2,B3,B4	Concentration factors for individual chemical elements and plant types leafy	-	6.4.7	P	

- CEDE for a one-year intake of home-grown plant and animal products, DGR_i;
- CEDE for ingestion of drinking water and irrigated food, DWR_i; and
- CEDE for ingestion of aquatic foods, DAR_i.

The mathematical formulation of the above is (NUREG/ CR-5512, Vol. 1, p. 5.70):

$$TEDER_i = DEXR_i + DHR_i + DGR_i + DWR_i + DSR_i + DAR_i \quad (6.1)$$

The calculation of the components of TEDER is based on the concentrations of the parent, C_i, and daughter radionuclides, C_j, in the surface soil layer. Each component is a linear, but algebraically complicated, function of the soil concentration.

Initial soil concentrations are specified as input parameters. The model uses a mass balance calculation to update these concentrations due to the effects of radioactive decay, transport from the soil layer to the groundwater, groundwater pumping, and recirculation of some pumped groundwater as irrigation.

Relevant parts of the mathematical model are discussed in Sections 6.2 through 6.4 below to define the connection of the model parameters to dose. The complete mathematical formulation of the model is contained in Chapter 5 of NUREG/CR-5512, Vol. 1.

6.1 Definition of Screening Group

The screening group is a site-independent population, appropriate for use at all sites, which is reasonably expected to receive the greatest exposure given the scenario definition. For the residential scenario, the screening group is adult males who live and work on a farm, producing and consuming a fraction of their diet from the site. They obtain all water required for drinking, domestic and agricultural use from an on-site well.

6.2 Behavioral Parameters

6.2.1 Behavioral Parameters with Constant Values

In this analysis the behavioral parameters that do not have significant variability or uncertainty for the defined screening group are held constant at the average value for the screening group. Other parameters, for example, the exposure period of one year, are held constant by definition of the exposure scenario. Table 6.2 lists the behavioral parameters that were held constant and the values used.

DIET is a behavioral parameter that originally represented the fraction of the diet of an individual at the site that was derived from the intake of home-grown agricultural products. Kennedy and Strenge (1992) (hereafter referred to as "Volume 1") defined the parameter in Table 6.23 (NUREG/CR-5512, Vol. 1) as the Fraction of Diet from Garden; however, the diet

Table 6.2 Behavioral parameters with constant values

Parameter	Description	Units	Value
DIET	Fraction of annual diet derived from home-grown foods	-	1
TTR	Total time in the 1-year exposure period	d	365.25
TCA(1)	Food consumption period for beef	d	365.25
TCA(2)	Food consumption period for poultry	d	365.25
TCA(3)	Food consumption period for milk	d	365.25
TCA(4)	Food consumption period for eggs	d	365.25
TCV(1)	Food consumption period for leafy vegetables	d	365.25
TCV(2)	Food consumption period for other vegetables	d	365.25
TCV(3)	Food consumption period for fruits	d	365.25
TCV(4)	Food consumption period for grain	d	365.25
TD	Drinking-water consumption period	d	365.25
TF	Fish consumption period	d	365.25
THA(1)	Holdup period for beef	d	20
THA(2)	Holdup period for poultry	d	1
THA(3)	Holdup period for milk	d	1
THV(1)	Holdup period for leafy vegetables	d	1
THV(2)	Holdup period for other vegetables	d	14
THV(3)	Holdup period for fruits	d	14
THV(4)	Holdup period for grains	d	14
TTG	Total time in gardening period	d	90
XF(1)	Fraction of contaminated beef cattle forage	-	1
XF(2)	Fraction of contaminated poultry forage	-	1
XF(3)	Fraction of contaminated milk cow forage	-	1
XF(4)	Fraction of contaminated layer hen forage	-	1
XG(1)	Fraction of contaminated beef cattle grain	-	1
XG(2)	Fraction of contaminated poultry grain	-	1
XG(3)	Fraction of contaminated milk cow grain	-	1
XG(4)	Fraction of contaminated layer hen grain	-	1
XH(1)	Fraction of contaminated beef cattle hay	-	1
XH(2)	Fraction of contaminated poultry hay	-	1
XH(3)	Fraction of contaminated milk cow hay	-	1
XH(4)	Fraction of contaminated layer hen hay	-	1
XW(1)	Fraction of contaminated beef cattle water	-	1
XW(2)	Fraction of contaminated poultry water	-	1
XW(3)	Fraction of contaminated milk cow water	-	1
XW(4)	Fraction of contaminated layer hen water	-	1

fraction pertains to all food products produced on-site for human consumption, including vegetables, fruits, grains, beef, poultry, milk, and eggs. The default value for DIET defined in NUREG/CR-5512 is 0.25. As used in the residential scenario model, a single, common value for the DIET parameter is assumed to apply to all food products. This assumption requires, for example, that the fraction of domestically-produced beef in the diet equal the fraction of domestically produced leafy vegetables. This assumption is unlikely to be satisfied in general, and is not representative of the screening group consisting of resident farmers. To better reflect the behavior of the average member of the screening group, who is expected to produce different fractions of each food product domestically, the human consumption rates U_v and U_a (Section 3.9) are defined as the rate of consumption of food *derived from on-site production* rather than the rate of consumption in general. With this definition of consumption rates, the DIET parameter is no longer used as originally defined, and its value is 1 in all cases.

The remainder of the parameters in Table 6.1 are set at the Volume 1 default values. The consumption periods for all foods is set equal to the total time in the exposure period (365.25 days) as determined by the assumptions in the screening scenario. No additional information on the holdup periods was gathered, and these are assumed to represent averages for the screening group. It is assumed for the screening analyses that all the animal feed is grown on-site, in contaminated soil, and that all of the animal's water is from onsite sources (fraction of contaminated feed and water is 1).

6.2.2 Area of Land Cultivated, A_r (m^2) (Behavioral)

6.2.2.1 Description of A_r

A_r is defined in the residential scenario as the area of land that is used for the production of agricultural products for both human and animal consumption. The default value for this parameter defined in NUREG/CR-5512 is 2500 m^2. The cultivated area is the area required to support that portion of the resident farmer's diet that derives from on-site production. Both food crops consumed directly by the resident farmer, and feed for animals raised by the farmer are produced on the cultivated area. As a behavioral parameter, the default value for cultivated area reflects the domestic crop production, and therefore the domestically-produced food consumption rates, for the average member of the screening group.

A distribution for A_r is not defined. Instead, A_r is treated in this analysis as a function of the agricultural pathway parameters describing human consumption, animal consumption, and crop yields. The functional connection between these parameters and the cultivated area is described in this section.

6.2.2.2 Use of A_r in Modeling

A_r is used to calculate the infiltration volume through the cultivated farmland area, V_{Ir}. The relationship between A_r and V_{ir} is described in NUREG/CR-5512, Vol. 1, p. 5.68, by the following equation:

$$V_{ir} = I\, A_r\, 1000 * 1 \qquad (6.2)$$

where I is the infiltration rate (m/y), A_r is the area of land under cultivation (m^2), 1000 is a unit conversion factor (L/m^3), and 1 is the time period for infiltration and irrigation (y). In the parameter analysis, the cultivated area is also used to calculate the volume of water used for irrigation:

$$V_{irr} = IR\, A_r\, 1 \qquad (6.3)$$

based on the specified annual average irrigation rate IR (L/m^2d).

As discussed in NUREG/CR-1549, the definition of the area to which a receptor is exposed is closely related to the definition of the source concentration. Concentrations at a site generally vary in space, however a single value is used in the default dose model and may be used in other dose models. The appropriate source concentration for calculating dose due to exposure along a particular pathway is the average concentration, over the scenario exposure period, to which the receptor is exposed via the pathway under consideration. To properly reflect the actual spatial variability of concentrations over a site, the specified concentration should be the largest average concentration, over the area to which the receptor is exposed, which is also consistent with available site data.

For agricultural pathways, the "exposed" area is the area on which produce and animal feed are grown for domestic consumption, A_r. The minimum cultivated area is that area required to support the specified consumption rates of an individual resident. This minimum required area is functionally related to other parameters of the agricultural pathways model, as described in the following section.

6.2.2.3 Area Required to Support Specified Consumption

The area required to support the specified domestic consumption of the resident, A_r, is given by:

$$A_r = \left[\sum_{v=1}^{N_v} \frac{U_v}{Y_v} + \sum_{a=1}^{N_a} \frac{U_a}{Y_a^*} \right] \qquad (6.4)$$

where:

- N_v is the number of food crops considered in the diet;
- N_a is the number of animal products considered in the diet;
- U_v is the ingestion rate of food crop type v by an individual (kg wet-weight/y);
- U_a is the ingestion rate of animal product type a by an individual (amount/y);

Y_v is the crop yield for food crop type v (kg wet-weight/m^{2}y);

Y_a^* is the animal product yield for animal product type a (amount/m^{2}y)

The units of the animal product ingestion rates U_a and the animal product yields Y_a^* may be different for different animal products, but must be consistent. In NUREG/CR-5512, U_a is specified as kg wet-weight/y for meat, poultry, and eggs, and as L/y for milk.

The animal product yield Y_a^* is the amount of consumable animal product produced through cultivation of 1 m^2 of animal feed, and can be defined in terms of the yield and requirements of an individual animal:

$$Y_a^* = \frac{Y_{Ia}}{A_{Ia}} \qquad (6.5)$$

where:

Y_{Ia} is the annual product yield from an individual animal (amount/y);

A_{Ia} is the area required to supply the domestically-produced portion of an individual animal's diet (m^2)

The cultivated area required to support an individual animal is related to the animal's consumption rate and the effective yield for the feed crops in the animal's diet:

$$A_{Ia} = \sum_{k=1}^{N_k} \frac{365.25 * Q_{ka}}{Y_{Eka}} x_{ka} \qquad (6.6)$$

where:

N_k is the number of animal feed crops in the animal's diet;

Q_{ka} is the consumption rate of feed crop type k by animal type a (kg wet-wt/d);

Y_{Eka} is the effective crop yield for feed crop type k (kg wet-wt/m^2/y);

x_{ka} is the fraction of feed crop type k consisting of domestic production in the diet of animal type a;

6.2.2.4 Parameters used to Calculate A_r

Equations 6.4 through 6.6 relate the model parameter A_r to other agricultural parameters used in the residential scenario model. Two additional parameters, which are not required in the default dose model, are required to calculated A_r: the individual animal product yields Y_{Ia}, and the effective crop yields Y_{Eka}.

The individual animal product yields. Y_{Ia}, were assigned using data from the U.S. Department of Agriculture. (USDA) Annual data from the latest complete reported year were used in each case. Per-animal yields for beef were estimated from two data sets. The average dressed weight of federally inspected cattle in 1993 was 315 kg (USDA, 1998a). Total red-meat yield from beef in 1993 was 10.4 billion kg (USDA, 1998b) and the total number of cattle slaughtered under federal inspection in that year was 33.3 million head, giving an average yield per head of 313 kg. The estimated values are consistent, and a median value of 314 kg per animal was assigned. The age at which beef cattle are slaughtered varies with the breed and with short-term economic factors such as current beef and feed price, but is typically between one and two years.[1] A representative age of 18 months gives an annual yield of 209 kg/year per head.

The average per-animal yield for poultry was estimated from the total net ready-to-cook production from young chickens of 11.3 million kg in 1995 (USDA, 1998c), and the total number of young chickens slaughtered in 1995, 7.37 million (USDA, 1998d), giving an average yield of 1.53 kg per chicken. Chickens are assumed to be no older than one year at slaughter.

Average annual milk production per cow, using data described in the USDA source as coming from "22 major states," was 16,333 lbs in 1994 (USDA, 1998e), Assuming a density equal to water, the average volume production was 7415 L per cow. The reported average production of table eggs in 1994 was 260.6 eggs per layer (USDA, 1998f). The individual product yields for beef, poultry, milk, and eggs are summarized in Table 6.3.

The effective crop yield Y_{Eka} is the mass of consumable feed produced per unit cultivated area. For hay and fresh forage, this yield is assumed to be identical to the standing biomass yield. The standing biomass yield, Y_{ka} is a required parameter for the residential scenario model in NUREG/CR-5512, Vol. 1 (see Sections 3.60 and 3.62). For grain, the effective crop yield was estimated from crop production figures for 1996 reported by the USDA (USDA, 1997c). The effective yield for "grain" was estimated from the reported average yield for three primary components of feed grain: corn, sorghum, and oats.

[1] Robert Pate, Bernalillo County Cooperative Extension Service, Oral Communication, January 15, 1997.

Table 6.3 Annual animal product yields per animal for the four animal product types considered in the residential scenario model

Animal product type	Individual animal product yield	Data source
Beef	209 kg/y	1994 average dressed-weight; assumed age at slaughter of 18 months
Poultry	1.53 kg/y	1995 young chicken ready-to-cook production and number slaughtered
Milk	7414 L/y	1994 average milk production; assumed density of 1 kg/L
Eggs	260.6 eggs/y	1994 average table-egg production per layer hen

$$Y_{Egrain} = f_{corn} Y_{corn} + f_{sorghum} Y_{sorghum} + f_{oats} Y_{oats} \quad (6.7)$$

where f is the fractional area planted with each grain type, and Y is the net feed yield per area for each grain type. Table 6.4 summarizes the fractional area and yield based on the reported national totals for 1996, giving an effective yield for grain of 0.73 kg wet-wt/m^2.

Table 6.4 Area fractions and net yields for feed grains in 1996

Feed grain crop	Fraction of area growing feed grains	Yield (kg wet-wt/m^2)
Corn	0.834	0.798
Sorghum	0.136	0.424
Oats	0.030	0.207

The remaining parameters are required input for the residential scenario dose model. Table 6.5 summarizes the residential scenario model parameters used to calculate cultivated area, and the report sections defining values or distributions for these parameters.

Table 6.5 Parameters of the residential scenario model used to calculate cultivated area

Parameter	Description	Section number
DIET	fraction of the resident's diet derived from domestic produce	6.2.1
U_v	ingestion rate of food crops	6.2.9
U_a	ingestion rate of animal products	6.2.9
Y_v	food crop yields	6.4.5
Q_{ka}	animal feed consumption rates	6.4.6
Y_{ka}	feed crop yields for hay and fresh forage	6.4.5
x_{ka}	fraction of domestically-produced feed in animal diets	6.2.1

6.2.2.5 Alternative Values of A_r

Equation 6.3 provides a cultivated area that is consistent with the consumption patterns of the receptor specified by the parameters of the agricultural pathway model. For the screening calculations, these parameters describe the average member of the screening group, and the default cultivated area is the corresponding area required to support their consumption. Site conditions may set physical limits on the area that can be cultivated: this limit in turn implies limits on one or more of the parameters describing the agricultural pathway. The cultivated area may be modified to conform to site-specific area restrictions by modifying these parameters.

Alternatively, the licensee may define a site-specific critical group. The behavioral parameters for the agricultural pathway model may be different for the average member of this group than for the average member of the screening group (AMSG), leading to a revised value of A_r consistent with the behavior of the critical group.

6.2.3 Exposure Period: Indoors, t_i, Outdoors, t_x, and Gardening, t_g (d/y) (Behavioral)

6.2.3.1 Description of Exposure Periods

The residential scenario model defines three distinct situations or contexts for potential exposure: indoor exposure, gardening exposure, and exposure outdoors other than while gardening. These separate contexts are defined due to the distinctive pathways or transport rates that might apply to these situations. During the one-year scenario period, the AMSG is assumed to divide their on-site time among these three contexts. The three exposure periods ti, tx, and tg are behavioral parameters which specify the number of 24-hour days per year the AMSG spends indoors, outdoors (other than gardening), and gardening. The default values defined in NUREG/CR-5512, Vol. 1, for the times spent indoors, outdoors, and gardening are 200 d/y, 70.83 d/y, and 4.17

d/y, respectively. No reference is provided for these values. Default time allocations in RESRAD are based on the assumption that 50% of a person's time is spent indoors, and 25% is spent outdoors in the contaminated area.

The exposure periods are behavioral parameters. For the screening calculations, the values for these parameters reflect the average member of the screening group, which consists of resident farmers. An estimate of the variability of exposure periods among individuals in this group is also required, to evaluate the homogeneity of the screening group.

Current information on human activity patterns was reviewed to establish screening values for these parameters. Values representative of the screening group, consisting of adult resident farmers, were selected from this literature. For each of the three contexts, the average of these values is proposed as defining the behavior of the AMSG. A distribution was also identified to describe the potential variability in exposure time among individual members of the screening group.

6.2.3.2 Use of Exposure Periods in Modeling

The time allocation factors are used to calculate doses due to direct exposure and inhalation, as discussed in the following section. The rate of exposure differs in each environment due to differences in the physical characteristics of the environment (reflected in the shielding factors, dust loadings, and resuspension factors) and differences in behavior (reflected in environment- specific breathing rates). Within each environment, dose from each pathway varies linearly with the time spent in that environment.

These parameters describe the time that the individual spends in various activities and are used to calculate external dose from exposure to radionuclide i in soils, $DEXR_i$, and inhalation committed effective dose equivalent, DHR_i, from exposure to radionuclide i during residential activity. Dose from external exposure is calculated as (see NUREG/CR-5512, p. 5.53).

$$\begin{aligned} DEXR_i = & \left[24(t_g/t_{tg})\, SFO\; C_{si}\; \Sigma_{(j=1,ji)}\; S\{A_{stj},\, t_{tg}\}\, DFER_j\right] \\ & + \left[24(t_x/t_{tr})\, SFO\; C_{si}\; \Sigma_{(j=1,ji)}\; S\{A_{stj},\, t_{tr}\}\, DFER_j\right] \\ & + \left[24(t_i/t_{tr})\, SFO\; C_{si}\; \Sigma_{(j=1,ji)}\; S\{A_{stj},\, t_{tr}\}\, DFER_j\right] \end{aligned} \quad (6.8)$$

where $DREF_j$ is the external dose rate factor for radionuclide j for exposure to contamination uniformly distributed in the top 15 cm of residential soil (mrem/h per pCi/g), A_{stj} is the concentration factor for radionuclide j in soil at the beginning of the current annual exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/g per pCi/g), t_{tg} is the gardening period (90 days per year), C_{si} corresponds to the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil), SFI and SFO are shielding factors by which external dose rate is reduced during periods of 1) indoor residence and 2) outdoor residence and gardening, respectively, J_i is the number of explicit members of the decay chain for parent radionuclide i, $S\{A_{stj},t_{tr}\}$ is the time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), $S\{A_{stj},t_{tg}\}$ is the time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during 1-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), t_g is the time during the gardening period that the individual spends outdoors gardening (d for a year of residential scenario), t_i and t_x are time in the one-year exposure period that the individual spends indoors and outdoors, other than gardening (d for a year of residential scenario), respectively, t_{tr} is the total time in the residential exposure period (d), and 24 is a unit conversion factor (h/d). Inhalation dose is given by (see NUREG/CR-5512, p. 5.55):

$$\begin{aligned} DEXR_i = & \left[24\, V_g(t_g/t_{tg})\; CDG\; C_{si}\; \Sigma_{(j=1,ji)}\; S\{A_{stj},\, t_{tg}\}\, DFH_j\right] \\ & + \left[24\, V_x(t_x/t_{tr})\; CDG\; C_{si}\; \Sigma_{(j=1,ji)}\; S\{A_{stj},\, t_{tr}\}\, DFH_j\right] \\ & + \left[24\, V_r(t_i/t_{tr})\, (CDI+P_dRF_r)\; \Sigma_{(j=1,ji)}\; S\{A_{stj},\, t_{tr}\}\, DFH_j\right] \end{aligned} \quad (6.9)$$

where V_g, V_r, and V_x correspond to volumetric breathing rates for time spent gardening, indoors, and outdoors, respectively (m^3/h), t_g is the time during the gardening period that the individual spends outdoors gardening (d for a year of residential scenario), t_i and t_x are time in the one-year exposure period that the individual spends indoors and outdoors, other than gardening (d for a year of residential scenario), respectively, t_{tr} is the total time in the residential exposure period (d), CDI and CDO are dust loading factors for indoor and outdoor exposure periods, respectively, (g/m^3), CDG is the dust loading factor for gardening activities (g/m^3), C_{si} corresponds to the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil), J_i is the number of explicit members of the decay chain for parent radionuclide i, $S\{A_{stj},t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), $S\{A_{stj},t_{tg}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil), DFH_j is the inhalation committed effective dose equivalent factor for radionuclide j for exposure to contaminated air (in units of mrem per pCi inhaled), P_d is the indoor dust-loading on floors (g/m^2), and RF_r is the indoor resuspension factor (m^{-1}).

6.2.3.3 Information Reviewed to Define Exposure Periods

The literature review conducted to support the EPA *Exposure Factors Handbook* (EPA 1996) was adopted as the most current compilation of relevant literature. This document contains a review and summary of current time allocation studies, along with detailed results from selected studies. Time allocations are reported for a variety of activities and environments. All reviewed studies minimally provide mean time allocations over the individuals surveyed. Defining ranges or distributions for the time allocation parameters of the residential scenario model, however, requires information on the variability of time allocation among individuals. In addition, time allocation data is required for the three environments considered in the residential scenario. Among the time allocation studies identified in the literature review, three primary sources were considered for the time allocation estimates in the three residential contexts. These sources are summarized below.

Tsang and Klepeis (1996) is "the largest and most current human activity pattern survey available" (EPA, 1996). Over 9000 respondents provided minute-by-minute 24-hour diaries between October 1992 and September 1994, and the responses weighted to produce results representative of the U.S. population. Percentile values are reported for the distributions of time spent in a wide variety of activities for "doers" of those activities. These values describe the variability of day-to-day time allocation, and therefore cannot be used directly as estimates of annual average values. Among the activities and environments considered, reported values for "Minutes Spent Working in a Garden or Other Circumstances Working with Soil" (EPA, 1996, Table 14-60), "Minutes Spent at Home in the Yard or Other Areas Outside the House" (EPA, 1996, Table 14-118), and "Minutes Spent Indoors in a Residence (All Rooms)" (EPA, 1996, Table 14-129) were used to estimate average values for the critical group of resident farmers, as well as distributions for individual members of this group, as described in Section 6.2.3.4.

Hill (1985) also reports on individual variability in time allocation among a variety of activities. Data were collected in four waves, one per season, in 1975 and 1976. Weekly average values, and standard deviations of those weekly averages, are reported for various age and gender cohorts. Unlike other activity pattern studies (exemplified by Tsang and Klepeis) which provide data on daily time allocation, Hill's study provides information on the variability of longer-term averages for individuals. Although the study period was also quite short in Hill (1985), observation periods were distributed throughout the year. The results of this study therefore appear to be the best basis for estimating the variability of annual average activity patterns among individuals. Hill provides time allocation information for a number of specific activities that are typically conducted at residences, including meal preparation and cleanup, indoor cleaning, washing/dressing, and reading. Data on total time spent indoors, however, is not provided. While the mean value for time spent indoors, for example, can be estimated from the mean values reported for activities typically conducted indoors, the variability in total indoor time among individuals cannot be estimated from the reported data without information on (or assumptions about) the correlation of time allocation among these component activities. Similarly, the time spent in a variety of outdoor activities is reported, however the total time spent outdoors at the residence is not. Among the outdoor activities, data on time spent in "gardening/ pet care" (Hill 1985, Table 7.A.1) was considered in defining the distribution for t_g, as discussed in Section 6.2.3.4.

Robinson and Thomas (1991) compare data from the 1987–1998 California Air Resources Board (CARB) time activity study and from a 1985 national study *American's Use of Time*. Reported values from the national study were assumed to be more representative of the screening group because of the broader geographical basis. Time allocation data are reported for a number of activities, locations, and micro-environments. For each of these categories, data are summarized by the average time spent, the standard error of this average, the average value for "doers," and the percentage of "doers" in the total sample. Among activities, locations, and micro-environments considered in this study, data on time spent outdoors at a residence (Robinson and Thomas, 1991, Table 9-1) were considered in defining the distribution for t_x. Data on time spent indoors are provided for two classifications: time spent in the kitchen, and time spent elsewhere indoors. As in the case of the data reported by Hill (1985), the average time spent indoors can be estimated by adding the average values for each classification. Information or assumptions regarding the correlation between time spent in these two locations is required to estimate the variability in the total time spent indoors.

Both Tsang and Klepeis (1996) and Hill (1985) report separate time allocation data for men and women, as well as aggregate time allocation data. There are significant differences between the gender-specific time allocation values for some environments. For example, Tsang and Klepeis (1996) report an average time spent outdoors at the residence of 158 min/d for men, while women were found to spend and average of 115 min/d in the same environment. This difference presumably reflects a specialization of domestic roles which is relevant for characterizing the screening group for the residential scenario. Because the screening group is defined as resident farmers, data for men, who typically spend more time outdoors and gardening, but less time indoors, were used to estimate the three exposure time parameters.

6.2.3.4 Assumptions and Procedures Used to Derive Time Allocation Distributions

A large amount of information on individual time allocation is available in the literature, however this information cannot be used to directly assign distributions for the exposure periods. In each of the three key studies discussed in Section 6.2.3.2, a number of assumptions and inferences are required to derive parameter distributions from the reported data. These assumptions and inferences are needed to supplement reported information, and to reconcile differences between the data reported and the model parameter values, in three areas:

- Time allocation values are "measured" over a single 24-hour period, while the model parameters reflect annual average values.

- Tsang and Klepeis (1996) provide detailed distributional information; in both Hill (1985) and Robinson and Thomas (1991), however, variability in time allocation among individuals is only characterized by the sample standard deviation. The form of the distribution is not available from the latter two studies, and must be assumed.

- Robinson and Thomas (1991) do not directly report the standard deviation of time spent by "doers." This information must be derived from their reported values for the average times spent by "doers" and by all respondents, the standard deviation of time spent by all respondents, and the fraction of respondents considered "doers."

In each area, the reported variability in time allocation does not directly correspond to the variability in annual average values among individuals in the screening group. The following sections describe the assumptions and procedures used to estimate the parameter distributions from the reported data. The average values over all individuals can be estimated directly from the reported data. These averages do not depend on the assumptions and procedures which are required to estimate the full distribution.

6.2.3.4.1 Estimating Annual Average Values from Daily Values

The time allocation studies found in the literature review use either diaries or retrospective questionnaires to measure individual's time allocation during a single day. Variability in these values represents both variability among individuals, and day-to-day variability of time allocation for a single individual. The time allocation parameters for the residential scenario should describe average behavior of an individual over one year, and the distributions for these parameters should describe variability in this annual average over individuals in the screening group. Because reported distributions generally describe variability of daily time allocation rather than annual average time allocation, they cannot be directly used to assign parameter distributions. Instead, estimating variability of annual average values from the reported distributions of daily values requires information or assumptions on the similarity of an individual's time allocation from one day to the next.

The similarity of an individual's time allocations on successive days can be described by an autocorrelation function. Autocorrelation information is not available in the reviewed literature: three alternative assumptions were therefore considered in order to define the effect of uncertainty in the autocorrelation of daily time allocation on the distribution of annual average time allocation. These alternative assumptions lead to alternative distributions for individual time allocation. The average time allocation over all individuals, as discussed above, does not depend on these assumptions, and can be calculated directly from the reported data. Alternative assumptions will, however, lead to different estimates for variability in dose among members of the screening group.

For a single individual, the correlation between the time spent in a given environment on one day was assumed to be positively correlated with the time spent on any subsequent day: individuals who report spending a large amount of time gardening on a single day, for example, are assumed to be likely to spend a large amount of time gardening on subsequent days. Given this assumption, the three alternative autocorrelations considered correspond to the two extreme limits on non-negative autocorrelation, and an intermediate degree of autocorrelation.

The first case assumes perfect correlation in a single individual's time allocation from one day to the next. In this case, the time spent in each environment on each day is identical to the time spent on any other day in the year. Under this assumption, the distribution of annual average time allocation values is identical to the distribution of daily values. This case produces the largest variability in the estimated annual average values: all variability in the reported daily values is assumed to be due to variations among individuals. The resulting distributions are probably unrealistically broad: this assumption is used to illustrate the upper limit of variability of annual average time allocation values.

The second case assumes no correlation in time allocation from one day to the next. In this case, an individual's annual average value for time allocation consists of 365 independent samples from the reported distribution of daily time allocation. By the central limit theorem, the distribution of annual average values over individuals will be well approximated by a normal distribution, with a mean value equal to the mean daily value, and a variance equal to 1/365th of the variance of the daily values. This case produces the smallest variability in the estimated annual average values: all variability in the reported daily values is assumed to be due to "random" day-to-day variations which are the same for all individuals, and no variability is attributed to variations in individual habits. The resulting distributions are generally very narrow, and represent a lower limit on the variability of annual average values.

The third case assumes an intermediate degree of autocorrelation. A single individual is assumed to spend a constant amount of time in each environment for 30 successive days. The time spent in each environment is assumed to be independent from one 30-day period to the next. This assumed autocorrelation is not intended to be a realistic description of behavior: a realistic autocorrelation function might be expected to decay gradually with time, rather than to be limited to values of 1 and 0. The simple autocorrelation function used in this case was designed to produce a plausible distribution of annual average values representing an intermediate degree of autocorrelation, and to simplify derivation of the distribution of annual average values. For a single individual, the annual average time allocation for each environment consists of the average of 12 independent samples from the reported distribution of daily values.

6.2.3.4.2 Assumed Distributions for Daily Values Reported by Hill (1985) and Robinson and Thomas (1991)

Hill (1985) reports the mean time spent by individuals, and describes the variability among the sample population by the standard deviation; Robinson and Thomas (1991) report the mean, along with other information from which the sample standard deviation can be derived (see below). No additional information on the form of the distribution is provided in either study. In each environment, and for any individual, the time spent is physically bounded by 0 and 365.25 days/year. Without more specific information on the form of these distributions, distributions were assigned using the principle of maximum entropy. As stated by Jaynes (1982), this principle requires that "when we make inferences based on incomplete information, we should draw from them that probability distribution that has the maximum entropy permitted by the information we do have." In as much as the form of the exposure time distributions are unknown, the assumption of any specific distribution is arbitrary, and likely to be wrong. Given this uncertainty, the maximum entropy distribution was judged the most reasonable choice in that "most information theorists have considered it obvious that, in some sense, the possible distributions are concentrated strongly near the one of maximum entropy" (Jaynes, 1982). Given the mean, standard deviation, and upper and lower limits, the maximum entropy distribution corresponds to a beta distribution. Beta distributions were therefore defined to describe the variability in individual time allocation based on these four pieces of information.

6.2.3.4.3 Calculating Standard Deviation in "Doer" Time from Data Reported in Robinson and Thomas (1991)

Robinson and Thomas (1991) report the average and standard error for the time spent outdoors over all individuals in the national survey *American's Use of Time.* This sample includes both individuals who regularly spend time outdoors ("doers"), as well as those who do not. A separate average value is reported for "doers," as well as the number of individuals in the overall sample, and the fraction of the total sample classified as "doers." Individuals who spend time outdoors are considered to be more representative of the screening group, however the variability in time spent by this sub-group is not reported in Robinson and Thomas (1991).

This variability can, however, be derived from the information presented. The standard error (SE) is related to the sample standard deviation (S) and the sample size (n) by:

$$SE = \frac{S}{\sqrt{n}} \tag{6.10}$$

while the sample standard deviation is (for large n):

$$S^2 = \sum_{i=1}^{n} \frac{\left(t_i - \bar{t}\right)^2}{n} \tag{6.11}$$

where t_i is the time spent by an individual I. The overall sample of size n can be divided into n_Z "non-doers" of the activity (all of whose time values are zero), and n_D "doers" with non-zero time values. The standard deviation of all time values in Equation 6.10 can then be expressed as the sum of two terms:

$$S^2 = \sum_{i=1}^{n_Z} \frac{\bar{t}^2}{n_Z + n_D} + \sum_{i=n_Z+1}^{n_Z+n_D} \frac{\left(t_i - \bar{t}\right)^2}{n_Z + n_D} \tag{6.12}$$

The standard deviation of the sub-population of "doers" is defined as:

$$S_D^{\,2} = \sum_{i=n_Z+1}^{n_Z+n_D} \frac{\left(t_i - \overline{t_D}\right)^2}{n_D} \tag{6.13}$$

which can be expressed in terms of the overall standard deviation, and the other quantities reported in Robinson and Thomas (1991), using Equation 6.14:

$$S_D^{\,2} = \frac{n_Z + n_D}{n_D}\left(S^2 - \bar{t}^2\right) + 2\overline{t_D}\left(\bar{t} - \overline{t_D}\right) \tag{6.14}$$

6.2.3.5 Time Allocation Distributions

Tsang and Klepeis (1996) provide data on daily time allocation for each of the three environments considered in the residential scenario. These data were used to estimate distributions for each of the three time allocation parameters. As discussed above, three alternative autocorrelation functions were considered to explore the effect of this unknown information on the derived distribution of individual annual average values.

Robinson and Thomas (1991) report data on time spent outdoors at residences. Detailed distributional information is not provided however, and a beta distribution was assumed. Like the data from Tsang and Klepeis (1996), these time allocations are daily values, and three alternative autocorrelation functions were used estimate the distribution of annual average values for t_x from this data.

For the distributions derived from the daily measurements reported by both Tsang and Klepeis (1996) and Robinson and Thomas (1991), the distribution based on the intermediate degree (30 day period) of autocorrelation is recommended, although the bounding distributions (as well as other intermediate distributions) are equally consistent with the data.

Hill (1985) reports the average and standard deviation of time spent gardening. Unlike the two other studies, each single time allocation value is an average of four separate reports from the same individual, taken in four seasonal "waves." As such, these values provide a more direct estimate of the annual average time allocation for each individual. The quality of this estimate is, however, uncertain, as it based on very limited data for each individual. A beta distribution was assumed based on the reported average, reported standard deviation, and the absolute physical upper and lower limits of 0 and 365.25 days/year. Note that although the beta distribution fitted to the data from Hill (1985) has a theoretical upper limit of 365.25 days, this limit is not practically approached: 98% of the distribution values are less than 20 days.

6.2.3.5.1 Time Spent Indoors (t_i)

Data describing the variability in daily values of total time spend indoors at a residence, reported by Tsang and Klepeis (1996), were used to define the distribution for t_i. Table 6.6 reproduces the reported distribution of daily values for men, converted to units of 24-hour days/year. Figure 6.1 shows the distributions for indoor time resulting from the three assumed autocorrelation functions considered. There is considerable uncertainty in the distribution of annual average values due to uncertainty in the autocorrelation of daily values, although the bounding cases of no correlation and 365-day correlation can arguably be dismissed as unreasonable: the former shows very little variability in individual behavior around the common mean value of 266 days, while the latter shows nearly 5% of individuals spending less than 8 hours/day (approximately 120 24-hour days/year) indoors.

6.2.3.5.2 Time Spend Outdoors at the Residence (t_x)

Data describing the variability in daily values of time spent outdoors at a residence, reported by both Tsang

Table 6.6 Distribution of daily values of time spent indoors at a residence (all rooms)*

Sample size = 4269	
Population characteristic	**Value (24-hour days/year)**
Mean	240
Standard deviation	69.4
Minimum	2.03
Maximum	365.25
Percentile values:	
0.05	137
0.25	190
0.5	228
0.75	294
0.9	342
0.95	363
0.98	365
0.99	365

*from Tsang and Klepeis (1996) cited in EPA (1996) Table 14-129, Data for Men

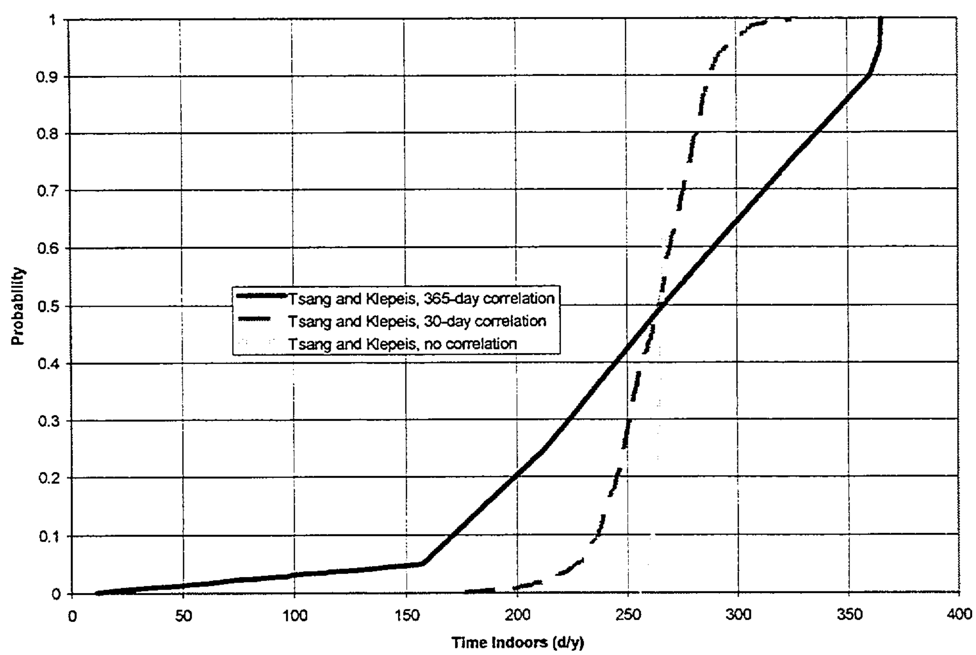

Figure 6.1 CDF of annual average time spent indoors based on daily from Tsang and Klepeis (1996) for three assumed autocorrelations

and Klepeis (1996), and by Robinson and Thomas (1991) were considered in defining the distribution for t_x. Table 6.7 reproduces the distribution reported by Tsang and Klepeis (1996) of daily values for men converted to units of 24-hour days/year. Data for men were selected as more representative of the screening group. Figure 6.2 shows the distributions for outdoor time based on this data, resulting from the three assumed autocorrelation functions considered.

Table 6.7 Distribution of daily values of time spent outdoors at a residence*

Population characteristic	Value (24-hour days/year)
	Sample size = 1198
Mean	40.2
Standard deviation	40.6
Minimum	0.3
Maximum	327
Percentile values:	
0.05	2.53
0.25	15.2
0.5	30.4
0.75	50.2
0.9	91.3
0.95	127
0.98	159
0.99	185

* from Tsang and Klepeis (1996) cited in EPA (1996) Table 14-118, Data for Men

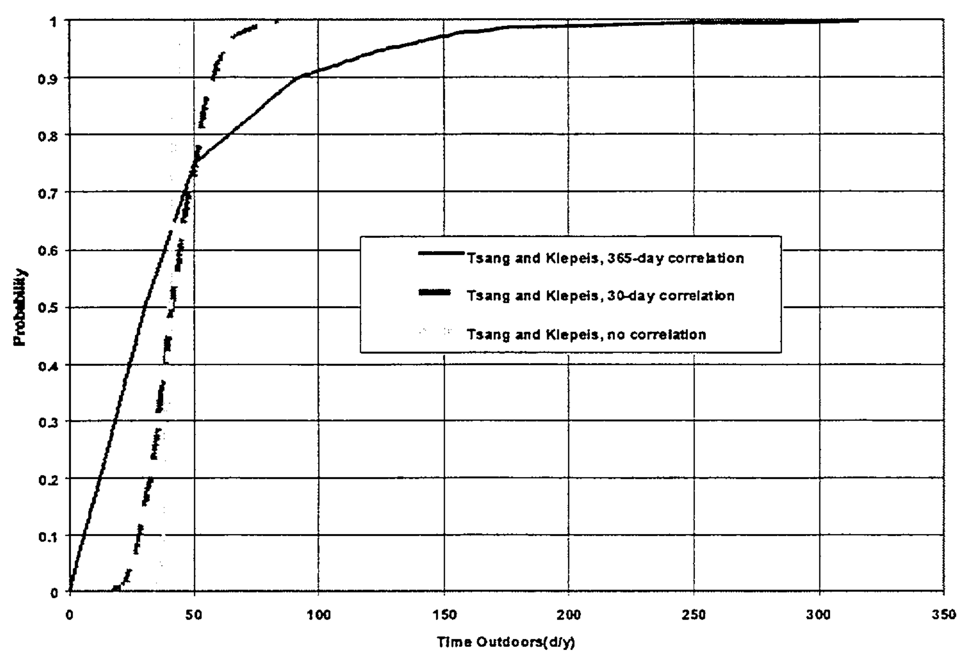

Figure 6.2 CDF of annual average time spent outdoors based on daily data from Tsang and Klepeis (1996) for three assumed autocorrelations

Average daily values reported by Robinson and Thomas (1991), and the sample standard deviation derived from the reported standard error, average for "doers," and sample size (see Section 6.2.3.5), were used to define a beta distribution for daily values of outdoor time. Table 6.8 summarizes the parameters of this distribution. Figure 6.3 shows the distributions for outdoor time resulting from the three assumed autocorrelation functions considered.

Table 6.8 Distribution of daily values of time spent outdoors at a residence*

Sample size = 2762	
Distribution parameter	**Value**
Reported parameters	
Mean (all subjects) (24-hour days/year)	12
Standard error (all subjects) (24-hour days/year)	0.8
Mean (doers) (24-hour days/year)	29.2
% doers	41
Derived parameters for doers	
Standard deviation (doers) (24-hour days/year)	58.3
Minimum (24-hour days/year)	0
Maximum (24-hour days/year)	365.25
Alpha	0.17
Beta	1.9

* from Robinson and Thomas (1991) Table 9-1, National Survey Data

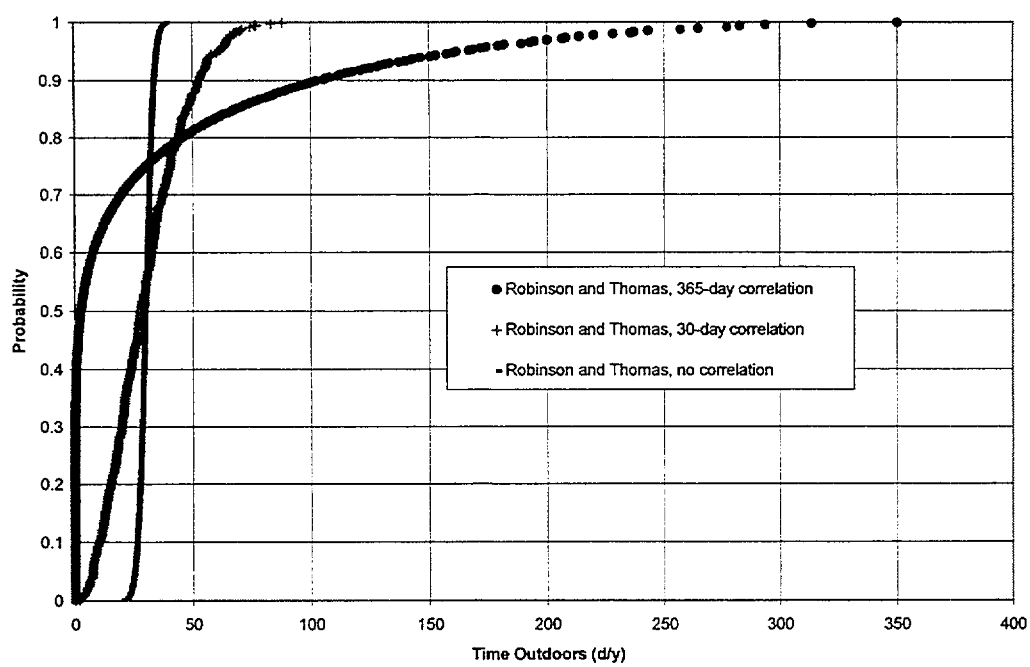

Figure 6.3 PDF of annual average time spent outdoors based on daily data from Robinson and Thomas (1991) for three assumed autocorrelations

Using either set of data, there is considerable uncertainty in the distribution of outdoor time due to uncertainty in autocorrelation of daily values. The distribution based on data from Tsang and Klepeis (1996) has a larger mean value (40 24-hour days/year) than the data from Robinson and Thomas (1991) (29 24-hour days/year). The former is recommended as the distribution for t_x because of this conservative characteristic, and because the underlying distribution of daily time allocation values is more accurately defined.

6.2.3.5.3 Time Spent Gardening (t_g)

Data describing the variability in daily values of time spent gardening, reported by both Tsang and Klepeis (1996), and by Hill (1985) were considered in defining the distribution for t_g. Table 6.9 reproduces the distribution reported by Tsang and Klepeis (1996) of daily values for men of time spent working in a garden or other circumstances working with soil, converted to units of 24-hour days/year. Data for men were selected as more representative of the screening group.

Table 6.9 Distribution of daily values of time spent working in a garden or other circumstances working with soil*

Sample size = 2125	
Population characteristic	**Value (24-hour days/year)**
Mean	2.92
Standard deviation	9.50
Minimum	0
Maximum	365.25
Percentile values:	
0.05	0
0.25	0
0.5	0
0.75	0.761
0.9	5.07
0.95	12.7
0.98	38.0
0.99	58.3

* from Tsang and Klepeis (1996) cited in EPA (1996) Table 14-60, Data for Men

Gardening times reported by Hill (1985) were assumed to approximate annual average values. A beta distribution for t_g was developed directly from the reported mean and standard deviation, and the absolute physical limits of 0 and 365.25 days/year. Unlike the results of Tsang and Klepeis (1996), reported mean values for men and women are quite similar: the overall average and standard deviation using both genders was therefore used to define the distribution. Table 6.10 summarizes the key parameters of this distribution.

Figure 6.4 shows the three distributions for gardening time based on the data of Tsang and Klepeis (1996) (using three alternative autocorrelation functions), along with the beta distribution based on the mean and standard deviation reported by Hill (1985). Although Hill's procedure yields estimates of annual average time allocation (based on four daily measurements of the same individual, distributed throughout the year), the fitted distribution is quite similar to the distribution of daily gardening times reported by Tsang and Klepeis (1996). Note that although the beta distribution fitted to the data from Hill (1985) has a theoretical upper limit of 365.25 days, this limit is not practically approached: 98% of the distribution values are less than 20 days.

Table 6.10 Distribution of annual values of time spent gardening*

Sample size = 971	
Distribution parameter	**Value**
Reported parameters	
Mean (24-hour days/year)	2.1
Standard deviation (24-hour days/year)	5.4
Derived parameters for doers	
Minimum (24-hour days/year)	0
Maximum (24-hour days/year)	365.25
Alpha	0.17
Beta	29

* from Hill (1985) Table 7.A.1, Data for Men and Women

Three considerations favor the distribution based on Tsang and Klepeis (1996) (assuming a 30-day autocorrelation) over the distribution fitted to Hill (1985): the better definition of the distributional form provided by Tsang and Klepeis (1996); the similarity of the distribution based on Hill (1985) to the distribution of daily values reported by Tsang and Klepeis (1996), suggesting that Hill's data are more representative of daily values than annual average values; and the small number of daily measurements on which Hill's annual average estimates are based. As in the case of annual average values for indoor time and outdoor time, there is considerable uncertainty in the distribution of gardening time due to uncertainty in autocorrelation of daily values.

6.2.3.6 Summary

The National Human Activity Patterns Survey analysis of Tsang and Klepeis (1996) was used to define exposure periods for the average member of the screening group, and to estimate variability in exposure periods among individuals in the screening group. This study was preferred over available alternatives because of the large sample size, the availability of exposure period data for micro-environments considered in the residential scenario, the availability of data for sub-populations approximating the screening group (i.e., "doers" of gardening), and the availability of

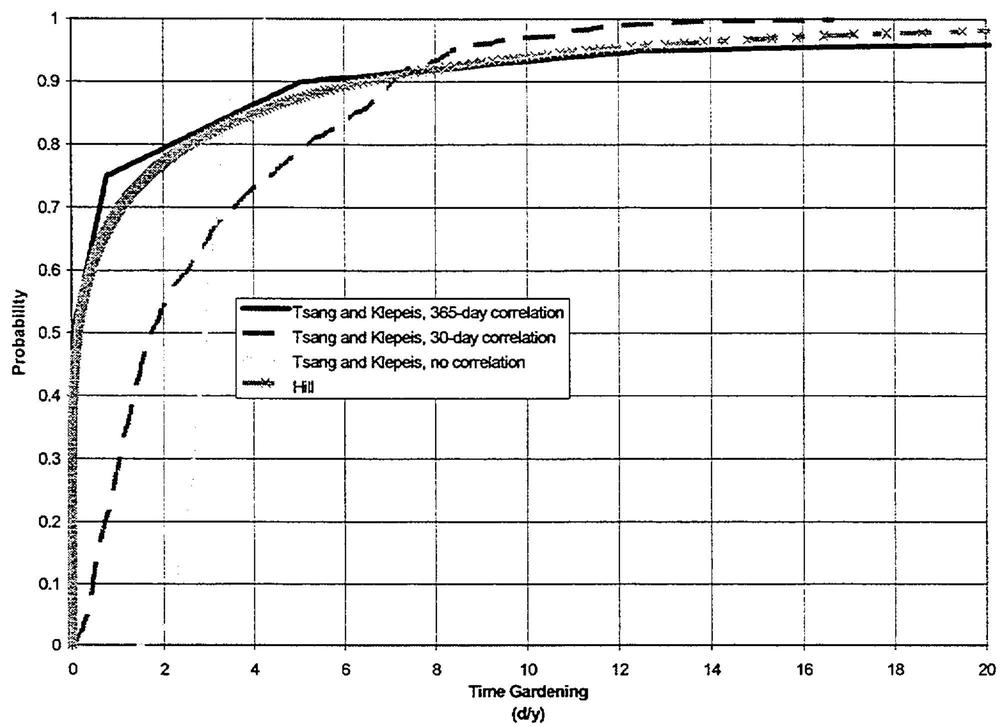

Figure 6.4 CDF of annual average time spent gardening based on data from Hill (1985) and daily data from Tsang and Klepeis (1996) for three assumed autocorrelations

distributions of daily individual exposure time values. Mean values and distributions for time indoors were developed from data in Robinson and Thomas (1991), and Hill (1985) was used to estimate mean values and distributions for gardening time. These estimates are provided for comparison with the recommended values, but are not recommended for use in the residential scenario because of the lack of detailed distribution data from either study, and the difficulty in estimating exposure times for all three contexts from either study alone.

6.2.3.6.1 Average Exposure Time

The exposure time for the average member of the screening group were directly estimated by daily time allocation values for men available in the literature. Tsang and Klepeis (1996) report average values for time spent indoors at a residence and outdoors at a residence. This study also provides quantile values for the distribution of time spent gardening or working with soil. The average value was calculated from this distribution. Robinson and Thomas (1991) report an average for "doers" of time spent outdoors at a residence; Hill (1985) reports an average value for time spent gardening. Table 6.11 summarizes these reported average values. The average values given by Tsang and Klepeis (1996) have been adopted due to the large number of samples in the study, the availability of exposure time values for each of the three scenario contexts in a single study, and the availability of distributions of individual values for each context.

Table 6.11 Summary of average exposure time values (24-hour days/year)

Parameter	Reported average (24-hr days per year)	Source
Indoor time (t_i)	240	Tsang and Klepeis (1996)
Outdoor time (t_x)	40.2	Tsang and Klepeis (1996)
	29.2	Robinson and Thomas (1991)
Gardening time (t_g)	2.92	Tsang and Klepeis (1996)
	2.1	Hill (1985)

6.2.3.6.2 Distribution of Exposure Times

The recommended distributions for annual average time spent in each residential environment are shown in Figures 6.5 and 6.6, and summary properties are listed in Table 6.12. Table 6.13 list quantile values of these distributions, which were generated by Monte-Carlo sampling of the empirical distributions of daily time allocation reported in Tsang and Klepeis (1996) (see Tables 6.6, 6.7, and 6.9 above). Each distribution is based on daily values reported in Tsang and Klepeis (1996). Among the three key studies considered, this survey presents the most complete definition of the distribution of daily values, from which the distributions of annual average values were estimated. The estimated distribution of annual average values is based on an assumed autocorrelation of 30 days. The autocorrelation of daily values is uncertain, and the assumed value is intermediate between the limiting values of no correlation between daily values, and perfect correlation between daily values. The spread of the time allocation distributions is sensitive to the assumed autocorrelation, however the mean value over all individuals does not depend on this assumption.

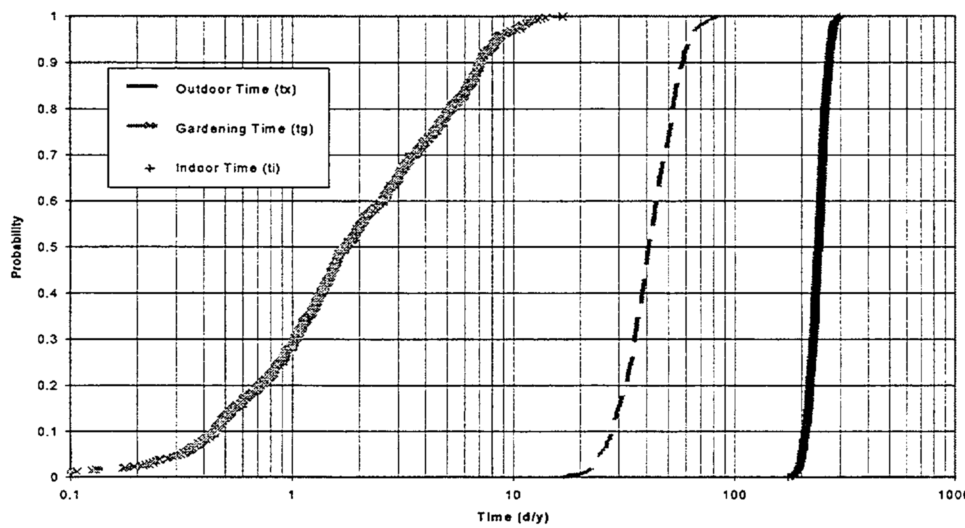

Figure 6.5 Cumulative probability functions for indoor time (ti), outdoor time (tx), and gardening time (tg)

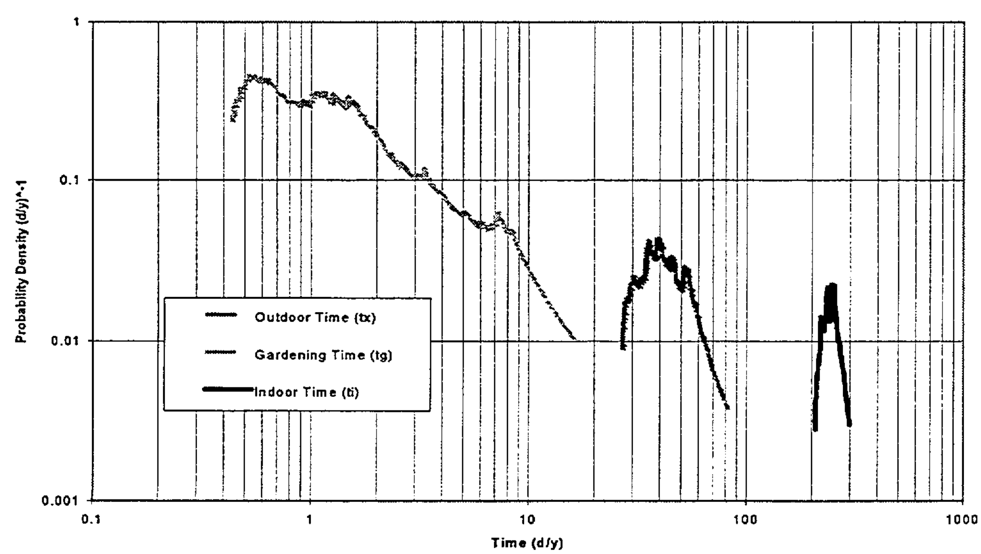

Figure 6.6 Probability density functions for indoor time (ti), outdoor time (tx), and gardening time (tg)

Table 6.12 Summary properties for time allocation parameter distributions

Parameter	Distribution properties (24-hour days/year)			
	Mean	Median	1st percentile	99th percentile
Indoor time (t_i)	240	238	189	285
Outdoor time (t_x)	40.2	40.9	20.1	75.8
Gardening time (t_g)	2.92	1.73	9.10×10^{-2}	12.0

Table 6.13 Quantile values for exposure period distributions

Probability	t_g (d/y)	t_i (d/y)	t_x (d/y)
0.00e+00	2.00e-02	1.74e+02	1.68e+01
1.00e-03	3.50e-02	1.74e+02	1.68e+01
1.10e-02	9.49e-02	1.90e+02	2.11e+01
5.10e-02	3.25e-01	2.02e+02	2.48e+01
1.01e-01	4.50e-01	2.08e+02	2.79e+01
2.01e-01	7.20e-01	2.18e+02	3.25e+01
3.01e-01	1.03e+00	2.26e+02	3.54e+01
4.01e-01	1.35e+00	2.32e+02	3.83e+01
5.01e-01	1.74e+00	2.38e+02	4.09e+01
6.01e-01	2.56e+00	2.44e+02	4.43e+01
7.01e-01	3.58e+00	2.49e+02	4.80e+01
8.01e-01	5.21e+00	2.55e+02	5.23e+01
9.01e-01	7.07e+00	2.66e+02	5.81e+01
9.51e-01	8.44e+00	2.73e+02	6.34e+01
9.81e-01	1.10e+01	2.80e+02	6.99e+01
9.99e-01	1.67e+01	2.98e+02	8.43e+01
1.00e+00	1.70e+01	3.00e+02	9.00e+01

6.2.3.6.3 Correlations Among Exposure Times and Other Parameters

The time that an individual spends in a given context is constrained by the time spent in each of the other two contexts. Some amount of negative correlation should therefore exist between each pair of time allocation distributions, however the size of this correlation is uncertain. The total time an individual spends on site (i.e., the sum of indoor time, outdoor time, and gardening time) was calculated using two limiting assumptions about this correlation: zero correlation, and a rank correlation coefficient of -0.5 between each pair of time categories. The latter correlation is the largest (negative) common correlation coefficient that still produces a positive-definite covariance matrix for the three time allocation parameters. Figure 6.7 shows the distribution of total on-site time under these two assumptions.

The distribution of total time is somewhat narrower when the component distributions are negatively correlated. For example, the 99th percentile value for total time on site is 342 days assuming no correlation, but 325 days when a rank correlation coefficient of -0.5 is assumed. Because the distributions for the two limiting correlation assumptions are similar, uncertainty in the appropriate correlation will not have a large influence on the estimated variability of dose over individuals in the screening group. A correlation coefficient of -0.5 is recommended because it reflects the competition for an individual's time among indoor, outdoor, and gardening activities.

The amount of time spent gardening is also presumably related to the amount of food produced in the garden, although the magnitude of the correlation between these parameters is unknown. A correlation coefficient of 1 between the gardening time and food production rate is

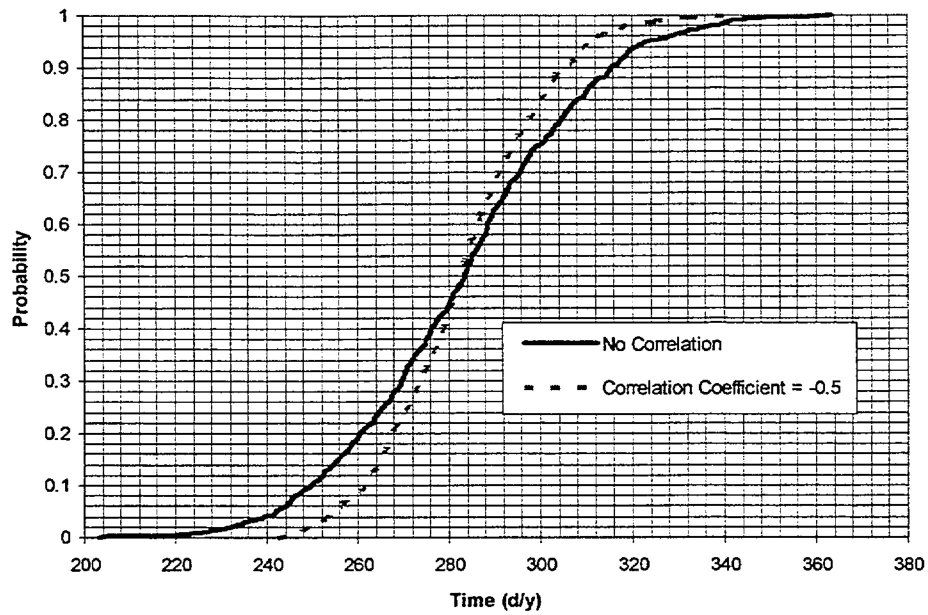

Figure 6.7 CDF of total on-site time (ti + tx + tg) for two assumed rank correlation coefficient values

assumed. Because the calculated dose is an increasing function of both gardening time and ingestion rate for domestic produce, this assumption conservatively bounds the potential variability in dose among members of the screening group. Neither the assumed correlation among exposure times, nor the assumed correlation between gardening time and ingestion rate, affect the estimated mean values for these parameters. Table 6.14 lists the assumed rank correlation coefficients among the exposure times and other model parameters.

Table 6.14 Correlations among exposure times

Parameters	Rank correlation coefficient
t_i, t_x	-0.5
t_x, t_g	-0.5
t_g, t_i	-0.5
t_g,U_V	1.0

6.2.3.7 Uncertainty in Exposure Periods

The proposed distributions describing the variability of time allocation factors for individuals in the screening group rests on several assumptions which introduce uncertainty into the proposed distributions:

(1) The screening group consists of resident farmers. Data from Tsang and Klepeis (1996) on "Time Spent Gardening or Other Activities Working With Soil," for the subset of individuals who engage in these activities, was assumed to be representative of this group. Data for time indoors and outdoors at a residence from this study were not available for this subset of the sample subjects. Exposure periods for the latter two parameters therefore include non-gardeners, and may overestimate the values for the screening group. Because gardening time represents a relatively small proportion of total time, the extent of overestimation would appear to be small.

(2) The majority of reported time allocation values reflect daily values rather than annual average values. The autocorrelation of daily values for individuals is required to estimate annual averages. This function is unknown, however bounding and intermediate approximations can be defined. Uncertainty in this function introduces considerable uncertainty in the variability of annual average time allocation over individual members of the screening group. The average value for this group does not depend on the assumed correlation.

(3) In two key studies, variability in time allocation is only characterized by a standard deviation. The underlying distributions were assumed to follow a beta distribution defined by the reported mean and standard deviation, and by absolute limiting values of 0 and 365.25 days/year. These limits represent theoretical bounds, and the effective range of the fitted distributions are smaller than the theoretical ranges in all cases.

6.2.3.8 Alternative Exposure Period Values

The exposure period parameters are behavioral parameters. Alternative values could be proposed by defining a site-specific critical group, as discussed in NUREG/CR-1549. If this screening group does not grow produce, gardening time (along with ingestion rates of domestic produce, cultivated area, and irrigation rate) for this group would be 0.

6.2.4 Indoor Shielding Factor, SFI (Behavioral)

6.2.4.1 Description of SFI

The indoor shielding factor, SFI, as defined for NUREG/CR-5512, Vol. 1, is a measure of the attenuation of gamma radiation by structural materials such as walls, floors, foundations, and support structures in buildings, and is defined as the ratio of equivalent dose behind the shield to that in front of the shield. The model uses a single, constant value for all radionuclides, and for all structural materials. SFI is classified as a behavioral parameter because its value depends on the type of construction of the residence.

6.2.4.2 Use of SFI in Modeling

SFI is directly related to dose. For a given concentration of a given radionuclide in soil, external dose is proportional to SFI (i.e., the higher the value for SFI, the higher the total annual dose).

This parameter is used for calculating external dose from exposure to radionuclides in soils, DEXRi, (mrem for a year of residential scenario) as described by the following (Equation 5.69, p. 5.53 in NUREG/CR-5512, Vol. 1):

$$\begin{aligned} DEXR_i = & \left[24\left(t_g/t_{tg}\right) SFO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\left\{A_{stj},\ t_{tg}\right\} DFER_j\right] \\ & + \left[24\left(t_x/t_{tr}\right) SFO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\left\{A_{stj},\ t_{tr}\right\} DFER_j\right] \\ & + \left[24\left(t_i/t_{tr}\right) SFO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\left\{A_{stj},\ t_{tr}\right\} DFER_j\right] \end{aligned} \quad (6.15)$$

where $DFER_j$ is the external dose rate factor for radionuclide j for exposure to contamination uniformly distributed in the top 15 cm of residential soil (mrem/h per pCi/g); A_{stj} is the concentration factor for radionuclide j in soil at the beginning of the current annual exposure period per initial unit concentration of parent radionuclide i in soil at time of site release (pCi/g per pCi/g); C_{si} is the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil); SFI and SFO are shielding factors by which external dose rate is reduced during periods of indoor residence and outdoor residence, including gardening; J_i is the number of explicit members of the decay chain for parent radionuclide i; $S\{A_{stj},t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); $S\{A_{stj},t_{tg}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); t_g, t_i, and t_x are times in the one-year exposure period that the individual spends gardening, indoors, and outdoors (excluding gardening); t_{tr} is the total time in the residential exposure period (d); and 24 is a unit conversion factor (h/d). The same shielding factor is used for all radionuclides and is not dependent on the energy of the gamma radiation.

6.2.4.3 Information Reviewed to Define SFI

The value of 0.33 for SFI was adopted as the default value in NUREG/CR-5512, Vol. 1, and is based on information derived from studies on deposition of radioactive material from atmospheric plumes (Alrich 1978; Kocher 1978; Jensen 1985). The radiation sources considered in these models are fallout radioactivity deposited on roofs, outer walls, and ground surfaces, and may have different energy profiles than decommissioned sites. Although these models can be used to approximate shielding factors for contaminants deposited around and on buildings, they do not account for contaminants under structures, as required in DandD dose modeling. The RESRAD value for this parameter is 0.7.

References cited in NUREG/CR-5512, Vol. 1, and more recent publications on radiation shielding were reviewed to determine if information was available to estimate shielding factors for structures or buildings that were constructed or placed on contaminated land. (Jensen 1985) estimated shielding factors for a number of single-family and multistory houses using the computer model, DEPSHIELD. Leung (1992) calculated shielding factors for concrete and glass based on equivalent dose build-up factors in materials, and the shielding factors were used for estimating the protection against radioactive plumes. Graf and Bayer (1991) performed shielding calculations for 12 building types and compared the calculated factors with shielding factors derived from fallout measurements.

Shielding factors can be estimated for structures built or placed on contaminated soil using MicroShield 4.20®. The model simulates radiation levels inside a structure from external contamination beneath or adjacent to the structure for a wide range of structural materials and, therefore, would approximate the scenario conditions. The shielding factor is determined from the following:

$$SFI = e^{-\mu x}$$

where μ is the attenuation coefficient for the structural material (e.g., wood, concrete, gypsum) and x is the thickness of the material. μ varies with energy of the incident gamma radiation and the type and density of the material. Other factors, such as source geometry and buildup (i.e., scattering of radiation to the detector), are included in MicroShield 4.20®. Attenuation coefficients, buildup factors, and buildup factor coefficients are available from a library of reference data. The spatial distribution of contaminants in soils, energy range of gamma radiation, and physical characteristics and compositions of shielding materials are input parameters for MicroShield 4.20®.

6.2.4.4 Determination of PDF for SFI

Estimates of shielding factors were based on the attenuation of external gamma radiation in a wood frame building with wood siding and either a wood or concrete floor. A wood frame structure assembled from common building materials was selected for these calculations because this type of structure would not overestimate the shielding provided by the residence. Other wall types (brick, cinder block) would be expected to provide somewhat greater shielding.

6.2.4.4.1 Description of Structure

The structure used in this model is a single-story wood frame building (1000 ft^2) with a wood or concrete floor. The construction and materials are based on current standard practice (Marks' Standard Handbook for Mechanical Engineers) The walls consist of parallel 2" × 6" studs spaced 16" apart with gypsum wallboard (1/2" thick) on the internal surface of the wall and external sheathing covered with cedar siding on the outside surface. Fiberglass insulation fills the void volume between the gypsum wallboard and external sheathing. The wood floor is constructed of 1" thick plywood sheathing over parallel 2" × 8" floor joists spaced 16" apart, with fiberglass insulation placed beneath the plywood sheathing and between the parallel floor joists. The thickness of the concrete floor was varied at increments to estimate the effects of varying thicknesses of concrete on shielding. Gamma activity was calculated for a position at the center of the building at a height of 1 m above the contaminated soil surface as shown in Figure 6.8. The model simulates the level of radiation through the floor and walls of the building from an infinite source uniformly distributed over the top 15 cm of soil and neglects shielding by floor joists and studs. The input parameters for the model are identified in Table 6.15.

6.2.4.4.2 Calculation of Shielding Factors

MicroShield 4.20® calculates the effective dose equivalent, EDE (mSv/h) with, and without, shielding. The shielding factor, SFI, is calculated as the ratio of the EDE rate for gamma radiation at the center of the structure, EDE_S, to the EDE rate for gamma radiation expected if no shielding were present, EDE_U:

$$SFI = EDE_S/EDE_U$$

EDE_S is the sum of the attenuated EDE rates attributed to gamma radiation shielding by the floor, EDE_F, and by the walls, EDE_W:

$$EDE_S = EDE_F + EDE_W$$

The energy range used in MicroShield 4.20® represents the range of energies for radionuclides identified in NUREG/CR-5512, Vol. 1. Shielding factors were calculated for discrete gamma energies for wood and concrete floors, and the results are tabulated in Table 6.16 and presented in Figure 6.9. The range of gamma energies used in the model represents variations across radionuclides and not uncertainty in the energies for single isotopes. The information in Table 6.16 can be used for estimating shielding factors for specific radionuclides based on their gamma energy spectrum.

6.2.4.4.3 Distribution for SFI

The distribution for SFI describes the variability in shielding factors over individual members of the screening group, which consists of resident farmers, and depends on the structural and material properties of the residence. Alternative assumptions about the residence corresponding to a range of current residential construction practices were used to define the variability of SFI over members of the screening group. The cumulative probability distribution in Figure 6.10 was derived by conservatively selecting the maximum shielding factor for each of the four floor types in Table 6.16 and assigning equal probabilities to each floor type.

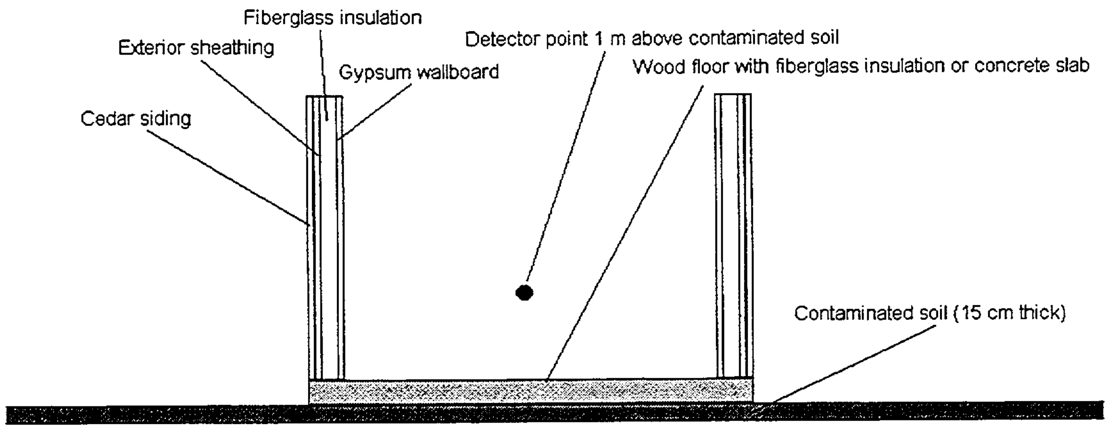

Figure 6.8 Cross section of building for calculating gamma activity from contaminants in soil

Table 6.15 Input parameters for MicroShield 4.20®

Factor	Type or value	Remarks
Wood floor	1" plywood (0.6 g/cm^3)	mobile homes, or manufactured houses, have no concrete slab foundation
Concrete floor	3.5", 5.25", & 7" thick	3.5" is the minimum thickness for concrete slab allowed by the uniform building code
Surface area of floor	1000 square feet	
Density of concrete	2.309 g/cm^3	Marks' Standard Handbook for Mechanical Engineers
Windows, %	20% of total wall area	" "
Window thickness	3 mm, density 2.58 g/cm^3	" "
Wall, gypsum	½" sheet rock, 2.025 g/cm^3	" "
Wall, glass fiber	density 2 g/cm^3	" "
Wall, sheathing	1 cm thick, density 0.35 g/cm^3	" "
Wall, external	½" cedar, density 0.35 g/cm^3	" "
Contaminated soil	Infinite slab, 15 cm thick	Assumed thickness of contaminated soil
Gamma activity	0.037 d/sec/cm^3	d/sec/cm^3 = pCi/g
Energy range	0.03 to 2.25 MeV	Energy range established from: ^{140}Ba (0.0299 MeV); ^{156}Eu (2.27 MeV)

Table 6.16 Shielding factor as a function of gamma energy

Energy (MeV)	Wood (pier & beam)	Shielding factor		
		3.5" concrete	5.25" concrete	7" concrete
0.03	0.0967	0.00810	0.00810	0.00810
0.06	0.608	0.241	0.241	0.241
0.08	0.722	0.380	0.377	0.377
0.10	0.767	0.438	0.432	0.431
0.20	0.807	0.507	0.486	0.479
0.40	0.814	0.517	0.478	0.462
0.80	0.824	0.489	0.425	0.394

Table 6.16 Shielding factor as a function of gamma energy (continued)

Energy (MeV)	Wood (pier & beam)	Shielding factor		
		3.5" concrete	5.25" concrete	7" concrete
1.5	0.845	0.491	0.405	0.359
2.25	0.857	0.514	0.422	0.369

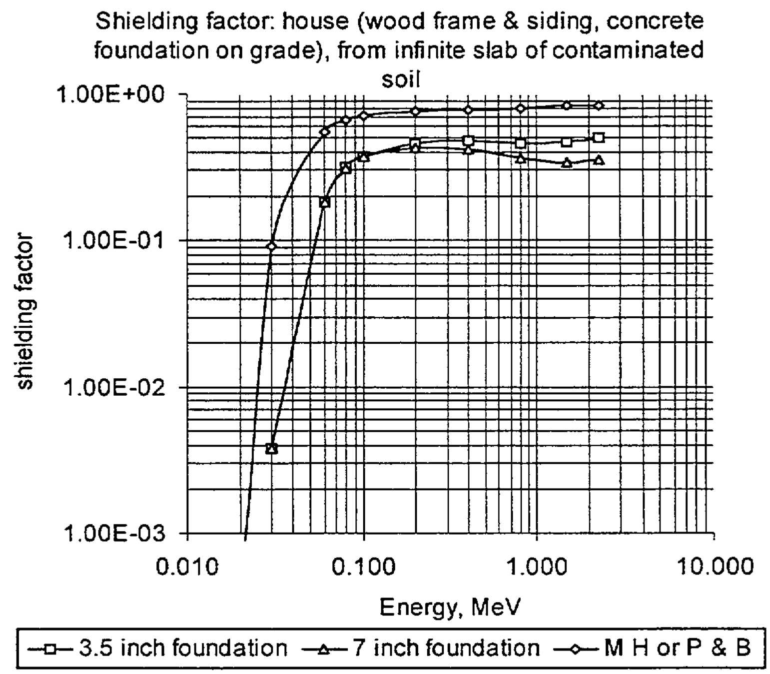

Figure 6.9 Shielding factor as a function of energy for three different floors in building

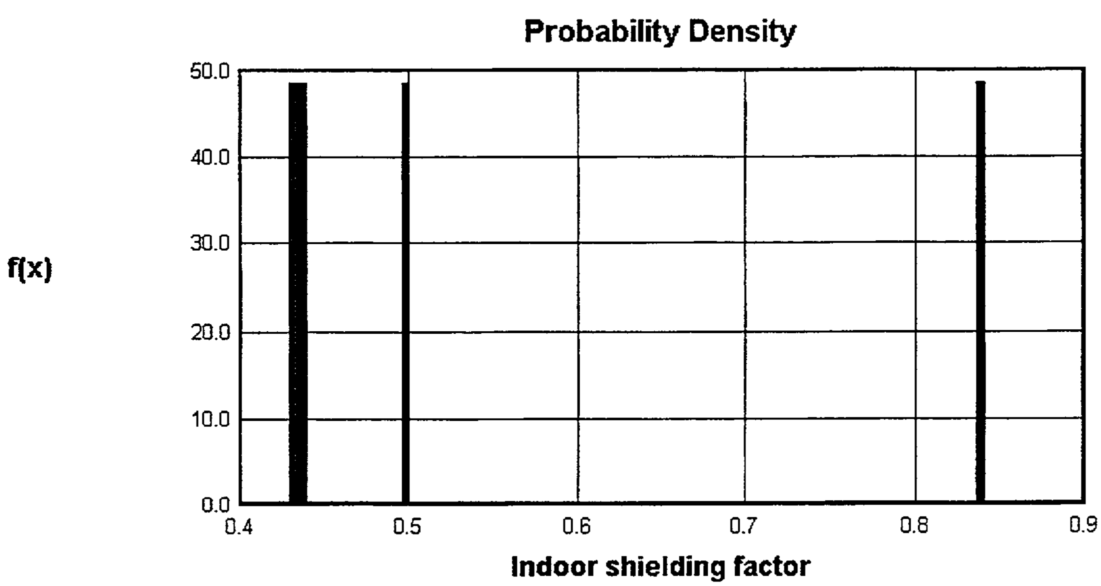

Figure 6.10 Cumulative probability distribution for indoor shielding factor, SFI

6.2.4.5 Uncertainty in SFI

The proposed distribution describing the variability in the shielding factor over members of the screening group of resident farmers rests on several assumptions:

- A wood frame house was used in the model. This type of construction is typical of current practices, although other assumptions (e.g., brick) are also consistent with screening group assumptions.
- Other structural materials that may contribute to shielding, such as steel reinforcement, wall studs, and floor joists, were not included in the model calculations.

6.2.4.6 Variability Across Sites

This parameter is expected to vary from site to site depending on the type and construction of buildings or structures. Alternative distributions for this parameter could be proposed based on site-specific information about the source energy profile.

6.2.5 Soil Ingestion Transfer Rate for the Residential Scenario, GR (g/d) (Behavioral)

6.2.5.1 Parameter Description

The soil ingestion transfer rate, GR, is a behavioral parameter that represents the average daily intake of soil by the AMSG for the residential scenario. GR is the quantity of soil ingested per day, averaged over the one year duration of the scenario, by inadvertent transfer from hands or other objects that have been in contact with a contaminated surface, such as food, cigarettes, etc., into the mouth.

The default value for this parameter defined in Volume 1, is 5×10^{-2} g/d. This value was defined based on published reports on soil ingestion studies. Nine references are listed for this data (National Academy of Sciences, 1980; Lepow, 1975; Hawley, 1985; Binder et al., 1986; Calabrese, 1989; Davis et al., 1990; Calabrese, 1990; Van Wijnen et al., 1990; EPA, 1991). Six of these studies focused on soil ingestion by children. The screening group consists of adult resident farmers, and soil ingestion rates for children are not representative of this group. The range of reported ingestion rates for the adult-workers/ members of the public is 5×10^{-5} to 1×10^{-1} g/d.

6.2.5.2 Use of Parameter in Modeling

As detailed below, the dose from the ingestion pathway is directly proportional to GR. Overall dose will be sensitive to GR for those sources with significant contributions of ingestion dose to total dose. The parameter GR is used to calculate CEDE for internal ingestion dose, DSR_i, resulting from inadvertent ingestion of soil and contaminants on surfaces. The relationship between GR and internal dose due to ingestion is defined in NUREG/CR-5512, Vol. 1, p. 5.73 as:

$$DSR_i = GR\ C_{si} \sum_{(j=1,Ji)} DFG_j\ S\{A_{stj},\ t_{tr}\} \qquad (6.16)$$

where GR is effective transfer rate for ingestion of soil and dust transferred to the mouth (g/d), $S\{A_{stj}, t_{tr}\}$ is time-integral operator used to develop the radionuclide j concentration in soil, over the residential exposure period for a unit initial concentration of parent radionuclide i in soil at the time of site release (pCi*d/g per pCi/g for 1 year of residential scenario), J_i = number of explicit members of the decay chain for parent radionuclide i, C_{si} is concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil), and DFG_j is the ingestion CEDE factor for radionuclide j (mrem per pCi ingested). The resulting internal dose is directly proportional to the soil ingestion rate.

6.2.5.3 Review of Additional Information to Define PDF for GR

A literature review was conducted to define a distribution for GR describing the variability in ingestion rate among members of the screening group. The average value of this distribution defines the ingestion rate for the AMSG.

In general, soil ingestion is the inadvertent oral intake of soil through a process whereby soil-contaminated objects (hands, cigarettes, food, etc.) are placed in the mouth. The average value for the parameter GR represents the annual average quantity of soil ingested per day by the AMSG, and the distribution of this parameter describes the variability in annual ingestion rate among individuals in the screening group. Most of the published measurements of soil ingestion found in the literature review pertain to children. The screening group is defined as adult resident farmers, and the soil ingestion rates of children are not representative of this group.

Volume 1 summarizes reported soil ingestion rates published prior to 1992. These estimates were derived from limited studies on soil ingestion in adults, and postulates about mouthing behavior. Additional information was reviewed to determine if other data or approaches, preferably more recent than those cited in Volume 1, were available to provide a defensible basis for constructing a PDF for GR for use in the analysis. Additional information reviewed included the EPA *Exposures Factors Handbook* (1996), and the references cited therein, LaCoy (1987), Calabrese et al. (1990), Gephart et al. (1994), and Stanek et al. (1997).

Soil ingestion rates in adults have been estimated by: 1) analysis of selected tracer elements in human diets and comparing the dietary intake of these elements with tracer elements found in feces and urine of adult volunteers; and 2) observation of individual behavior pattern in adults under a range of environmental conditions and activities. Numerous studies on soil ingestion have been conducted using a tracer method (BTM) developed by Binder et al. (1986) (Stanek and Calabrese, 1995; Sedman and Mahmood, 1994; Calabrese and Stanek, 1995; Stanek et al., 1997; and others).

Table 6.17, and the following discussion, summarizes published studies of soil ingestion by adults.

Hawley (1985) reported soil ingestion rates of 4.8×10^{-1} g/d for outdoor activities and 5.6×10^{-4} to 1.1×10^{-1} g/d for indoor activities. The highest ingestion rates occurred for outdoor physical activities (e.g., yard work, gardening, etc). The ingestion rates for indoor activities ranged over two orders of magnitude and included typical activities such as occupying a typical living space and working in uncleaned areas (e.g., attic, utility room, garage). Based on an estimated duration for each activity, Hawley calculated an annual average soil ingestion rate of 6.1×10^{-2} g/d for an adult in a typical residential setting. Krablin (1989) estimated the soil ingestion rate in adults from urine arsenic epidemiological studies, mouthing behavior, and time activity patterns. He concluded from these studies that adults ingest 1×10^{-2} g of soil per day. Sheppard (1995) estimated the intake of soil from non-food sources in adults based on indoor and outdoor activities and exposure durations. Based on estimates of exposure duration of 300 h/y and a soil ingestion rate of 2×10^{-2} g/h for gardening activities, and an exposure duration of 5000 h/y and a soil ingestion rate of 3×10^{-5} g/h for indoor activities, he calculated an average daily soil ingestion rate of 2×10^{-2} g/d. Stanek (1995) reviewed previous work and presented revised estimates on soil ingestion in adults. Using data on four tracer elements, they calculated an average soil ingestion rate of 6.4×10^{-2} g/d.

Calabrese et al. (1990), Stanek and Calabrese (1995), and Stanek et al. (1997) estimated soil ingestion rates in adults based on mass-balance studies in which intake rates were estimated from concentrations of several trace elements in ingested foods and medicines, environmental dust and soil, and body excretions (feces and urine). These studies collected data over multiple one-week periods, during which each subject ingested a controlled quantity of soil from their environment. This mass, along with soil mass ingested with food, was subtracted from the estimated mass that was derived from measured tracer elements in feces and urine. Although these studies draw on very limited data, the results are very consistent with previous studies reported in the literature. Calabrese et al. (1990) concluded from his evaluation, however, that the tracers used in his study failed to demonstrate adequate detection limits for assessing soil ingestion in adults.

Using quantitative data on zirconium tracers from Calabrese et al. (1990), Gephart et al. (1994) estimated soil ingestion rates in adults. Their analysis indicated that a soil ingestion rate of $1 \times 10^{-3} - 1 \times 10^{-2}$ g/d is a very conservative estimate and recommended this range for purposes of risk assessments. Gephart et al. (1994) derived a distribution of adult soil ingestion by Monte-Carlo simulation, however this distribution represents the variability in estimated daily ingestion values. These daily estimates were obtained from daily measurements of tracer concentrations in food and waste products. As discussed below, this procedure requires assumptions which create significant experimental error in the estimated daily rates. Because of the large measurement error, and because the distribution for GR should describe variations in average annual ingestion rate among individuals in the screening group, rather than day-to-day variations in ingestion rate, the distribution presented in Gephart et al. (1994) is not appropriate for this analysis.

The study by Stanek et al. (1997) included a larger number of subjects than the 1995 study (10 adults as opposed to six) and incorporated methodological and interpretative improvements based on earlier studies. However, the experimental approach used by Stanek et al. (1997) relies on a number of idealizing assumptions of questionable validity. The resulting estimates of daily ingestion rate are highly uncertain, and are frequently less than 0. For example, they neglected any absorption or metabolism of tracer substances in their studies, and they assumed that the transit time of the tracers in the intestinal tract was constant and consistent for all subjects in the study. The calculated soil ingestion rates were predicated on the assumption that the ratio of tracer element-to-soil in the fecal sample

Table 6.17 Soil ingestion rates in adults

Reference	Soil ingestion rate (g/d)	Comments
Hawley, 1985	6.1×10^{-2}	Ingestion rates and time activity patterns
Calabrese, 1987	$1 \times 10^{-3} - 1 \times 10^{-1}$	Based on CDC estimates
Krablin, 1989	1×10^{-2}	Arsenic studies, mouthing behavior, time activity patterns
Gephart et al., 1994	$1 \times 10^{-3} - 1 \times 10^{-2}$	Estimate based on mass balance studies of soil ingestion in adults
Sheppard, 1995	2×10^{-2}	Intake of soil from non-food sources
Stanek and Calabrese, 1995	6.4×10^{-2}	Revised estimate based on the measurement of four tracer elements in adults
Stanek et al., 1997	1×10^{-2}	Mass balance studies on 10 adults over a period of 28 days

is identical to the ratio of tracer element-to-soil in the local environment of the subject. As a result, their attempts to distinguish contributions from soil and house dust yielded conflicting results.

6.2.5.4 Proposed Distribution for GR

Although there is very little empirical data representative of the screening group, the above studies provide a rough estimate of soil ingestion rates in adults. According to studies on soil ingestion published between 1975 and 1997, soil ingestion rates vary over a range of about 4 orders of magnitude. The variations observed in these studies have been attributed to a number of factors, including the level of loose contaminants in the local environment, the behavior of individuals in the studies, controls that are imposed, and the exposure time. Based on the data in Table 6.17, soil ingestion rates range from a minimum of 0 g/d to a maximum of 1×10^{-1} g/d with a likely ingestion rate of 5×10^{-2} g/d. In the absence of a reliable quantitative estimate of variability in long-term average rates among adult individuals, a triangular distribution for the parameter GR is recommended. Figure 6.11 shows the assigned cumulative distribution function, and Figure 6.12 shows the corresponding probability density function, using the minimum, maximum, and mode values cited above. The mean value of this distribution, representing the AMSG, is 5×10^{-2} g/d.

6.2.5.5 Parameter Uncertainty

The proposed distribution describing the variability in the soil ingestion rate among members of the screening group is based on several assumptions that contribute to uncertainty in the distribution:

- Empirical support for this parameter is very limited. The most recent measurements of soil ingestion in adults are subject to wide variability.
- Soil ingestion has been studied in adults in residential settings using selected trace elements. Several assumptions were made in these experimental measurements:

  (1) The specific elements selected as tracers for soil ingestion studies are not absorbed or retained in the digestive tract of the adult subjects or undergo any metabolic changes that would prevent excretion of the tracer elements.

  (2) Tracer elements in the body excretions originate exclusively from foods, medicines, and ingested soils. The amount ingested in foods and medicines is the same amount found in duplicate samples.

  (3) The quantity of soil ingested is obtained from the ratio of the quantity of tracer excreted to the concentration of tracer in soil, with the assumption that the tracer element concentration is constant and distributed uniformly in soil and dust.

6.2.5.6 Alternative Parameter Values

The default parameter value is representative of the average member of the screening group of adult resident farmers. Alternative, site-specific critical groups may lead to a revised value for this parameter.

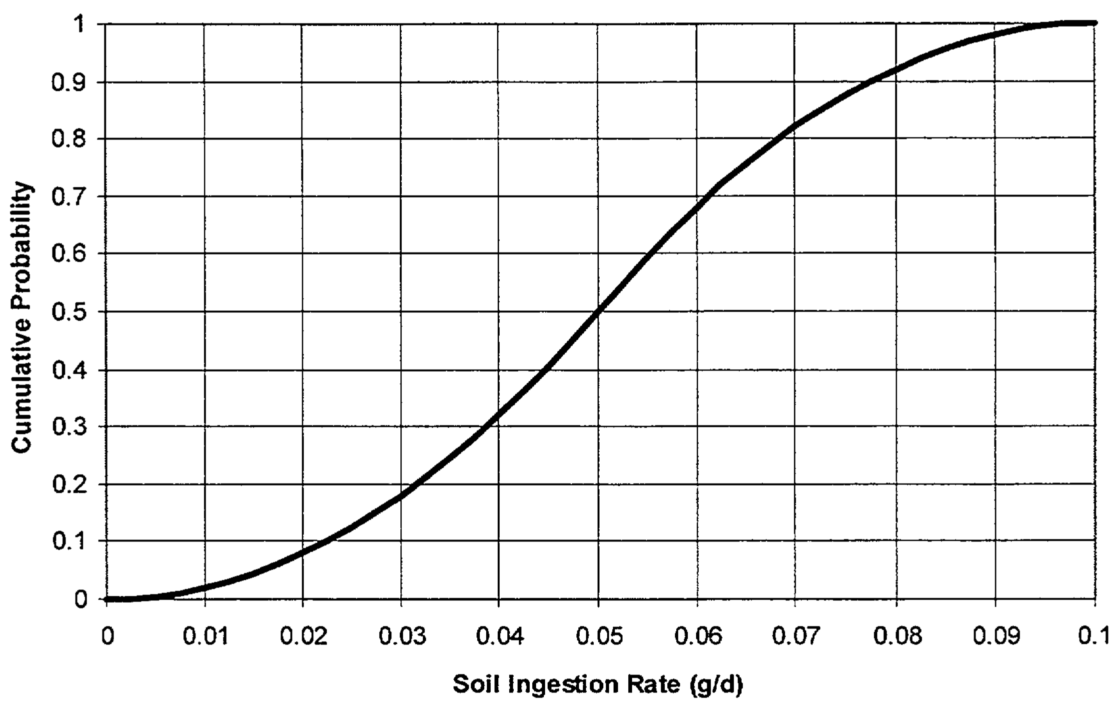

Figure 6.11 Cumulative probability function for GR

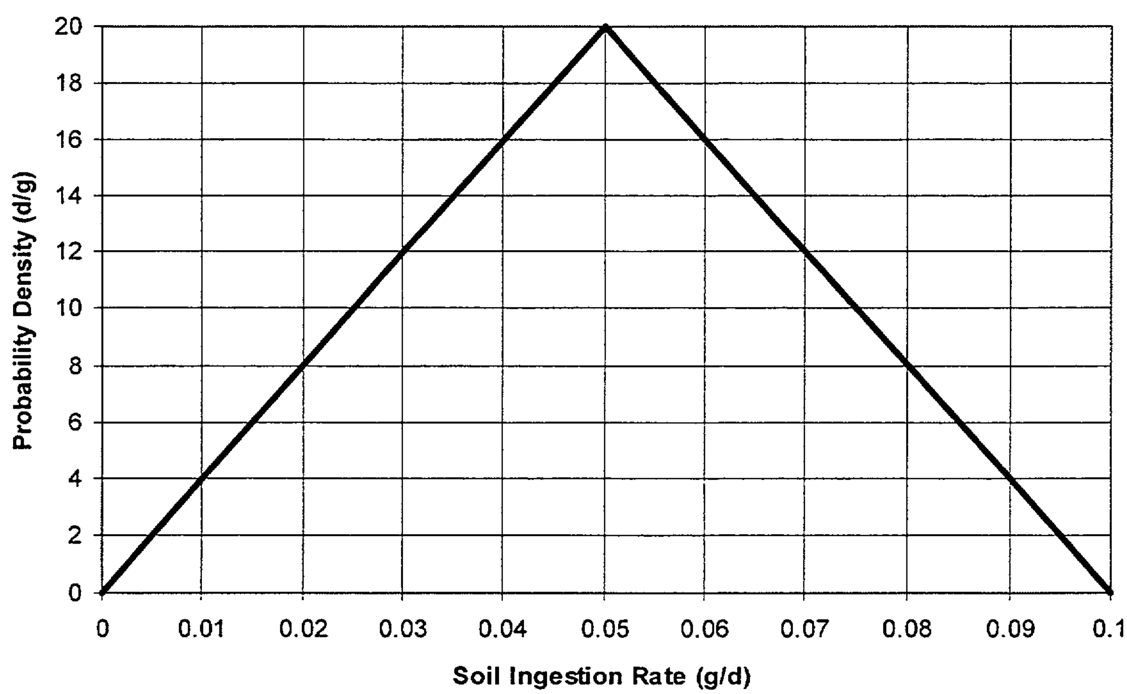

Figure 6.12 Probability density function for GR

6.2.6 Drinking Water Ingestion Rate, U_w (l/d) (Behavioral)

6.2.6.1 Description of U_W

Drinking water ingestion rate, U_w, is the daily average human consumption rate of groundwater from a well. The dose model uses a single, constant value.

6.2.6.2 Use of U_W in Modeling

Use of contaminated groundwater for human consumption increases the dose from radionuclides present in groundwater. The drinking water ingestion rate is used in calculating the dose due to consumption of contaminated groundwater and will depend to a large extent on the ages and dietary needs of individuals at the site. Therefore, U_w is considered a behavioral parameter.

This parameter is used in the irrigation and drinking water dose model for calculating the ingestion dose from contaminated water and may be used to calculate the volume in the aquifer. The drinking water ingestion factor, AF_{dj}, is determined from the drinking water ingestion rate from the following (Equation 5.75, p. 5.59 of NUREG/CR/5512, Vol. 1):

$$Af_{dj} = U_w \, DFG_j \, t_d \left(C_{wj}/C_{wj}\right) \qquad (6.17)$$

where U_w is the daily intake of drinking water (l/d), DFG_j is the ingestion CEDE factor for radionuclide j (mrem per pCi ingested), t_d is the duration of water intake period (d for 1 year of residential scenario), and C_{wj} is the average annual concentration of radionuclide j in groundwater.

6.2.6.3 Information Reviewed to Define a Distribution for U_w

The default value for this parameter, as defined in NUREG/CR-5512, Vol. 1, is 2 l/d. There was no justification or explanation provided for this value. The RESRAD value for the parameter is 1.4 l/d.

The 1977-1978 Nationwide Food Consumption Survey (NFCS) of the USDA collected information about food and beverage consumption from a random sample of the U.S. population (USDA, 1983). Survey results from 26,081 individuals were analyzed, and a statistical analysis of the water intake rates were reported (Ershow and Canter, 1989). Roseberry and Burmaster (1992) fit lognormal distributions to NFCS data and developed distributions for use in public health risk assessments.

The justification for applying these data to the screening group (i.e., adult males who garden and obtain drinking water from groundwater sources) is based on the assumption that the screening group would be represented by individuals in the group from 20 to 65 years of age. Although we do not have data specific to adult males or limited just to groups who garden, it is assumed that drinking water intake rates from these large populations is representative of the screening group.

6.2.6.4 Proposed Distribution for Uw

The distribution for drinking water ingestion was determined for adults (20 to 65 years) from data reported by Roseberry and Burmaster (1992). The intake rates for adults are lognormally distributed. The mean and standard deviation of the natural log (drinking water intake rate (l/d)) are 0.1152 and 0.489, respectively, for individuals in the age group from 20 to 65 years. The cumulative distribution for U_w is shown in Figure 6.13 along with the NUREG/CR-5512, Vol. 1, default and RESRAD values. The distribution applies to the screening group by assuming that water intake rates in adults 20 to 65 years old are representative of adult male consumption.

6.2.6.5 Uncertainty in U_W

The distribution for the drinking water ingestion rate was based on a survey of 11,731 adults that were selected randomly from the U.S. population. The individual survey data represents the average daily consumption of water over a three-day period. Results from individual participants in the survey could be influenced by activities of individuals during the three-day survey period and the season of the year. These factors, however, would be expected to balance since the three-day survey periods were spread over the entire year. Drinking water ingestion rates could be less in females than in males.

6.2.6.6 Alternative Values for U_W

This parameter would be expected to vary from site to site due to uncertainty in the activities, dietary habits, and ages of individuals at the site. If a site-specific critical group is defined, an alternative value may be appropriate. Other factors such as the quality of the groundwater could have an influence on the ingestion rate (e.g., use of bottled water for drinking).

The licensee may collect information on water quality at the site and evaluate alternatives for groundwater use based on economic factors. For example, the cost for digging an on-site well may be greater than the cost for

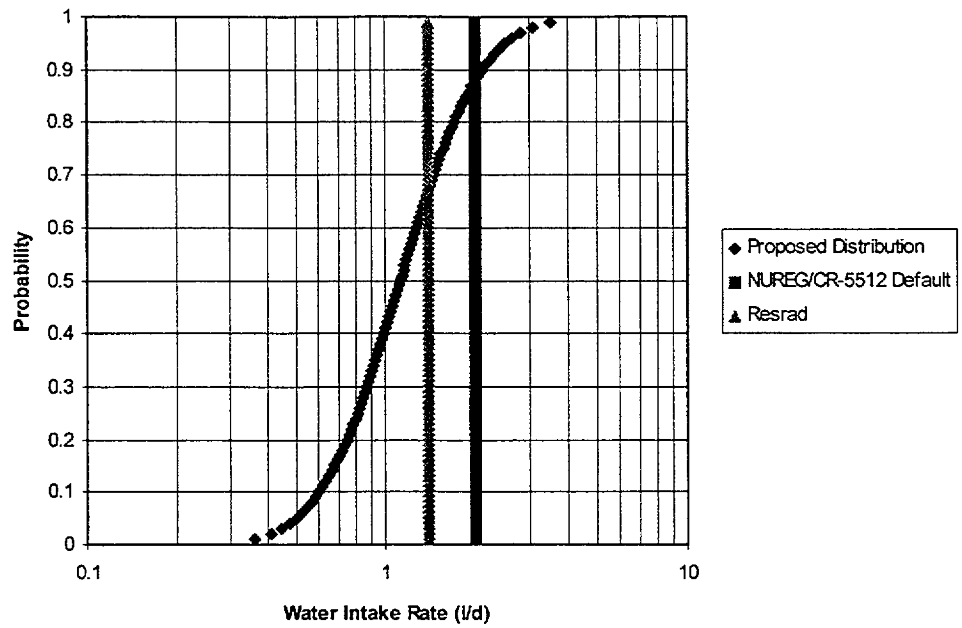

Figure 6.13 Cumulative distribution for drinking water ingestion rate (L/d)

connection to a municipal or a rural water system. Water quality may be very poor, requiring pretreatment of water suitable for drinking.

6.2.7 Irrigation Water Application Rate, IR ($L/m^2 \cdot d$) and Volume of Water Removed From the Aquifer for Irrigation Use, V_{irr} (L/d) - (Behavioral)

6.2.7.1 Description of IR and V_{irr}

The irrigation water application rate is the amount of water, from groundwater, applied on a daily basis per unit area of irrigated land. Parameter IR represents a long-term average rate of water application. The irrigation water application rate is used in the residential scenario to estimate the transfer of radionuclides from irrigation water to food crops. Use of contaminated water via irrigation systems deposits radionuclides on plant surfaces or directly on the soil, resulting in resuspension and plant uptake and transfer to edible parts of the plant. The value for this parameter is 2.08 L/m^2-d in NUREG/CR-5512, Vol. 1, based on an annual average irrigation rate of 76 cm/y, which was considered a representative value sufficient to produce most crops.

V_{irr} is the volume of groundwater removed from the aquifer used for irrigation. NUREG/CR-5512, Vol. 1, does not define a default value for V_{irr}. Instead, V_{irr} is determined from the irrigation rate, IR, and the area of land cultivated, A_r, by assuming that the area defined by A_r is irrigated from groundwater at the site. Since the volume of water for irrigation use is a function of other parameters, an independent probability distribution function is not defined for V_{irr}.

6.2.7.2 Use of IR and V_{irr} in Modeling

The irrigation water application rate, IR, is used in calculating the dose due to consumption of edible plants that are grown in land that is irrigated with contaminated groundwater and the consumption of beef, milk, eggs, and poultry products from animals that consume forage, hay, and grain crops that are grown on the irrigated land.

V_{irr} is important in estimating the transport of radionuclides from contaminated irrigation water to soil and to edible plant and animal products. V_{irr} is used to calculate the total water volume in the aquifer, along with the withdrawn water volume for domestic purposes. It is also used for deriving the fraction of pumped water that is applied to the surface layer.

The higher the irrigation water application rate, the higher will be the deposition rate of radionuclides to edible plants and soil, and consequently the higher the dose due to ingestion of contaminated plants by humans and domesticated livestock. The concentration of contaminants in animals will increase due to ingestion of plant material and soil, and therefore dose to humans will also increase with consumption of animal products (i.e., meat, milk, eggs).

6.2.7.2.1 Irrigation Water Application Rate, IR

The irrigation water application rate, IR, is used in nine different pathways in the residential scenario model for estimating the transfer of radionuclides from contaminated groundwater to edible foods. The equations for each of the nine pathways can be found in Section 5.4.1, Food Crops Contaminated by Irrigation Water, and Section 5.4.2, Animal Products Contaminated by Irrigation Water, in NUREG/CR-5512, Vol. 1, and are summarized in the following:

a) irrigation water-plant-human pathway (Equation 5.22, p. 5.27 of NUREG/CR-5512, Vol. 1)

$$R_{wvjg} = IR\ r_r\ T_v/Y_v\ \left[C_{wj}/C_{wi}\right] \qquad (6.18)$$

where R_{wvjg} is the average deposition rate of radionuclide to edible parts of plant v from application of irrigation water per unit average concentration of parent radionuclide i in water, IR is the average annual application rate of irrigation water, r_v is the fraction of initial deposition (in water) retained on the plant, T_v, is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant, Y_v is the yield of plant v, and C_{wj}, and C_{wi} are the average annual concentration of radionuclides j and i, respectively, in irrigation water over the current annual period.

b) irrigation water-soil-plant-human pathway (Equation 5.27, p. 5.30 of NUREG/CR-5512, Vol. 1)

$$R_{wsjg} = IR/P_s\ \left[C_{wj}/C_{wi}\right] \qquad (6.19)$$

where R_{wsjg} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the growing period for an average unit concentration of parent radionuclide i in water, and P_s is the areal soil density (kg/m^2).

c) irrigation water-forage-animal-human pathway. (Equation 5.37, p. 5.36 of NUREG/CR-5512, Vol. 1)

$$R_{wfjf} = IR\ r_f\ T_f/Y_f\ \left[C_{wj}/C_{wi}\right] \qquad (6.20)$$

where R_{wfjf} is the average deposition rate of parent radionuclide j to forage crop f from the application of irrigation water during the feeding period for an average unit concentration of parent radionuclide i in water, r_f is the fraction of initial deposition of radionuclides in water retained on the plant, T_f, is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant, and Y_f is the yield of forage crop f.

d) irrigation water-soil-forage-animal-human pathway (Equation 5.43, p. 5.40 of NUREG/CR-5512, Vol. 1)

$$R_{wsjf} = IR/P_s\ \left[C_{wj}/C_{wi}\right] \qquad (6.21)$$

where R_{wsjf} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the feeding period for an average unit concentration of parent radionuclide i in water.

e) irrigation water-stored hay-animal-human pathway. (Equation 5.48, p. 5.41 of NUREG/CR-5512, Vol. 1)

$$R_{whjg} = IR\ r_h\ T_h/Y_h\ \left[C_{wj}/C_{wi}\right] \qquad (6.22)$$

where R_{whjg} is the average deposition rate of radionuclide j to stored hay crop h from irrigation water application for an average unit concentration of parent radionuclide i in water, r_h is the fraction of initial deposition of radionuclides in water retained on plant h, T_h is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant, and Y_h is the yield of stored hay crop h.

f) irrigation water-soil-stored hay-animal-human pathway. (Equation 5.50, p. 5.43 of NUREG/CR-5512, Vol. 1)

$$R_{wsjg} = IR/P_s\ \left[C_{wj}/C_{wi}\right] \qquad (6.23)$$

where R_{wsjg} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the growing period for an average unit concentration of parent radionuclide i in water, and P_s is the areal soil density (kg/m^2).

g) irrigation water-stored grain-animal-human pathway. (Equation 5.53, p. 5.46 of NUREG/CR-5512, Vol. 1)

$$R_{wgjg} = IR\ r_g\ T_g/Y_g\ \left[C_{wj}/C_{wi}\right] \qquad (6.24)$$

where R_{wgjg} is the average deposition rate of radionuclide j to stored grain crop g from irrigation water application for an average unit concentration of parent radionuclide i in water, r_g is the fraction of initial deposition of radionuclides in water retained on grain plant g, T_g is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of grain plant g, and Y_g is the yield of stored grain crop g.

h) irrigation water-soil-stored grain-animal-human pathway (Equation 5.55, p. 5.47 of NUREG/CR-5512, Vol. 1)

$$R_{wsjg} = IR/P_s \left[C_{wj}/C_{wi}\right] \qquad (6.25)$$

where R_{wsjg} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the growing period for an average unit concentration of parent radionuclide i in water, and P_s is the areal soil density (kg/m^2).

I) irrigation water-soil-animal-human pathway (Equation 5.58, p. 5.48 of NUREG/CR-5512, Vol. 1)

$$R_{wsjf} = IR/P_s \left[C_{wj}/C_{wi}\right] \qquad (6.26)$$

where R_{wsjf} is the average deposition rate of radionuclide j to soil from irrigation water applied onto the soil during the feeding period for an average unit concentration of parent radionuclide i in water.

IR is also used to calculate V_{irr}, along with the land area under cultivation, A_r (m^2), as shown in the following equation:

$$V_{irr} = IR * A_r \qquad (6.27)$$

6.2.7.2.2 Volume of Water for Irrigation, V_{irr}

The total water volume in the aquifer remains constant during the simulation and is used as the dilution volume in determining the average annual contaminant concentration in groundwater. The total water volume is taken as the greater of the infiltration water volume or the sum of the water volumes used for irrigation, and domestic purposes.

Thus, the total volume of water is evaluated as (modified from Equation 5.88, p. 5.68 of NUREG/CR-5512, Vol. 1):

$$V_{Tr} = \text{greater of:} V_{lr} \text{ or } V_{irr} + V_{dr} \qquad (6.28)$$

where V_{Tr} is the total volume of water in the aquifer for dilution of activity over a one-year period, and V_{dr} is the annual volume of water for domestic water use.

The infiltration volume, V_{lr}, is the sum of the annual net infiltration due to precipitation and irrigation added to the surface layer of soil over the cultivated area. It is calculated (from Equation 5.87, p. 5.68, NUREG/CR-5512, Vol. 1) as follows:

$$V_{lr} = I\, A_r\, 1000 \cdot 1 \qquad (6.29)$$

where I is the infiltration rate, A_r is the area of land under cultivation, 1000 is the area unit conversion factor, and 1 is the annual one-year time period.

Irrigation volume represents recycling of contaminant activity from the aquifer (box 3 of the water use model) to the surface soil layer (box 1). Note that the irrigation rate is an annual average including non-growing periods.

The fraction of irrigation water applied to the surface layer, F_r, is calculated as follows:

$$F_r = \frac{V_{irr}}{V_{Tr}} \qquad (6.30)$$

During analysis and testing of the original methodology proposed in NUREG/CR-5512, it was found that the groundwater contamination models described in Volume 1 do not adequately account for possible natural discharge from the aquifer. The result was radionuclide build up in the aquifer box. A water balance model was added to the methodology to correct this problem. These changes are documented in Appendix A of NUREG/CR-5512, Vol. 2. Equations 6.28 and 6.30 reflect these changes.

V_{irr} (and F_r) represent the quantity of groundwater removed for irrigation in the water-use model. F_r is used to calculate the rate of change of the total activity of radionuclide j in box 1, (dC_{1j}/dt) as shown in the following (Equation 5.80, p. 5.65 of NUREG/CR-5512, Vol. 1):

$$dC_{1j}/dt = F_r w_r C_{3j} + \lambda_{rj} \; E_{(n=1,j-1)}\, d_{nj}\, C_{1n} - \left(\lambda_{rj} + L_{12j}\right) C_{1j} \qquad (6.31)$$

where w_r is the removal rate constant for pumping of water from box 3 (d^{-1}), C_{3j} is the total activity of radionuclide j in box 3 at time t, j is the index of the current chain-member position in the decay chain, n is the index of precursor chain members in the decay chain ($n<j$), C_{1n} is the total activity of the precursor radio-

nuclide n in box 1 at time t, λ_{rj} is the decay rate constant for decay of radionuclide j (d^{-1}), L_{12j} is the rate constant for movement of radionuclide j from box 1 to box 2 (d^{-1}), and d_{nj} is the fraction of transitions of radionuclide n that result in production of radionuclide j.

It would appear from Equations 6.30 and 6.31 that as V_{irr} increases, F_r increases and will tend to increase the concentration in Layer 1. However, if the modeled infiltration rate (and thus V_{Tr}) is high, contaminants will be removed (flushed) quickly from Layer 1 into the aquifer. Therefore, if total aquifer volume is determined by infiltration water volume (and thus is large compared to removal flows), a high rate of contaminant flushing to the aquifer will occur.

At the same time, if outflows from the aquifer (for irrigation, for instance) are larger than net infiltration, the groundwater water balance model (in Volume 2 of NUREG/CR-5512) allows for natural recharge to make up the deficit, maintaining reasonable aquifer contaminant concentration levels.

6.2.7.3 Information Reviewed to Define the Distribution for IR

The Farm and Ranch Irrigation Survey (1994) (USDC, 1994) provides the most recent and complete compilation of irrigation practices for farms and ranches in the United States. The document contains detailed information on irrigation, including farm size, total irrigated acres, and estimated quantities of water applied by irrigation for individual states and water resource areas over the continental United States. Table 6.18 shows the irrigated land area and the quantities of water used for irrigation in 27 states. These states accounted for 98.22% of total irrigated land area for farms and ranches from which $1,000 or more of agricultural products were produced or sold. These data provide an estimate of long-term (annual) average irrigation rates across a variety of soils, crops, water quality and availability. The data may include surface water as well as groundwater sources. As such, this data set provides an estimate of the irrigation rate for the screening group.

6.2.7.4 Proposed Distribution for IR

The data from Table 6.18 were binned and fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The data from regional land areas (states) were evenly weighted in developing the distribution. The best fit was obtained with a log normal distribution. Distribution parameters were $\mu = 0.67$, $\sigma = 0.87$, and $\epsilon = 0.32$.

Figure 6.14 depicts the probability density for the irrigation water application rate. This plot includes the corresponding data from Table 6.18 used to generate the fitted distribution. Figure 6.15 is the corresponding cumulative distribution function.

Table 6.18 Irrigation of farm and ranch land in the conterminous U.S. (USDC, 1994)

State	Irrigated area (acres)	Water applied (acre-feet/y)	Ave irrigation rate (acre-feet per acre)	Ave irrigation rate (L/m^2/day)
Arizona	752,019	3,310,159	4.40	3.67
Arkansas	2,853,929	3,196,019	1.12	0.93
California	7,245,487	22,474,499	3.10	2.59
Colorado	2,998,888	5,241,741	1.75	1.46
Florida	1,416,019	1,922,166	1.36	1.13
Georgia	619,536	325,009	0.52	0.44
Idaho	3,183,733	6,023,644	1.89	1.58
Illinois	271,725	168,518	0.62	0.52
Kansas	2,501,925	3,336,027	1.33	1.11
Louisiana	820,816	885,335	1.08	0.90
Michigan	305,481	165,843	0.54	0.45
Minnesota	326,781	185,034	0.57	0.47
Mississippi	646,761	684,643	1.06	0.88
Missouri	702,183	513,940	0.73	0.61
Montana	1,936,292	3,057,884	1.58	1.32
Nebraska	5,979,661	5,025,201	0.84	0.70

Table 6.18 Irrigation of farm and ranch land in the conterminous U.S. (USDC, 1994) (continued)

State	Irrigated area (acres)	Water applied (acre-feet/y)	Ave irrigation rate (acre-feet per acre)	Ave irrigation rate (L/m^2/day)
Nevada	519,507	1,138,138	2.19	1.83
New Mexico	685,695	1,630,390	2.38	1.98
North Dakota	157,426	138,954	0.88	0.74
Oklahoma	474,201	589,076	1.24	1.04
Oregon	1,587,152	2,946,868	1.86	1.55
South Dakota	304,454	302,997	1.00	0.83
Texas	5,100,979	7,605,827	1.49	1.24
Utah	1,085,083	2,412,250	2.22	1.86
Washington	1,434,800	3,125,619	2.18	1.82
Wisconsin	306,096	205,210	0.67	0.56
Wyoming	1,374,447	2,481,740	1.81	1.51

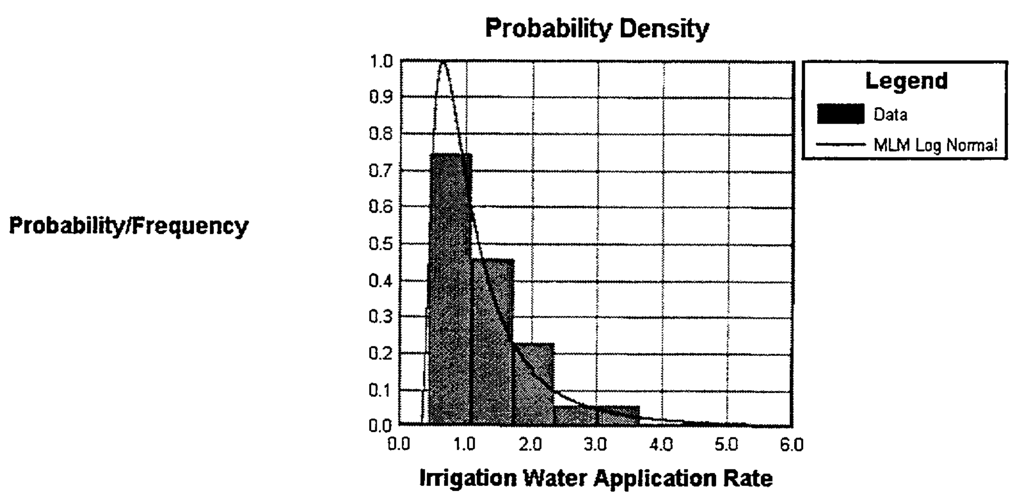

Figure 6.14 Calculated probability distribution for irrigation water application rate

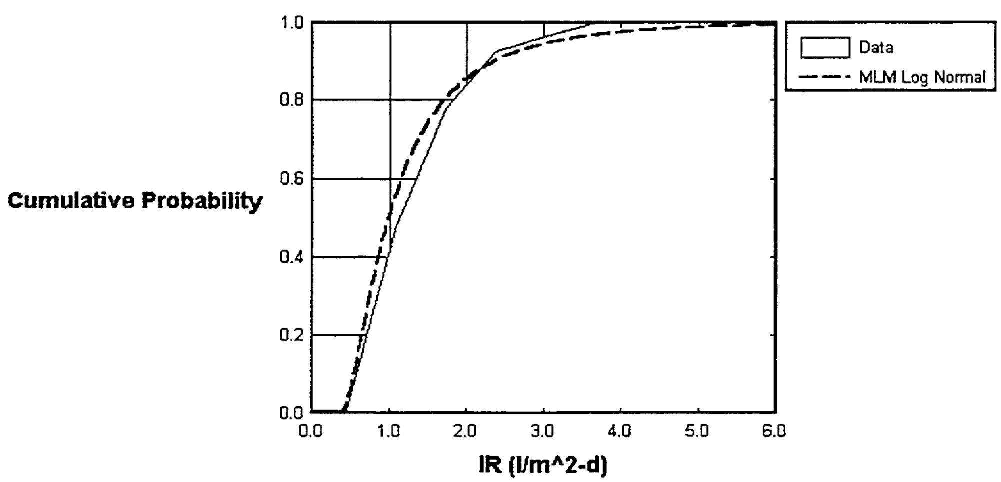

Figure 6.15 Cumulative distribution for irrigation water application rate, IR

6.2.7.5 Uncertainty in IR

The distribution for the irrigation water application rate, IR, was based on annual average irrigation rates throughout the United States. Since most farm and ranch land is irrigated only during the growing season, the data may underestimate the actual daily water irrigation rate for some areas of the country. The amount of water used for irrigation would be expected to vary from year to year, depending on the quantity of added moisture from rainfall. Abnormal levels of rainfall could bias the survey data and skew the proposed distribution.

V_{irr} is a dependent parameter derived from parameters IR and Ar.

6.2.7.6 Alternative Parameter Values

The irrigation rate parameter, IR, would be expected to vary from site to site depending on local climatic conditions, seasonal changes at the site, crops grown, soil hydraulic properties, groundwater quality and quantity, and location and availability of surface water that may also be used for irrigation. In the arid west, high values of irrigation would be expected, whereas, in portions of the northwest, eastern and southeastern states, and humid coastal areas, no irrigation may be needed. This can be seen in the data for arid states like Arizona (3.67 L/m^2-d) versus more humid states like Wisconsin (0.56 L/m^2-d) in Table 6.18.

Applicants may elect to collect data at the site in an attempt to support limits on IR. Limiting values may be supported due to regional precipitation and soil moisture levels (as well as evapotranspiration rates, infiltration rates, etc.), regional soil properties, and data that support alternative irrigation rates for forage crops or edible foods that may be cultivated due to local dietary patterns or land use patterns. IR may also be modified by defining a site-specific critical group different from resident farmers.

6.2.8 Volume of Water Removed from the Aquifer Per Year for Domestic Uses, V_{dr} (L) (Behavioral)

6.2.8.1 Description of V_{dr}

V_{dr} is the annual volume of groundwater removed from the aquifer for domestic uses. This parameter, along with the annual volume of water used for irrigation, V_{irr}, is used for determining aquifer volume. Of the total volume for all domestic uses (showers, washing, etc.), a portion of this domestic use is directly ingested as drinking water or in consumable products made from the drinking water source. Other pathways of contaminated water, such as direct immersion while showering, are not included in the exposure calculations.

In NUREG/CR-5512, Vol. 1, the default value for this parameter was set to 91,250 liters. No basis is provided for this value and the variability of this parameter is not discussed in Volume 1. V_{dr} is used in estimating the transport of radionuclides from contaminated groundwater to humans in the residential scenario. This parameter, along with the volume used for irrigation, establishes the total volume of the aquifer.

6.2.8.2 Use of V_{dr} Modeling

The total water volume in the aquifer (V_{Tr}) remains constant during the simulation and is used as the dilution volume in determining the annual average water concentration. The total water volume is the greater of the infiltration water volume or the sum of the water volumes used for irrigation, and domestic purposes.

The contribution to the ingestion dose from the use of contaminated groundwater, DWR_i, is evaluated for drinking water and ingestion of irrigated foods as follows (Equation 5.74, p. 5.58, NUREG/CR-5512, Vol. 1):

$$DWR_i = C_{si} \left[\sum_{j=1}^{j_i} A_{wtj} AF_{dj} + DIET \sum_{j=1}^{j_i} A_{wtj} AF_{wj} \right] \qquad (6.32)$$

where C_{si} is the initial concentration of radionuclide i in soil at the time of site release, A_{wtj} is the average concentration factor for radionuclide j in water over the current one-year exposure period per initial unit concentration of parent radionuclide i in soil at the time of site release, AF_{dj} is the CEDE factor for the ingestion of drinking water per unit average concentration of radionuclide j in water, and AF_{wj} is the CEDE factor for radionuclide j per unit average concentration of radionuclide j in groundwater used for irrigation for the current one-year period.

The drinking water ingestion factor, AF_{dj}, is calculated (Equation 5.75, p. 5.59, NUREG/CR-5512, Vol. 1) as follows:

$$AF_{dj} = U_w \, DFG_j \, t_d \left(C_{wj} / C_{wj} \right) \qquad (6.33)$$

where U_w is the daily intake of drinking water, DFG_j is the ingestion CEDE factor for radionuclide j, and t_d is the duration of water intake period (one year). The concentration ratio C_{wj}/C_{wj} equal to 1 indicates normalization to unit average concentration in water over the year of the residential scenario.

The fraction of irrigation water applied to the surface layer, F_r, is calculated as follows:

$$F_r = \frac{V_{irr}}{V_{Tr}} \qquad (6.34)$$

where V_{irr} is the volume of water used for irrigation during a one-year period (L/d), V_{ir} is the total volume of water in the aquifer, and V_{dr} is the volume of water used for domestic purposes during a one-year period (L/d).

6.2.8.3 Information Reviewed to Define the Distribution for V_{dr}

USGS water use data (USGS, 1990a and USGS, 1995b) provide estimates of domestic water use in the United States by state. Per capita water use estimates were provided for both self-supplied as well as public-supplied delivery systems. Table 6.19 provides the original per capita use of water, by state, from self-supplied water systems in gallons per day. These quantities are converted to total liters/year by assuming a single resident in the household (for consistency with all other parameters in the residential scenario) and 365.25 days per year.

The 50 values for annual per capita domestic water use by state define the distribution for V_{dr}. Each value was assumed to be equally likely. The cumulative distribution for V_{dr}, based on the data in Table 6.19, is shown in Figure 6.16.

6.2.8.4 Uncertainty in V_{dr}

The values in Table 6.19 are based on estimates that depend on population estimates, reported meter readings or other self-supplied means to measure water use, and on the definition of domestic use. Population estimates can be a significant source of uncertainty when considering transient and non-resident users and may also depend on whether the approach used for estimation is consistent with the approach used for determining water use. Reported domestic water use may represent different uses and sources depending on the distribution and metering system and on non-domestic use. It is assumed that uncertainty in the reporting of total annual domestic water use is small relative to regional variability in actual use.

The domestic water use figures given in Table 6.19 include water used for household purposes such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, car washing, and watering lawns and gardens. Depending on the local climate, generally the largest indoor uses are for toilet flushing and bathing. Outdoor uses can range from near zero in humid areas to 60% of total domestic use in arid areas. The data reported in Table 6.19 captures the variability of total domestic water use for the continental United States as well as Alaska and Hawaii.

Table 6.19 Estimated annual domestic water use for U.S. (L)

State	Per capita (gal/d)	Total use (L)	State	Per capita (gal/d)	Total use (L)
AL	75.1	103,824	MT	77.9	107,694
AK	39.7	54,884	NE	124.8	172,532
AZ	117.9	162,993	NV	119.8	165,620
AR	88.3	122,072	NH	65.0	89,861
CA	74.2	102,579	NJ	74.9	103,547
CO	75.9	104,930	NM	77.6	107,280
CT	75.0	103,685	NY	58.2	80,460
DE	79.2	109,492	NC	55.0	76,036
FL	175.1	242,071	ND	78.1	107,971
GA	75.2	103,962	OH	75.0	103,685
HI	188.8	261,011	OK	86.1	119,031
ID	199.8	276,218	OR	103.5	143,086
IL	84.1	116,266	PA	51.6	71,335
IN	76.0	105,068	RI	70.1	96,911
IA	66.6	92,073	SC	75.0	103,685

Table 6.19 Estimated annual domestic water use for U.S. (L) (continued)

State	Per capita (gal/d)	Total use (L)	State	Per capita (gal/d)	Total use (L)
KS	99.5	137,556	SD	62.5	86,404
KY	49.8	68,847	TN	65.0	89,861
LA	82.7	114,330	TX	108.2	149,583
ME	90.0	124,422	UT	85.9	118,754
MD	82.9	114,607	VT	71.9	99,400
MA	72.0	99,538	VA	75.0	103,685
MI	72.8	100,644	WA	115.5	159,675
MN	116.6	161,196	WV	80.0	110,598
MS	49.9	68,985	WI	60.7	83,916
MO	60.0	82,948	WY	75.0	103,685

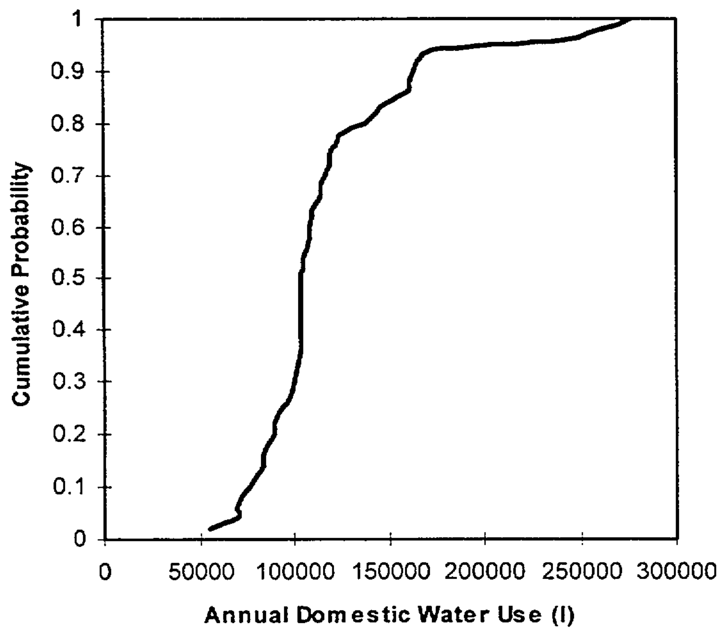

Figure 6.16 Cumulative distribution for annual domestic water use, V_{dr}

6.2.8.5 Alternative Values for V_{dr}

Licensees may attempt to define site specific values for the annual domestic water use for their site under the constraints of the residential farmer scenario. Those alternative values will need to be consistent with typical domestic water use in that region of the country, unless site characteristics, requirements, or use restrictions can be used to defend significant deviation from the representative state-specific values given in Table 6.19 and captured in the parameter distribution derived for V_{dr}.

Licensees may wish to defend new values for the total annual domestic water volume due to site specific considerations impacting water use. Some of those considerations may include regional climate (temperature and humidity), rainfall and its impact on water use for outdoor requirements, local water rates and water use restrictions and other conservation efforts that may not be reflected in typical reported values of water use, and such. The simplest approach for site specific analysis is to select, as an alternative to the default value, the value from Table 6.19 that corresponds to the location of the site. If a licensee defines a critical group different from resident farmers, the distribution for V_{dr} may be affected.

For the purpose of defining the distribution of total annual domestic water use, supporting data similar to that provided in this document could be used to develop such a distribution. More detailed USGS data for all U.S. counties are available.

6.2.9 Ingestion Rates of Home Produced Food, U_v (kg/y), U_a(kg/y) and U_f (kg/y)

6.2.9.1 Description of Ingestion Rates

The ingestion rates of homegrown produce, U_v (kg/y), and other home produced food, U_a (kg/y), and U_f (kg/y), as defined for Volume 1, represent the consumption rate of specific contaminated food. The dose model uses different constant values of U_v for "leafy" vegetables, "other" vegetables, fruits and grains, different constant values of U_a for beef, poultry, milk and eggs and a constant value of U_f for fish. U_v, U_a and U_f are behavioral parameters. Distributions therefore represent the diet of the average member of the screening group (i.e., residential and light farmers), and the default values are the average values of these distributions.

6.2.9.2 Use of Ingestion Rates in Modeling

Ingestion dose is linearly proportional to U_v, U_a and U_f. Therefore, the higher the values for U_v, U_a and U_f the higher the calculated dose. More specifically, the ingestion rates, U_v and U_a are used in the dose model to calculate the agricultural pathway transfer factors (PF). These factors are then used to calculate the annual dose from ingestion of home produced food. The mathematical expression to evaluate the PFs for unit average concentration of a parent radionuclide in soil is given in NUREG/CR-5512 (p. 5.51) as:

$$PF_{sij} = \Sigma_{(v=1,Nv)}\, U_v\, PPTF_{vsij} + \Sigma_{(a=1,Na)}\, U_a\, PPTF_{asij} \tag{6.35}$$

where:

PF_{sij} = the agricultural pathway transfer factors for radionuclide j as a progeny of radionuclide i per unit initial concentration of parent radionuclide in soil (pCi ingested per pCi/g dry-weight soil for a year of residential scenario),

U_v = the ingestion rate for food crop type v by an individual (kg wet-weight/y),

$PPTF_{vsij}$ = the partial pathway transfer factor for food crop type v, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in soil (pCi y/kg dry-weight food per pCi/g dry-weight soil for a year of residential scenario),

U_a = the ingestion rate of animal product type a by an individual (kg wet-weight/y),

$PPTF_{asij}$ = the partial pathway transfer factor for animal product type a, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in soil (pCi y/kg wet-weight food per pCi/g dry-weight soil for a year of residential scenario),

N_a = the number of animal products considered in the diet, and

N_v = the number of food crops considered in the diet.

The mathematical expression to evaluate the PFs for unit average concentration of a parent radionuclide in irrigation water is given in NUREG/CR-5512 (p. 5.52) as:

$$PF_{wij} = \Sigma_{(v=1,Nv)}\, U_v\, PPTF_{vwij} + \Sigma_{(a=1,Na)}\, U_a\, PPTF_{awij} \tag{6.36}$$

where:

PF_{wij} = the agricultural pathway transfer factor for radionuclide j as a progeny of radionuclide i per unit initial concentration of parent radionuclide in irrigation water (pCi ingested per pCi/L water for a year of residential scenario),

U_v = the ingestion rate for food crop type v by an individual (kg wet-weight/y),

$PPTF_{vwij}$ = the partial pathway transfer factor for food crop type v, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in water (pCi y/kg wet-weight food per pCi/L water for a year of residential scenario),

U_a = the ingestion rate of animal product type a by an individual (kg wet-weight/y),

$PPTF_{awij}$ = the partial pathway transfer factor for animal product type a, radionuclide j as a progeny of radionuclide i, for unit average concentration of parent radionuclide i in irrigation water (pCi y/kg wet-weight food per pCi/L water for a year of residential scenario),

N_a = the number of animal products considered in the diet, and

N_v = the number of food crops considered in the diet.

The ingestion rate of fish, U_f, is used in calculating the aquatic food ingestion factor (AF). AF is then used to calculate the annual dose from ingestion of aquatic foods. The mathematical expression for AF is given in NUREG/CR-5512, Vol. 1 (p. 5.60), as:

$$AF_{fj} = U_f\, t_f\, DFG_j\, BA_{jf}\, (C_{wj}/C_{wj})/365.25 \qquad (6.37)$$

where:

AF_{fj} = the aquatic pathway transfer factor for radionuclide j as a progeny of radionuclide i, per unit average concentration of radionuclide j in surface water (mrem per pCi/L for a year of the residential scenario),

U_f = the ingestion rate of aquatic foods produced in contaminated surface water,

t_f = the duration of fish consumption in days,

DFG_j = the ingestion CEDE factor for radionuclide j (mrem pr pCi ingested),

Ba_{jf} = the bioaccumulation factor for radionuclide j in aquatic foods, and

C_{wj} = the average annual concentration of radionuclide j in water (pCi/L).

U_v and U_a are also used to determine the area of land cultivated, A_r. Section 5.4.1.2 provides a detailed description of the relationships among ingestion rates, crop yields, and the cultivated area.

6.2.9.3 Information Reviewed to Define Distributions for U_v, U_a, and U_f

The values used for U_v and U_a in NUREG/CR-5512, Vol. 1, are based on food ingestion rates found in the 1977–78 Nationwide Food Consumption Survey (USDA, 1983). The specific values are derived from mean values compiled by Higley and Strenge (1988) and Pao et al. (1985). These values are based on consumption data that represent all food sources and not just home grown food. The dose calculation described in Volume 1 uses a single parameter (DIET) to describe the fraction of homegrown food in each food category. This assumption requires, for example, that the fraction of domestically-produced beef in the diet equals the fraction of domestically produced leafy vegetables. This assumption is unlikely to be satisfied in general, and is not representative of the screening group. In this analysis, ingestion rates of homegrown food are estimated separately for each of the food product categories. The DIET parameter is therefore unneeded (see Section 6.2.1). This approach allows consumption patterns to be more accurately represented. In addition, redefining these parameters in this manner makes them consistent with the definition of U_f.

The default value used in NUREG/CR-5512, Vol. 1, for U_f was based on summary data presented by Rupp et al. (1980). The regional percentiles reported in Rupp et al. are based on the entire population, including those individuals who eat no fish, which is not representative of the screening group. To try to compensate for this inaccuracy, (i.e., Rupp et al. reported that over 85% of the population eat no freshwater fish), the value for the highest regional rate reported by Rupp et al. was used as the default value in NUREG/CR-5512, Vol. 1. In the dose calculations, U_f is not scaled by the DIET parameter, which implies that it represents the consumption of domestically-produced fish.

Table 6.20 displays the default values of ingestion rates for the eight food groups defined in NUREG/CR-5512, Vol. 1.

Table 6.20 NUREG/CR-5512 U_v, U_a and U_f default values

Food type	Consumption rate
Leafy vegetables (U_v)	11(kg/y)
Other vegetables (U_v)	51 (kg/y)
Fruit (U_v)	46 (kg/y)
Grain (U_v)	69 (kg/y)
Beef (U_a)	59 (kg/y)
Poultry (U_a)	9 (kg/y)
Milk (U_a)	100(kg/y)
Eggs (U_a)	10 (kg/y)
Fish (U_f)	10 (kg/y)

The most recent Nationwide Food Consumption Survey (USDA, 1993) was conducted in 1987–88 and is more reflective of long-term nationwide consumption trends compared to the 1977–78 survey data. Like the earlier survey, the individual survey data could not be used directly to measure consumption of home produced food because the source of the food item is not identified. However, EPA reports intake rates for various home produced food items (EPA, 1996) based on an analytical method that combined data from both the household and individual 1987-88 USDA survey components. The data is reported in the form of cumulative probability distributions. This data set provides estimates of U_v and U_a defined as rates of consumption of food from *on-site production.*

The data provided by EPA (1996) represent consumption of home-produced food, however the reported values do not directly correspond to the dose model parameters in some respects. Some additional assumptions are required to estimate parameter distributions from the reported data. First, the eight food categories have to be related to the EPA data. EPA reports intake rates that directly match the "other" vegetables, fruits, beef, poultry, eggs and fish categories. For the "leafy" vegetables category, it is assumed that this category is equivalent to EPA's "exposed" vegetables category. EPA defines the "exposed" vegetables category as those vegetables that are grown above ground. Therefore, assuming that the category of "leafy" vegetables is equivalent to EPA's "exposed" vegetable category is reasonable given the fact that all leafy vegetables are grown above ground, although it may overestimate this category since not all vegetables that are grown above ground are leafy. For the food grain group it is assumed that the EPA data for corn is appropriate, given that corn is the only grain for which data was reported. This assumption is consistent with the study by McKone (1994), where he also used corn to represent the grain category. The milk category is assumed to be equivalent to the EPA's dairy category. Again, this assumption is reasonable but conservative because the reported rates include dairy products other than milk.

EPA notes that the survey data were taken during a week long period, and therefore may not be representative of annual behavior (i.e., more home grown foods are typically eaten in the summer). EPA generated seasonally adjusted intake distributions for all meats, vegetables and fruits by averaging the corresponding percentiles of each of the four seasonal intake distributions reported. This same approach was used to generate seasonally adjusted distributions for the eight food group categories required for the dose model.

EPA reports ingestion rates indexed to the actual body weights of the survey respondents in units of mass ingested per time per respondent body weight. Although EPA does not recommend converting the intake rates into average ingestion rates of mass/time by multiplying by a single average body weight, they do indicate that if this is done, a weight of 60 kg should be used because the total survey population included children.

6.2.9.4 Proposed Distributions for U_v, U_a, and U_f

In order to use the EPA data to represent the average member of the screening group, the seasonally adjusted data were scaled by the percentile average of the ratio of the 20–39 age data to the total population data and then converted by multiplying by the body weight, 70 kg, of the average member of the screening group. This data adjustment assumes that the data scales linearly. EPA does not provide any information about whether or not this assumption is valid, but it is a reasonable approximation.

The homegrown food ingestion rate distributions reported by EPA are based on the amount of food "consumed" in an economic sense (i.e., food that has been brought into the house). EPA recommends converting these intake rates to reflect actual ingestion by decreasing the amounts by percent weight losses from preparing the foods. EPA provides percent weight losses for various meats, fruits and vegetables. Therefore, these losses were accounted for in deriving the distributions for U_v, U_a and U_f. However, losses were not reported for eggs and milk, so these losses were not accounted for in these two food categories.

Table 6.21 lists percentiles of the distributions for U_v, U_a and U_f for the members of the screening group, estimated from the values reported by the EPA as described above. Summary statistics are also listed, along with the equivalent values defined in Volume 1 (i.e., rates multiplied by the DIET parameter), and the 1995 total consumption rates, including both homegrown and purchased food (USDA, 1997a). Figures 6.17, 6.18, and 6.19 present the cumulative distribution functions for U_v, U_a and U_f, respectively. These cumulative distribution functions define the probability distribution functions for U_v, U_a and U_f.

Comparing the equivalent NUREG/CR-5512 default parameters (i.e., consumption rate default parameters multiplied by the default DIET parameter of 0.25) with the mean of the new distributions indicates that the mean of the new distributions are consistently higher than their 5512 equivalent, except for the grain category. However, given the differences in their derivations, the means and the Volume 1 default values are reasonably consistent. The Volume 1 default values typically fall between the upper and lower quantiles of the individual distributions. Poultry and egg consumption rates are notable exceptions: both Volume 1 default values are below their 0.01 quantile values. For both categories the ratio of the average homegrown consumption rate to the average total consumption rate is near 1, suggesting that domestic producers in these categories tend to derive most of their total consumption from domestic production. In this case the default Volume 1 DIET parameter value of 0.25 would be inappropriate for these categories.

6.2.9.5 Uncertainty in Ingestion Rates

The information collected in the Nationwide Food Consumption Survey as interpreted in EPA (1996) describes consumption rates for home-produced food items over a broad range of individuals. Rates were measured over a small time span, but these measurements were seasonally distributed. Estimating annual average ingestion rates for members of the screening

Table 6.21 Statistical characteristics of the distributions for U_v, U_a and U_f

Cumulative %	Leafy vegetables (kg/y)	Other vegetables (kg/y)	Fruits (kg/y)	Grain (kg/y)	Beef (kg/y)	Poultry (kg/y)	Milk (L/y)	Eggs (kg/y)	Fish (kg/y)
Ingestion rates of homegrown foods									
0.01	1.71(1)	2.23	1.93	1.41	2.42	3.85	6.59	2.80	1.85
0.05	1.04	4.15	3.64	2.22	7.03	4.18	6.86	4.50	1.92
0.10	2.40	5.95	5.08	3.22	8.20	5.94	7.67	5.30	2.84
0.25	5.90	11.27	9.48	4.83	13.26	9.57	58.63	8.23	3.68
0.50	11.68	26.64	20.48	8.20	28.79	19.85	148.56	12.36	7.77
0.75	24.58	55.57	45.36	15.80	48.41	38.22	294.81	21.35	16.14
0.90	46.27	77.07	125.96	31.78	76.75	50.83	554.94	35.90	39.08
0.95	66.03	145.57	190.05	44.01	105.71	58.52	721.00	47.35	79.05
0.99	135.52	301.49	460.84	84.78	220.06	72.81	1210.78	120.71	112.82
1.00	222.95	384.03	673.57	99.47	222.75	72.81	1210.78	120.71	852.06
Summary statistics									
Mean[1]	21	45	53	14	40	25	233	19	21
Equivalent 5512 value	2.8	13	12	17	15	2.3	25	2.5	10
1995 U.S. total ingestion rates	185(total)	185(total)	128	87	29	28.5	358	12	7
Ratio of homegrown mean to 1995 totals	(leafy + other)/total = 0.36	(leafy + other)/total = 0.36	0.41	0.17	1.4	0.89	0.65	1.6	2.9

[1] Estimated as average of 580 sample values

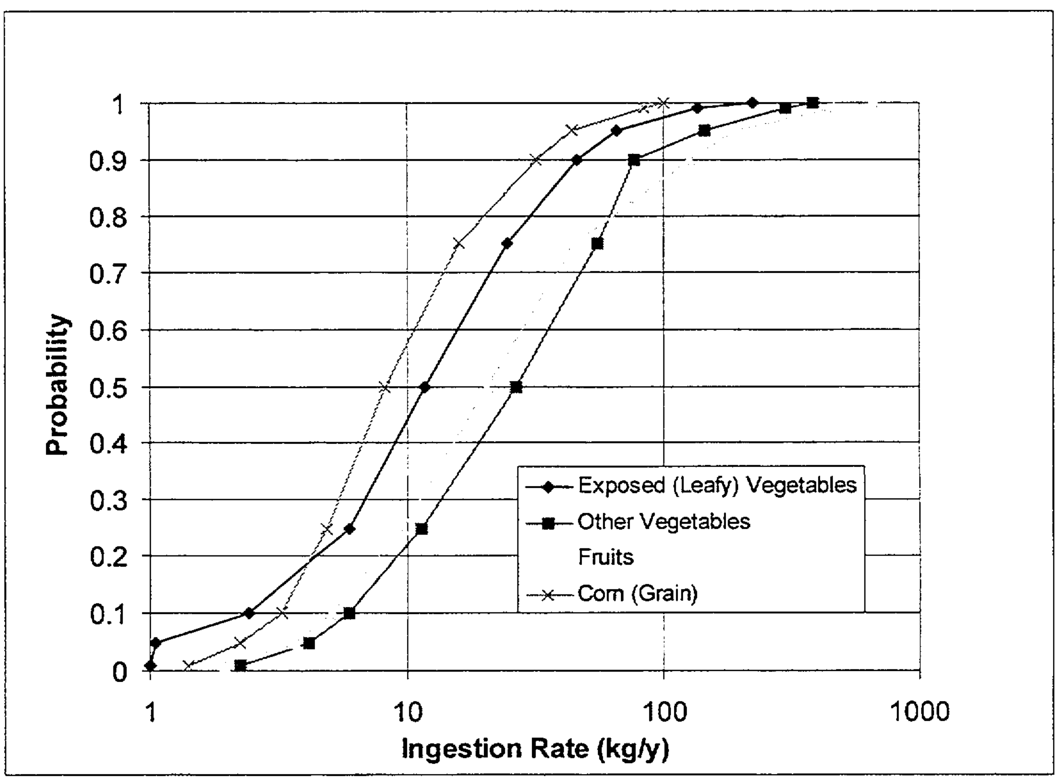

Figure 6.17 Cumulative distribution of U_v for exposed (leafy) vegetables, other vegetables, fruits, and corn (grain)

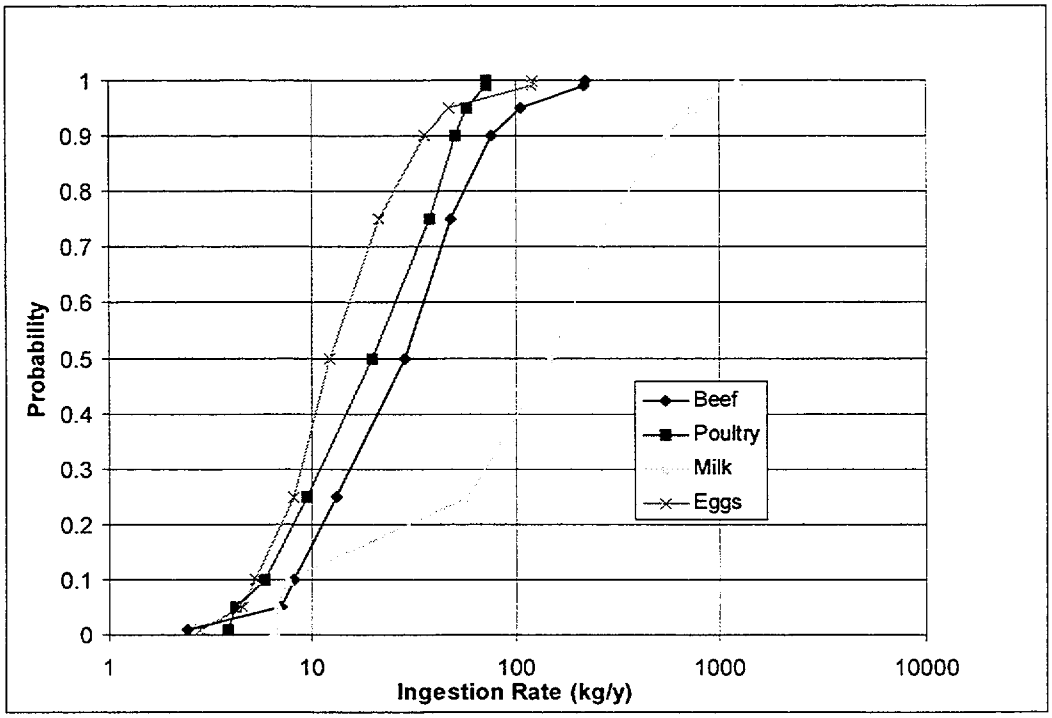

Figure 6.18 Cumulative distribution of U_a for beef, poultry, dairy (milk) and eggs

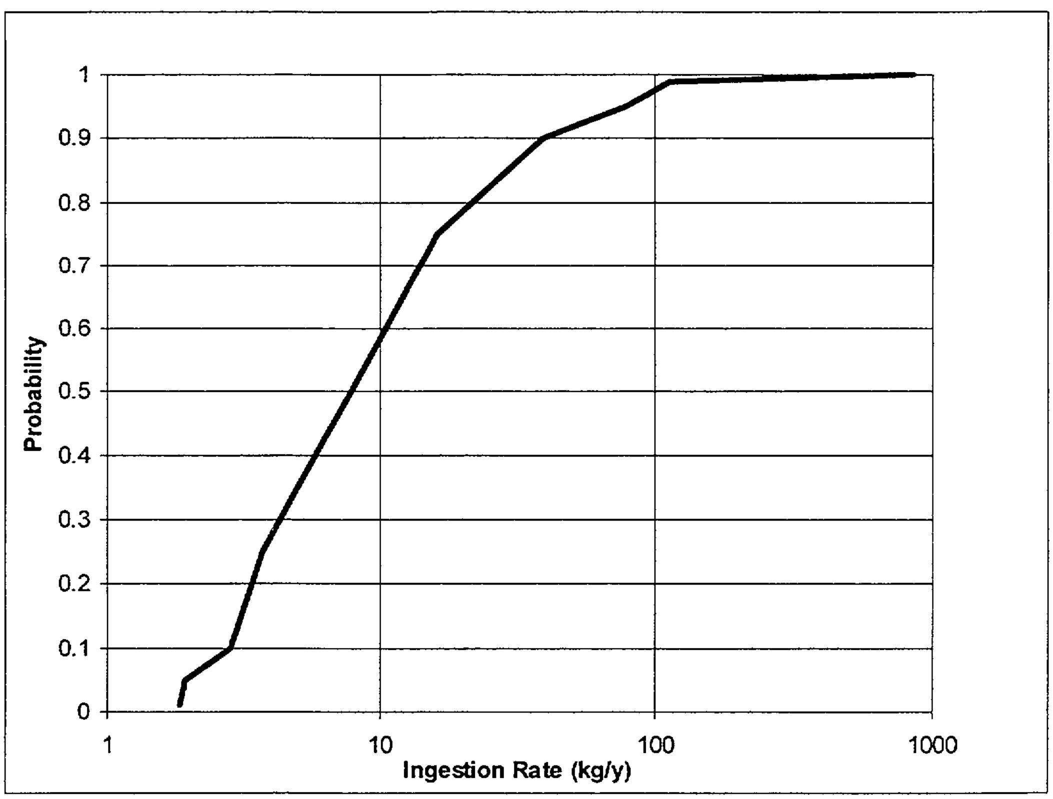

Figure 6.19 Cumulative distribution for U_f for fish

group requires assumptions about the variability of short term versus chronic consumption, the composition of the sample population versus the screening group, and the relative rates of ingestion versus economic consumption. These assumptions introduce some uncertainty about the distributions. We do not expect this uncertainty to be large relative to the mean parameter values, however, and these mean values are comparable to other estimates of ingestion rate.

6.2.9.6 Alternative Ingestion Rate Values

The proposed distribution functions presented above represent the behavioral variability of the members of the screening group and are not related to the physical characteristics of the specific site being considered. Site-specific values for these parameters, like other behavioral parameters, are established by defining a site-specific critical group. Some critical groups may have substantially different consumption rates, for example, groups that do not grow food in one or more categories.

6.3 Volumetric Breathing Rates (Metabolic), V_r, V_x, and V_g (m^3/h)

6.3.1 Description of Breathing Rates

The residential scenario defines three exposure situations or contexts for resident farmers: indoors, outdoors, and gardening. These exposure contexts are distinguished because the transport rates may differ significantly among them. The breathing rate parameters, in conjunction with the indoor resuspension factor, dust loadings, and isotope-specific inhalation CEDE factors, are used to calculate the average annual dose due to inhalation. The breathing rate parameters represent the annual average breathing rate of the average member of the screening group while indoors (V_r), outdoors (V_x) and gardening (V_g). As described in Section 3.2.2 above, default values for metabolic parameters are established by the average value for adult males in the general population.

The default value defined for each of the three breathing rates in NUREG/CR-5512, Vol. 1, is 1.2 m^3/h. This value corresponds to an average for the eight-hour work day assuming light activity for a person, as suggested in International Commission on Radiological Protection (ICRP) Publication 23 (1975). Revised default values for these parameters were defined based on a review of current literature on breathing rate.

6.3.2 Use of Breathing Rates in Modeling

Within each of the three contexts defined for the residential scenario (indoors, outdoors, and gardening), inhalation dose is directly proportional to breathing rate. The overall importance of breathing rate in determining dose depends on the relative contribution of inhalation dose to total dose, which in turn depends on exposure rates via alternative pathways, and on nuclide-specific dose factors.

The breathing rate parameters are used to calculate the committed effective dose equivalent, CEDE, resulting from inhalation of resuspended surface contamination. The relationship between the volumetric breathing rates and internal dose due to inhalation (DHRi) is described by the following (see NUREG/CR-5512, p. 5.55):

$$\begin{aligned} DEXR_i = & \left[24\ V_g (t_g/t_{tg})\ CDG\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tg}\}\ DFH_j\right] \\ & + \left[24\ V_x (t_x/t_{tr})\ CDO\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tr}\}\ DFH_j\right] \\ & + \left[24\ V_r (t_i/t_{tr})\ (CDI + P_d RF_r)\ C_{si}\ \Sigma_{(j=1,ji)}\ S\{A_{stj},\ t_{tr}\}\ DFH \right. \end{aligned} \tag{6.38}$$

where V_g is the volumetric breathing rate for time spent gardening (m^3/h); V_r is the volumetric breathing rate for time spent indoors (m^3/h); V_x is the volumetric breathing rate for time spent outdoors (m^3/h), t_g is the time during the one-year exposure period that the individual spends outdoors gardening (d); t_i is the time in the one-year exposure period that the individual spends indoors (d); t_x is the time in the one-year exposure period that the individual spends outdoors, other than gardening (d); t_{tr} is the total time in the residential exposure period (d); CDI, CDO, and CDG are the dust loading factors for indoor, outdoor, and gardening activities (g/m^3); respectively, C_{si} corresponds to the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil); J_i is the number of explicit members of the decay chain for parent radionuclide i; $S\{A_{stj}, t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); $S\{A_{stj}, t_{tg}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); DFH_j is the inhalation committed effective dose equivalent factor for radionuclide j for exposure to contaminated air (in units of mrem per pCi inhaled); P_d corresponds to the indoor dust-loading on floors (g/m^2); and RF_r is the indoor resuspension factor (m^{-1}). The resulting internal inhalation dose is directly proportional to the volumetric breathing rates for indoor, outdoor, and gardening activities.

6.3.3 Information Reviewed to Define Breathing Rate Distributions

The review conducted to support the EPA *Exposure Factors Handbook* (EPA, 1996) was adopted for this study as the most current compilation of relevant literature. Eleven studies are reviewed and summarized in the Handbook. Five are identified as "key studies," and form the basis for inhalation values recommended there. The six remaining studies are considered "relevant," and contain supporting information relating to inhalation rate. Separate breathing rate estimates are not reported in any study for the specific contexts defined for the residential scenario. Instead, daily average values are reported, as well as breathing rates for individuals engaged in various levels of activity. These activity levels are descriptively defined, for example as "rest," "sedentary," "light," "moderate," and "heavy."

Reported average daily values include a range and relative weighting of activities typical of an entire day: this range and weighting of activities is not representative of activities specifically conducted indoors, outdoors, or while gardening. For this reason, average daily values reported in the handbook are not appropriate for these parameters. The three exposure contexts in the residential scenario can be distinguished by the types of activities that would typically take place in each: indoor activities would typically include sleeping and resting, for example, while outdoor activities would not. For this reason, breathing rates for each context have been assigned based on the range of activities that would occur in each context, and the reported average values for the corresponding activity levels.

The summaries in the Handbook were used to evaluate the five "key" studies for the purpose of defining breathing rates for the average member of the screening group. Each of these five studies, and the resulting breathing rates that reflect the screening group, are summarized below.

Layton (1993) presents a method for estimating breathing rate based on metabolic information:

$$V_E = E \times H \times VQ \qquad (6.39)$$

where:

V_E = the ventilation rate
E = the energy expenditure rate
H = the volume of oxygen consumed in the production of 1 KJ of energy, and
VQ = the ratio of intake volume to oxygen uptake

Three approaches are used to estimate the energy expenditure rate: annual caloric intake (corrected for reporting bias), elevation above basal metabolic rate (BMR) with BMR values estimated from body weight using a fitted regression model, and elevations above BMR using activity-specific elevation factors and time allocation data. These methods are used to estimate average inhalation rates over various population subsets defined by age and gender. This study draws from comparatively large data sets, and provides information on the relative contributions of the diverse factors influencing inhalation rate, including general health, body weight, diet, activity level, age, and gender. The first two methods provide estimates of long-term average breathing rate, which is not specific to the residential exposure contexts. The third method provide estimates of breathing rate for different levels of activity. Average inhalation rates for adult males for five activity levels, estimated by the third method, are summarized in Table 6.22. Estimates for two sets of activity classifications are reported. For each set, activity level is characterized by a qualitative description as well as by a BMR value or range. Different sets of BMR values were used for each activity classification.

Linn et al. (1992) estimates inhalation rates for "high-risk" sub-populations, including outdoor workers, elementary school students, high school students, asthmatic adults, young asthmatics, and construction workers. Of these sub-populations, outdoor workers and construction workers approximate the screening group. The average breathing rate for healthy adult outdoor workers, consisting of 15 women and five men between the ages of 19 and 50, is reported as 0.78; construction workers, consisting of seven men between the ages of 26 and 34 have an average breathing rate of 1.50 m^3/hr. Activity-dependent breathing rates are also reported for both subject groups at three activity levels, as shown in Table 6.23.

Linn et al. (1993) reports breathing rates for 19 construction workers who perform heavy outdoor labor both before and during a typical work shift. The subjects of this study approximate the screening group, although the number of subjects is small. A regression model relating breathing rate to heart rate was developed from data collected in a controlled laboratory protocol. Occupational breathing rates were estimated from measured heart rates using this regression model. Average breathing rates are reported for three self-estimated activity levels, as shown in Table 6.24.

Table 6.22 Estimated breathing rates for males from Layton (1993) for two sets of five activity levels (m^3/hr)

Inhalation rates for short-term exposures[1]					
Age (years)	Activity level				
	Rest BMR: 1	Sedentary BMR:1.2	Light BMR: 1.5 -2.5	Moderate BMR: 3 - 5	Heavy BMR: >5 - 20
18 - < 30	0.43	0.52	0.84	1.74	4.32
30 - < 60	0.42	0.50	0.84	1.68	4.20
Activity-Dependent Inhalation Rates used to Estimate Daily Inhalation Rate[2]					
Age (years)	Activity level				
	Sleep BMR: 1	Light BMR: 1.5	Moderate BMR: 4	Hard BMR: 6	Very Hard BMR: 10
20-34	0.4	0.7	1.7	2.6	4.3
35-49	0.4	0.6	1.7	2.5	4.2
50-64	0.4	0.6	1.7	2.5	4.2

[1] Source: EPA (1996) Table 5-5
[2] Source: EPA (1996) Table 5-6

Table 6.23 Estimated breathing rates from Linn et al. (1992) for two panels of healthy adult subjects[1] (m^3/hr)

Subject group	Mean self-estimated breathing rates		
	Slow	Medium	Fast
Outdoor workers	0.72	1.02	3.06
Construction workers	1.26	1.50	1.68

[1] Source: EPA (1996) Table 5-7

Table 6.24 Estimated breathing rates from Linn et al. (1993) for outdoor workers[1] (m^3/hr)

Mean self-estimated breathing rates		
Slow	Medium	Fast
1.44	1.86	2.04

[1] Source: EPA (1996) Table 5-9

Spier et al. (1992) reports breathing rates for elementary and high-school students. Although considered a key study in the Handbook, this sub-population does not correspond to the screening group for the residential scenario. Results of this study were not used to establish values for the screening group.

The California Air Resources Board (CARB) (1993) reports breathing rates in routine daily activities for children and adults at various activity level classifications. The study included a laboratory protocol, in which ventilation rate, heart rate, breathing frequency, and oxygen consumption were measured during treadmill tests. Heart rate, ventilation rate, and breathing frequency were also measured during a "field" protocol, which included (for adult males) driving and riding in cars, yard work, and mowing. Average breathing rates during the laboratory protocol are reported for five activity classifications. Average values during the field protocol are reported for three activity classifications. Table 6.25 summarizes the reported values for adult males.

The six studies classified as "Relevant" provide supporting information, such as assessments of the quality of individual's subjective judgments of their breathing rate and activity level. These studies were not judged to provide information directly related to estimating breathing rates for the screening group. Three literature surveys are also classified as "Relevant." The U.S. EPA (1985) provides a summary of inhalation rates by age, gender, and activity level. This study compiles results of earlier investigations, and does not present information on the accuracy and methods used in these investigations. Reported breathing rates range from 0.7 to 4.8 m^3/hr for adult males depending on activity level. The ICRP (1981) presents ventilation estimates for reference adult males and females at two activity levels ("Resting" and "Light Activity") as well as daily inhalation rates based on an assumed activity pattern during the day. For adult males, the respective rates are given as 0.45 m^3/hr, 1.2 m^3/hr, and 22.8 m^3/day. (The default values for V_r, V_x, and V_g defined in Volume 1 of NUREG/CR-5512 were based on the "Light Activity" breathing

Table 6.25 Average inhalation rates for adult males from CARB (1993) (m^3/hr)

	Activity level				
	Resting	Sedentary	Light	Moderate	Heavy
Laboratory protocols[1]	0.54	0.60	1.45	1.93	3.63
Field protocols[2]		0.62	1.40	1.78	

[1] Source: EPA (1996) Table 5-13
[2] Source: EPA (1996) Table 5-14

rate for males from this study.) This study was not considered a sufficient basis for defining default values for these parameters because of the availability of more recent empirical data in four of the five key studies discussed above. The AIHC (1994) Exposure Factors Sourcebook recommends an average adult inhalation rate of 18 m^3/day based on data presented in other studies. This report draws from information presented elsewhere, does not present new data on breathing rate, and may not be representative of the screening group.

6.3.4 Average Breathing Rates for the Residential Scenario Contexts

For the indoor, outdoor, and gardening contexts defined for the residential scenario, breathing rates of the average member of the screening group were estimated from the average breathing rates for adults discussed in Section 6.3.3. Where separate estimates are provided for males and females, estimates for males were adopted as being more representative of the screening group.

Each context was first characterized by the range of activity levels for the activities that would typically occur in each. Indoor activities include sleeping, reading, watching television, kitchen work and housework, and repair and maintenance. Such activities correspond to the "Resting," "Sedentary," "Light," and "Moderate" level classifications used by Layton (1993) and CARB (1993). Outdoor activities include yard work, recreation, and car and equipment repair and maintenance. Typical outdoor activities were therefore assumed to correspond to the "Sedentary," "Light," and "Moderate" categories of Layton (1993) and CARB (1993), and to the "Slow" and "Medium" subjective breathing rate classifications used in Linn's studies of outdoor workers.

Gardening activities include soil preparation, planting, weeding, hoeing, and harvesting. These activities are assumed to correspond to the "Light," "Moderate," "Heavy," "Hard," and "Very Hard" levels adopted by Layton (1993) and by CARB (1993), and to lead to breathing rates subjectively classified as "Medium" or "Fast" by Linn's subjects.

For the outdoor and gardening contexts, the reported average breathing rates for the activity levels typical of each context were identified. (For each of the two sets of values reported by Layton (1993), the median breathing rate over the individual age groups was selected as typical of adult males.) Table 6.26 lists the reported breathing rate values for activity levels expected to occur outdoors, while Table 6.27 lists breathing rate values for activity levels expected to occur while gardening. For both the outdoor and gardening contexts, estimated breathing rates cover a range of values due to differences among the studies, and to differences in activity levels conducted in these contexts. An estimate of overall average breathing rate would require information on time allocation among these activity levels. Because detailed time allocation information is not available, the median reported value was selected to characterize each context: 1.4 m^3/hr for outdoor activities, and 1.7 m^3/hr for gardening activities.

As in the outdoor and gardening contexts, detailed time allocation information is not available for the variety of activities that might be conducted indoors. Time spent sleeping, however, is estimated in a number of activity surveys. Because a significant portion of indoor time is spent sleeping, and because of the low breathing rates characteristic of sleep, the average indoor breathing rate estimate distinguishes between the time spent sleeping and the time spent conducting other activities indoors:

$$V_r = \frac{T_S V_S + T_A V_A}{T_S + T_A} \qquad (6.40)$$

where T_S and T_A are the average time spent sleeping and awake indoors, and V_S and V_A are the average breathing rates while asleep and awake indoors.

Estimates for T_S and T_A are available from the National Human Activity Pattern Survey (NHAPS) (Tsang and Klepeis, 1996) (see Section 6.2.3 for a discussion of time allocation studies). The EPA Exposure Factors Handbook describes Tsang and Klepeis (1996) as "the largest and most current human activity pattern survey available" (EPA, 1996). Over 9000 respondents provided minute-by-minute 24-hour diaries between

Table 6.26 Reported average breathing rates corresponding to activity levels typical of outdoor activities (excluding gardening)

Breathing rate (m^3/h)	Reference study and activity level
0.5	Layton (1993), Set 1: Median of "Sedentary" values over adult age groups
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.6	CARB (1993): "Sedentary" value from laboratory protocol
0.6	CARB (1993): "Sedentary" value from field protocol
0.7	Linn et al. (1992): "Slow" value for outdoor workers
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.0	Linn et al. (1992): "Medium" value for outdoor workers
1.3	Linn et al. (1992): "Slow" value for construction workers
1.4	CARB (1993): "Light" value from field protocol
1.4	Linn et al. (1993): "Slow" value for outdoor workers
1.4	CARB (1993): "Light" value from laboratory protocol
1.5	Linn et al. (1992): "Medium" value for construction workers
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	Linn et al. (1993): "Medium" value for outdoor workers
1.9	CARB (1993): "Moderate" value from laboratory protocol

Table 6.27 Reported average breathing rates corresponding to activity levels typical of gardening activities

Breathing rate (m^3/h)	Reference study and activity level
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.0	Linn et al. (1992): "Medium" value for outdoor workers
1.4	CARB (1993): "Light" value from field protocol
1.4	CARB (1993): "Light" value from laboratory protocol
1.5	Linn et al. (1992): "Medium" value for construction workers
1.7	Linn et al. (1992): "Fast" value for construction workers
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	Linn et al. (1993): "Medium" value for outdoor workers
1.9	CARB (1993): "Moderate" value from laboratory protocol
2.0	Linn et al. (1993): "Fast" value for outdoor workers
2.5	Layton (1993), Set 2: Median of "Hard" values over adult age groups
3.1	Linn et al. (1992): "Fast" value for outdoor workers
3.6	CARB (1993): "Heavy" value from laboratory protocol
4.3	Layton (1993), Set 2: Median of "Very Hard" values over adult age groups
4.3	Layton (1993), Set 1: Median of "Heavy" values over adult age groups

October 1992 and September 1994, and the responses weighted to produce results representative of the U.S. population. Average time allocation values, as well as detailed distributional information, is provided for a number of cohorts defined by age, race, gender, and other factors, however average values for adult males are not reported. The average time spent sleeping and napping by males of all ages is 523 minutes/day, while females spend an average of 529 minutes/day sleeping and napping. Adults of either gender between the ages of 18 and 64 spend an average of 497 minutes/day sleeping and napping. Because time spent sleeping depends on age more strongly than gender, a T_S value of 497 minutes/day was assumed for the screening group. The total time spent indoors ($T_S + T_A$) by the average member of the screening group is 240 24-hour days/year, or 946 minutes/day (see Section 6.2.3).

The breathing rate while sleeping, V_S, was estimated as the median of the values reported in Layton (1993) and from the CARB (1993) laboratory protocols, 0.4 m^3/hr. Table 6.28 lists the reported breathing rate values for activity levels expected to occur while awake indoors. V_A was estimated as the median of these values, 1.4 m^3/hr. The average indoor breathing rate was then calculated from Equation 6.40:

$$V_r = \frac{497 \text{ min/day } 0.4 \text{ m}^3\text{/hr} + 449 \text{ min/day } 1.4 \text{ m}^3\text{/hr}}{946 \text{ min/day}} = 0.9 \text{ m}^3\text{/hr} \quad (6.41)$$

Table 6.29 summarizes the default breathing rate values for the three residential scenario exposure contexts. For comparison with breathing rate values recommended for other applications, the average long-term on-site breathing rate was also calculated using the average time spent in each context (see Section 6.2.3). The resulting long-term breathing rate of 23 m^3/day is the same as that recommended for adult males in ICRP (1981), but larger than the adult male breathing rate of 21.4 m^3/day based on EPA (1985) (see EPA (1996) Table 5-20), and the more recent estimate from Layton (1993) of 17 m^3/day.

6.4 Physical Parameters

6.4.1 Physical Parameters with Constant Values

Physical parameters that do not have significant variability were held constant at a represented value. Table 6.30 lists the physical parameters that were held constant and the value used in the parameter analysis. The constant values were the values defined in Volume 1, in most cases. Additional information was reviewed to determine the variability in the fraction of carbon in plants and animals. Although the data indicate little variability in these parameters, the average values are slightly different than the initial default values. These data are presented in Sections 6.4.1.1 and 6.4.1.2. The plant concentration factors for the noble gases (BjAr, BjKr, BjRn & BjXe) and tritium (BjH) are set to zero because the gases are assumed not to accumulate in plant tissue and tritium is modeled separately. The outdoor shielding factor (SFO) is set to 1 because this scenario is evaluating surface soil contamination.

The potential variability in the animal product transfer factors FA, the fish bioaccumulation factors BA, and mass loading factors MLV, MLF, MLG, and MLH was not assessed. The values defined for these factors in Volume 1 were used in this analysis. The constant values assigned to the mass loading factors appear to represent the upper end of a broad range of potential values.

6.4.1.1 Fraction of Carbon in Forage (f_{Cf}), Stored Grain (f_{Cg}), and Stored Hay (f_{Ch})

These parameters define the mass fraction of elemental carbon in forage, stored grain and stored hay for livestock and is used in the agricultural pathway model in the residential scenario for calculating the dose from ^{14}C. The dose model assumes that the specific activity of ^{14}C in the animal product that is consumed by a human is equal to the specific activity of ^{14}C in the food the animal consumes.

This section begins with brief discussions of the importance of f_{Cf}, f_{Cg} and f_{Ch} with regard to the calculated dose and how f_{Cf}, f_{Cg} and f_{Ch} are specifically used in the dose model. Next the default values used for f_{Cf}, f_{Cg} and f_{Ch} in NUREG/CR-5512, Vol. 1, are discussed. Lastly, distributions for f_{Cf}, f_{Cg} and f_{Ch} are presented and values are proposed based on these distributions.

The fraction of carbon in animal feed is important in estimating the dose from ^{14}C. The higher the value f_{Cf}, f_{Cg} and f_{Ch} the higher the total annual dose in the residential scenario.

The default values for f_{Cf}, f_{Cg} and f_{Ch} defined in NUREG/CR-5512, Vol. 1, are all 0.09.

Table 6.28 Reported average breathing rates corresponding to activity levels typical of waking indoor activities

Breathing rate (m^3/h)	Reference study and activity level
0.5	Layton (1993), Set 1: Median of "Sedentary" values over adult age groups
0.6	Layton (1993), Set 2: Median of "Light" values over adult age groups
0.6	CARB (1993): "Sedentary" value from laboratory protocol
0.6	CARB (1993): "Sedentary" value from field protocol
0.8	Layton (1993), Set 1: Median of "Light" values over adult age groups
1.4	CARB (1993): "Light" value from field protocol
1.4	CARB (1993): "Light" value from laboratory protocol
1.7	Layton (1993), Set 1: Median of "Moderate" values over adult age groups
1.7	Layton (1993), Set 2: Median of "Moderate" values over adult age groups
1.8	CARB (1993): "Moderate" value from field protocol
1.9	CARB (1993): "Moderate" value from laboratory protocol

Table 6.29 Default breathing rates for the residential scenario

Exposure context /parameter	Breathing rate (m^3/hr)	Time spent in context[1] (days/year)
Indoors - V_r	0.9	240
Outdoors - V_x	1.4	40.2
Gardening - V_g	1.7	2.92
Average on-site rate[2]	23 m^3/day	

[1] See Section 6.2.7
[2] Weighted by time spent in each context

Table 6.30 Constant physical parameters

Part 1			
Parameters	**Description**	**Units**	**Value**
BjAr,H,Kr,Rn, Xe	Concentration factors for leafy, root, fruit, grain	-	0
fca(1)	Carbon fraction for beef cattle	-	0.36
fca(2)	Carbon fraction for poultry	-	0.18
fca(3)	Carbon fraction for milk cows	-	0.06
fca(4)	Carbon fraction for layer hens	-	0.16
fcd05	Fraction of carbon in soil	-	0.03
fcf(a)	Carbon fraction for all forage	-	0.11
fcg(a)	Carbon fraction for all grain consumed by animals	-	0.4
fch(a)	Carbon fraction for all hay	-	0.07
fha(1)	Hydrogen fraction for beef cattle	-	0.1
fha(2)	Hydrogen fraction for poultry	-	0.1
fha(3)	Hydrogen fraction for milk cows	-	0.11
fha(4)	Hydrogen fraction for layer hens	-	0.11
fhd016	Fraction of hydrogen in soil	-	0.011

Table 6.30 Constant physical parameters (continued)

Part 1			
Parameters	**Description**	**Units**	**Value**
fhf	Hydrogen fraction for forage	-	0.1
fhg, fhv(4)	Hydrogen fraction for all grain	-	0.068
fhh	Hydrogen fraction for hay	-	0.1
fhv (1-3)	Hydrogen fraction for fruits and vegetables	-	0.1
KdH,Xe, Ke, Ar, Rn	Partition coefficients for H, Xe, Ke, Ar, Rn	mL/g	0
H1	Thickness of surface-soil layer	m	0.15
LAMBDW	Weathering rate for activity removal from plants	1/d	4.95E-02
MLF,MLG, MLH, MLV	Mass-loading factors for forage, grain, hay, fruit, and vegetables	g/g	0.1
QD(1)	Soil intake fraction for beef cattle	-	0.02
QD(2)	Soil intake fraction for poultry	-	0.1
QD(3)	Soil intake fraction for milk cows	-	0.02
QD(4)	Soil intake fraction for layer hens	-	0.1
QH(2)	Ingestion rate for poultry hay	kg/d	0
QH(4)	Ingestion rate for layer hen hay	kg/d	0
QW(1)	Water ingestion rate for beef cattle	L/d	50
QW(2)	Water ingestion rate for poultry	L/d	0.3
QW(3)	Water ingestion rate for milk cows	L/d	60
QW(4)	Water ingestion rate for layer hens	L/d	0.3
sasvh	Tritium equivalence: plant/soil	-	1
satac	Specific activity equivalence for livestock	-	1
satah	Tritium equivalence: animal product/intake	-	1
sawvh	Tritium equivalence: plant/water	-	1
SFO	Outdoor Shielding Factor	-	1
sh	Absolute humidity, H*	L/m^3	0.008
TF	Translocation factor for forage	-	1
TFF, TFG, TFH	Feeding period for all animals, forage, grain & hay	d	365.25
TFW	Water ingestion period for all animals	d	365.25
TG	Translocation factor for all animals grain	-	0.1
TGF	Minimum growing period for forage	d	30
TGG	Minimum growing period for stored grain	d	90
TGH	Minimum growing period for stored hay	d	45
TGV(1)	Minimum growing period for leafy vegetables	d	45
TGV(2)	Minimum growing period for other vegetables	d	90
TGV(3)	Minimum growing period for fruits	d	90
TGV(4)	Minimum growing period for grains	d	90
TH	Translocation factor for hay	-	1
THA(4)	Holdup period for eggs	d	1
TV(1)	Translocation factor for leafy vegetables	-	1
TV(2)	Translocation factor for other vegetables	-	0.1
TV(3)	Translocation factor for fruits	-	0.1
TV(4)	Translocation factor for grains	-	0.1
VSW	Volume of water in surface-water pond	L	1.30E+06
WG(1), WV(4)	Wet/dry conversion factor for grain	-	0.88

Table 6.30 Constant physical parameters (continued)

Part 2 - Animal product transfer factors (Faj) , wet-eight basis (from Volume 1, Table 6.18)				
Element	**Beef (d/kg)**	**Poultry (d/kg)**	**Milk (d/L)**	**Eggs (d/kg)**
H	(-)	(-)	(-)	(-)
Be	1.00E-03	4.00E-01	9.00E-07	2.00E-02
C	(-)	(-)	(-)	(-)
N	7.50E-02	1.00E-01	2.50E-02	8.00E-01
F	1.50E-01	1.00E-02	1.00E-03	2.00E+00
Na	5.50E-02	1.00E-02	3.50E-02	2.00E-01
Mg	5.00E-03	3.00E-02	4.00E-03	1.60E+00
Si	4.00E-05	2.00E-01	2.00E-05	8.00E-01
P	5.50E-02	1.90E-01	1.50E-02	1.00E+01
S	1.00E-01	9.00E-01	1.50E-02	7.00E+00
Cl	8.00E-02	3.00E-02	1.50E-02	2.00E+00
Ar	(-)	(-)	(-)	(-)
K	2.00E-02	4.00E-01	7.00E-03	7.00E-01
Ca	7.00E-04	4.40E-02	1.00E-02	4.40E-01
Sc	1.50E-02	4.00E-03	5.00E-06	3.00E-03
Cr	5.50E-03	2.00E-01	1.50E-03	8.00E-01
Mn	4.00E-04	5.00E-02	3.50E-04	6.50E-02
Fe	2.00E-02	1.50E+00	2.50E-04	1.30E+00
Co	2.00E-02	5.00E-01	2.00E-03	1.00E-01
Ni	6.00E-03	1.00E-03	1.00E-03	1.00E-01
Cu	1.00E-02	5.10E-01	1.50E-03	4.90E-01
Zn	1.00E-01	6.50E+00	1.00E-02	2.60E+00
Ga	5.00E-04	3.00E-01	5.00E-05	8.00E-01
As	2.00E-03	8.30E-01	6.00E-05	8.00E-01
Se	1.50E-02	8.50E+00	4.00E-03	9.30E+00
Br	2.50E-02	4.00E-03	2.00E-02	1.60E+00
Kr	(-)	(-)	(-)	(-)
Rb	1.50E-02	2.00E+00	1.00E-02	3.00E+00
Sr	3.00E-04	3.50E-02	1.50E-03	3.00E-01
Y	3.00E-04	1.00E-02	2.00E-05	2.00E-03
Zr	5.50E-03	6.40E-05	3.00E-05	1.90E-04
Nb	2.50E-01	3.10E-04	2.00E-02	1.30E-03
Mo	6.00E-03	1.90E-01	1.50E-03	7.80E-01
Tc	8.50E-03	3.00E-02	1.00E-02	3.00E+00
Ru	2.00E-03	7.00E-03	6.00E-07	6.00E-03
Rh	2.00E-03	5.00E-01	1.00E-02	1.00E-01
Pd	4.00E-03	3.00E-04	1.00E-02	4.00E-03
Ag	3.00E-03	5.00E-01	2.00E-02	5.00E-01
Cd	5.50E-04	8.40E-01	1.00E-03	1.00E-01
In	8.00E-03	3.00E-01	1.00E-04	8.00E-01
Sn	8.00E-02	2.00E-01	1.00E-03	8.00E-01
Sb	1.00E-03	6.00E-03	1.00E-04	7.00E-02
Te	1.50E-02	8.50E-02	2.00E-04	5.20E+00

Table 6.30 Constant physical parameters (continued)

Part 2 - Animal product transfer factors (Faj) , wet-eight basis (from Volume 1, Table 6.18)				
Element	**Beef (d/kg)**	**Poultry (d/kg)**	**Milk (d/L)**	**Eggs (d/kg)**
I	7.00E-03	1.80E-02	1.00E-02	2.80E+00
Xe	(-)	(-)	(-)	(-)
Cs	2.00E-02	4.40E+00	7.00E-03	4.90E-01
Ba	1.50E-04	8.10E-04	3.50E-04	1.50E+00
La	3.00E-04	1.00E-01	2.00E-05	9.00E-03
Ce	7.50E-04	1.00E-02	2.00E-05	5.00E-03
Pr	3.00E-04	3.00E-02	2.00E-05	5.00E-03
Nd	3.00E-04	4.00E-03	2.00E-05	2.00E-04
Pm	5.00E-03	2.00E-03	2.00E-05	2.00E-02
Sm	5.00E-03	4.00E-03	2.00E-05	7.00E-03
Eu	5.00E-03	4.00E-03	2.00E-05	7.00E-03
Gd	3.50E-03	4.00E-03	2.00E-05	7.00E-03
Tb	4.50E-03	4.00E-03	2.00E-05	7.00E-03
Dy	5.50E-03	4.00E-03	2.00E-05	7.00E-03
Ho	4.50E-03	4.00E-03	2.00E-05	7.00E-03
Er	4.00E-03	4.00E-03	2.00E-05	7.00E-03
Hf	1.00E-03	6.00E-05	5.00E-06	2.00E-04
Ta	6.00E-04	3.00E-04	3.00E-06	1.00E-03
W	4.50E-02	2.00E-01	3.00E-04	8.00E-01
Re	8.00E-03	4.00E-02	1.50E-03	4.00E-01
Os	4.00E-01	1.00E-01	5.00E-03	9.00E-02
Ir	1.50E-03	5.00E-01	2.00E-06	1.00E-01
Au	8.00E-03	5.00E-01	5.50E-06	5.00E-01
Hg	2.50E-01	1.10E-02	4.50E-04	2.00E-01
Tl	4.00E-02	3.00E-01	2.00E-03	8.00E-01
Pb	3.00E-04	2.00E-01	2.50E-04	8.00E-01
Bi	4.00E-04	1.00E-01	5.00E-04	8.00E-01
Po	3.00E-04	9.00E-01	3.50E-04	7.00E+00
Rn	(-)	(-)	(-)	(-)
Ra	2.50E-04	3.00E-02	4.50E-04	2.00E-05
Ac	2.50E-05	4.00E-03	2.00E-05	2.00E-03
Th	6.00E-06	4.00E-03	5.00E-06	2.00E-03
Pa	1.00E-05	4.00E-03	5.00E-06	2.00E-03
U	2.00E-04	1.20E+00	6.00E-04	9.90E-01
Np	5.50E-05	4.00E-03	5.00E-06	2.00E-03
Pu	5.00E-07	1.50E-04	1.00E-07	8.00E-03
Am	3.50E-06	2.00E-04	4.00E-07	9.00E-03
Cm	3.50E-06	4.00E-03	2.00E-05	2.00E-03
Cf	5.00E-03	4.00E-03	7.50E-07	2.00E-03

Table 6.30 Constant physical parameters (continued)

Part 3 - Fish bioaccumulation factors (Ba_{jf}) (from Volume 1, Table 6.19)			
Element	**Bioaccumulation factor (pCi/kg wet-weight per pCi/L)**	**Element**	**Bioaccumulation factor (pCi/kg wet-weight per pCi/L)**
H	1.00E+00	Sb	2.00E+02
Be	2.00E+00	Te	4.00E+02
C	4.60E+03	I	5.00E+02
N	1.50E+05	Xe	0.00E+00
F	1.00E+01	Cs	2.00E+03
Na	1.00E+02	Ba	2.00E+02
P	7.00E+04	La	2.50E+01
S	7.50E+02	Ce	5.00E+02
Cl	5.00E+01	Pr	2.50E+01
K	1.00E+03	Nd	2.50E+01
Ca	4.00E+01	Pm	2.50E+01
Sc	1.00E+02	Sm	2.50E+01
Cr	2.00E+02	Eu	2.50E+01
Mn	4.00E+02	Gd	2.50E+01
Fe	2.00E+03	Tb	2.50E+01
Co	3.30E+02	Ho	2.50E+01
Ni	1.00E+02	W	1.20E+03
Cu	5.00E+01	Re	1.20E+02
Zn	2.50E+03	Os	1.00E+01
As	1.00E+02	Ir	1.00E+01
Se	1.70E+02	Au	3.30E+01
Br	4.20E+02	Hg	1.00E+03
Rb	2.00E+03	Pb	1.00E+02
Sr	5.00E+01	Bi	1.50E+01
Y	2.50E+01	Po	5.00E+02
Zr	2.00E+02	Rn	0.00E+00
Nb	2.00E+02	Ra	7.00E+01
Mo	1.00E+01	Ac	2.50E+01
Tc	1.50E+01	Th	1.00E+02
Ru	1.00E+02	Pa	1.10E+01
Rh	1.00E+01	U	5.00E+01
Pd	1.00E+01	Np	2.50E+02
Ag	2.30E+00	Pu	2.50E+02
Cd	2.00E+02	Am	2.50E+02
In	1.00E+05	Cm	2.50E+02
Sn	3.00E+03	Cf	2.50E+01

Additional information was reviewed to define the variability in f_{Cf}, f_{Cg} and f_{Ch}. The major sources of carbon in foods are proteins, lipids, and carbohydrates (Lehninger, 1970). Therefore, the fraction of carbon in forage, stored grain or stored hay can be determined based on the protein, lipid, and carbohydrate contents of the forage, stored grain or stored hay and the fraction of carbon in proteins, lipids, and carbohydrates. The mathematical expression is given by:

$$f_{Cx} = f_{Px}(f_{Cp}) + f_{Lx}(f_{Cl}) + f_{Cx}(f_{Cc}) \quad (6.42)$$

where:

f_{Px}, f_{Lx} and f_{Cx} are the fraction of proteins, lipids and carbohydrates in the forage (x=f), stored grain (x=g) or stored hay (x=h), and f_{Cp}, f_{Cl} and f_{Cc} are the fraction of carbon in proteins, lipids and carbohydrates.

Equation 6.42 is based only on the major sources of carbon in livestock feed and neglects minor carbon-containing components such as vitamins and nucleic acids.

6.4.1.1.1 Fraction of Carbon in Proteins, Lipids and Carbohydrates

Protein is a polyamino acid with a molecular weight range of 6,000 to 40,000,000 and consists of 50 to 340,000 amino acid monomer units. Proteins contain approximately 50% carbon, 7% hydrogen, 23% oxygen, 16% nitrogen, and from 0 to 3% sulfur (Lehninger, 1970).

Lipids are esters of aliphatic acids and are composed of a hydrocarbon chain with a terminal carboxyl group linked to a acylglycerol moiety. The carbon composition of lipids varies slightly with the hydrocarbon chain length (14 to 24 carbon atoms in the fatty acid moiety) and the degree of saturation. Lipids contain approximately 76% carbon (Lehninger, 1970).

With the exception of milk, carbohydrates make up a very small portion of the total components in animal products. Carbohydrates consist of carbon, hydrogen, and oxygen in the approximate CHO ratio of 1:2:1 and vary slightly in carbon content from 40% (simple sugars) to about 45% (storage and structural polysaccharides) (Lehninger, 1970).

6.4.1.1.2 Nutrient Composition of Forage, Stored Grain, and Stored Hay

Tables 6.31, 6.32, and 6.33 list common forage crops, stored grain crops, and stored hay crops for livestock and the quantities of protein, lipids, and fibers in each. Fibers include structural polysaccharides and other carbohydrates. These three major components in the crops are readily digestible by livestock. There are, however, minor components of non-digestible proteins and fibers present in plant material (NRC, 1985).

The largest variability in the carbon fraction parameters is due to the variety in the types of forage, stored grain, and stored hay crops that livestock may eat. To account for this variability it is assumed that each type of potential feed is equally likely to be fed to livestock. Therefore, a uniform distribution representing each type was sampled to obtain the specific crop being consumed by the livestock. Given the specific feed type, the amount of nutrients can be determined from Tables 6.31, 6.32, and 6.33, combined with the specific fraction of carbon in the nutrients reported by Lehninger (1970) to calculate the mass fraction of carbon, using Equation 6.42.

Table 6.31 Composition of fresh forage crops (NAP, 1996)

Forage crop	Protein (%)	Lipids (%)	Fiber (%)
Alfalfa	18.9	3.2	77.9
Bermuda grass	12.6	3.7	83.7
Bluegrass	17.4	3.5	79.1
Broome grass	21.3	4.0	74.7
Canary grass	17.0	4.1	78.9
Clover, ladino	25.8	4.6	69.6
Clover, red	14.6	2.9	82.5
Fescue	15.0	5.5	79.5
Orchard grass	12.8	3.7	83.5
Rye grass	17.9	4.1	78.0
Trefoil	20.6	4.0	75.4
Timothy	12.2	3.8	84.0

Table 6.32 Composition of grain (NAP, 1996)

Grain	Protein (%)	Lipids (%)	Fiber (%)
Barley	13.2	2.2	84.6
Canola	30.7	7.4	61.9
Corn	9.8	4.1	86.1
Oats	13.6	5.2	81.2
Sorghum	12.6	3.0	84.4
Wheat	14.2	2.3	83.5

Table 6.33 Composition of stored hay (NAP, 1996)

Hay crop	Protein (%)	Lipids (%)	Fiber (%)
Alfalfa	18.6	2.4	79.0
Bermuda grass	7.8	2.7	89.5
Broome grass	6.0	2.0	92.0
Canary grass	10.2	3.0	86.8
Clover, ladino	22.4	2.7	74.9
Clover, red	15.0	2.8	82.2
Corn w/cob	2.8	0.6	96.6
Corn silage	8.7	3.1	88.2
Fescue	10.8	4.7	84.5
Orchard grass	12.8	2.9	84.3
Sorghum silage	9.4	2.6	88.0
Wheat grass	8.7	2.2	89.1
Wheat silage	12.5	6.1	81.4
Trefoil	15.9	2.1	82.0
Timothy	10.8	2.8	86.4

The variability in f_{Cf}, f_{Cg} and f_{Ch} is relatively small, as the results in Table 6.34 show. In addition, Table 6.34 presents the default values used in NUREG/CR-5512, Vol. 1, which are consistent with the distributions derived in this section. Given the small variability, the mean values were used for all calculations.

These parameters would not be expected to vary from site to site and it is very unlikely that a licensee would conduct any type of data collection activity to modify them. The one exception may be f_{Cf} because of the different forage crops that grow in different regions throughout the United States. A licensee may attempt to support alternative values for the fraction of carbon in forage based on regional data that supports specific forage crop growth.

6.4.1.2 Fraction of Carbon in Animal Products, f_{Ca}

This parameter defines the mass fraction of elemental carbon in meat (beef and poultry), milk, and eggs and is used in the agricultural pathway model in the residential scenario for calculating the dose from ^{14}C. The fraction of carbon in these animal products is a physical parameter because it is a function of the amount of ^{14}C in the specific animal product being considered.

The fraction of carbon in animal products is important in estimating the dose from ^{14}C. The higher the value for f_{Ca}, the higher the total annual dose in the residential scenario.

The default values for this parameter defined in NUREG/CR-5512, Vol. 1, are: beef cattle, 0.24; poultry, 0.20; milk, 0.07; and eggs, 0.15.

The major sources of carbon in foods are proteins, lipids, and carbohydrates (Lehninger, 1970). Therefore, the fraction of carbon in foods can be determined based on the protein, lipid, and carbohydrate contents of the food and the fraction of carbon in proteins, lipids, and carbohydrates. The mathematical expression is given by:

$$f_{Ca} = f_{Pa}(f_{Cp}) + f_{La}(f_{Cl}) + f_{Ca}(f_{Cc}) \qquad (6.43)$$

where f_{Pa}, f_{La}, and f_{Ca} are the fraction of proteins, lipids and carbohydrates in food type "a," respectively, and f_{Cp}, f_{Cl} and f_{Cc} are the fraction of carbon in proteins, lipids and carbohydrates, respectively.

Equation 6.43 is based only on the major sources of carbon in foods and neglects minor carbon-containing components such as vitamins and nucleic acids.

Table 6.35 lists the nutrient composition of products from beef cattle, poultry, milk cows, and layer hens.

The only uncertainty in the data is in the carbon content of lipids (73–79%) and the carbon content of carbohydrates (40–45%). Because there is no basis for any type of distribution of this uncertainty indicated by Lehninger (1970) these fractions are assumed to be uniformly distributed with the minimum and maximum values equal to the reported range. Using these distributions and Equation 6.43, Table 6.36 presents the data for f_{Ca} for milk, eggs, beef and poultry, along with the default values used in NUREG/CR-5512, Volume 1.

As can be seen in Table 6.36, there is little variability in f_{Ca}. The average value was used in all calculations.

Table 6.34 Data variability for f_{Cf}, f_{Cg} and f_{Ch}

Parameter	Minimum	Maximum	Mean	Standard deviation	NUREG/CR-5512 default
f_{Cf}	0.088	0.14	0.11	0.018	0.09
f_{Cg}	0.39	0.44	0.40	0.016	0.40
f_{Ch}	0.020	0.12	0.07	0.031	0.09

Table 6.35 Composition of animal products (Gebhardt and Matthews, 1985)

Product	Protein	Lipids	Carbohydrates (g)
Milk	3.3%	3.3%	4.5%
Eggs	12%	12%	2.0%
Beef	26%	31%	0
Poultry	31%	3.5%	0

Table 6.36 Data on variability of f_{C_a}

Product	Minimum	Maximum	Mean of the range	Default value from 5512
Milk	0.0606	0.0626	0.06	0.07
Eggs	0.157	0.164	0.16	0.15
Beef	0.353	0.371	0.36	0.24
Poultry	0.182	0.185	0.18	0.20

6.4.2 Thickness of the Unsaturated Zone, H_2 (m)

6.4.2.1 Description of H_2

As defined in Volume 1, H_2 is the thickness of the unsaturated zone for the three-box groundwater model used in the residential scenario. The top box in the three box model represents a 15-cm-thick soil layer. The middle box represents the unsaturated zone, and H_2 is the thickness of this middle box. H_2 is a physical parameter that is a characteristic of the specific site being assessed and is independent of the source term and group of exposed individuals.

6.4.2.2 Use of H_2 in Modeling

The thickness of the unsaturated zone is important to dose because it is the distance radionuclides must travel to get into the saturated zone. Once in the saturated zone, the radionuclides contaminate drinking and irrigation water which results in a dose to man via several different possible pathways. A thick unsaturated zone compared to a thin unsaturated zone would provide a longer distance for radionuclides to be transported. This longer distance translates into a longer travel time and, with radioactive decay occurring, may result in a decrease in the amount of radionuclides reaching the saturated zone. Besides travel distance, the unsaturated zone is characterized by adsorption coefficients, water content, and infiltration rate. These parameters, combined with H_2, provide the basis for estimating the total amount of radioactivity that reaches the saturated zone in a given time.

For NUREG/CR-5512, Vol. 1, dose modeling, the thickness of the unsaturated zone is used in determining radionuclide leach rates from the unsaturated zone to the saturated zone in the three box groundwater model. These leach rates are proportional to the amount of water that infiltrates into the unsaturated zone (infiltration rate) and inversely proportional to the thickness of the unsaturated zone, the volumetric water content of the unsaturated zone, and the radionuclide specific retardation factor (which is derived from adsorption coefficients). The mathematical relation between leach rate and unsaturated zone thickness is given in NUREG/CR-5512, Vol. 1 (p. 4.9), as:

$$L_{2j} = \frac{I}{H_2 \Theta_2 Rt_{2j} 365.25} \qquad (6.44)$$

where:

L_{2j} = Leach rate from the unsaturated zone to the saturated zone for radionuclide j (y^{-1})
I = Infiltration rate (my^{-1})
H_2 = Unsaturated zone thickness (m)
Θ_2 = Volumetric water content of the unsaturated zone (dimension less)
Rt_{2j} = Retardation factor for movement of radionuclide j from the unsaturated zone to the saturated zone (dimension less)

The retardation factor is given in NUREG/CR-5512, Vol. 1 (p. 4.9), as:

$$Rt_{2j} = 1 + \frac{Kd_{2j}\ \rho_2}{n_2} \qquad (6.45)$$

where:

Kd_{2j} = Partition coefficient for the jth radionuclide in the unsaturated zone
ρ_2 = Bulk density of the unsaturated zone
n_2 = Total porosity of the unsaturated zone

6.4.2.3 Information Reviewed to Define a Distribution for H_2

The default value for H_2 defined in NUREG/CR-5512, Vol. 1, is 1 m, which represents a thin unsaturated zone. A thin unsaturated zone was assumed to be conservative because it would result in relatively fast travel times through the unsaturated zone which would allow for more radionuclides to reach the groundwater. However, when contaminant transport is coupled with radioactive decay, it is difficult to define a priori whether or not a thin unsaturated zone is conservative. For example, a short travel time through the unsaturated zone would not allow for ingrowth of a particularly toxic daughter product.

Information concerning depth to the water table is a commonly reported quantity given the large number of observation wells located throughout the United States. For example, in New Mexico, there are 33,000 observation wells where data are regularly collected (USGS, 1990b). However, there is no readily available summary digital database for the continental U.S. A report by the USGS (USGS, 1990b), available on CD-ROM, does present State Water Data Reports from USGS observation wells throughout the continental U.S. This information was extracted from USGS open file reports. Therefore, there are inconsistencies in what data are reported and how they are reported from state to state. In addition, information from the western United States is particularly sparse, especially compared to the dense coverage of the eastern United States. For those areas where data is especially sparse, additional references were used (Idaho Department of Water Resources, 1998; USGS Colorado, 1998, Wyoming Water Resources Center, 1997). The only groundwater region where specific well data could not be found was the Columbia Plateau. However, Guzowski et al. (1981) provide summary water table depth information from this region, which was used to confirm that the resulting distribution included that range. Despite these problems with data availability, the combined data set is believed to be appropriate for representing the variability of unsaturated zone thickness throughout the United States for the screening calculation.

6.4.2.4 Proposed Distribution for H_2

To use the water table depths to generate a probability distribution function of H_2 from the referenced material, a 1.5 degree grid was overlayed onto a map of the continental U.S., which delineates the USGS groundwater regions (Fetter, 1988). The coarseness of the grid is chosen based on approximating the density of grid points per groundwater region to the areal density of the groundwater regions. The areal densities and grid point densities for the groundwater regions are presented in Tables 6.37 and 6.38, respectively.

Table 6.37 USGS groundwater regions areal density

Groundwater region	Area in square kilometers	Percent of total area
Alluvial Basins	1016791.19	13.06
Atlantic and Gulf Coastal Plain	889928.98	11.43
Colorado Plateau and Wyoming Basin	464019.23	5.96
Columbia Lava Plateau	369217.96	4.74
Glaciated Central Region	1253496.30	16.10
High Plains	382559.85	4.92
Nonglaciated Central Region	1859575.84	23.89
Northeast and Superior Uplands	379291.25	4.87
Piedmont and Blue Ridge	230726.81	2.96
Southeast Coastal Plain	194674.84	2.50
Western Mountain Ranges	743214.91	9.55

Table 6.38 USGS groundwater regions gridded sampling point density

Groundwater region	Number of grid points	Percent of total number of points
Alluvial Basins	46	12.81
Atlantic and Gulf Coastal Plain	38	10.58
Colorado Plateau and Wyoming Basin	20	5.57
Columbia Lava Plateau	21	5.85
Glaciated Central Region	61	16.99
High Plains	16	4.46
Nonglaciated Central Region	89	24.79
Northeast and Superior Uplands	17	4.74
Piedmont and Blue Ridge	10	2.79
Southeast Coastal Plain	8	2.23
Western Mountain Ranges	33	9.01

To associate a water table depth with a grid point location, the closest well to the grid point is used to assign a value of the water table depth to the grid point. For the eastern states, wells are typically found within a 20 mile radius of the grid point. West of the Mississippi River, wells are typically found within a 50 mile radius of the grid point. This process is chosen, as opposed to interpolation, in order to be consistent within a ground-water region (i.e., to avoid interpolating across ground-water regions) and because the resulting probability distribution is meant to represent the variability across the United States and not specific values at specific locations. The depth to water assigned to the specific grid point is an average of the highest and lowest water levels reported at the associated well, and therefore, represents the average of long term extremes. Values were not found for every grid point. Instead the search for values continued until a representative number of values was found for each groundwater region, based on the sampling point densities presented in Table 6.38. Figure 6.20 illustrates the 1.5 degree grid, along with the wells that were used to assign value to the nearest grid points. The exception to the data analysis process defined above is for Wyoming, where the data that was obtained was a depth to water two-dimensional surface. Therefore, the values at the surface that corresponded directly to the grid point locations were used.

The resulting data set of H_2 ranged from a minimum of 0.3 m in the High Plains groundwater region (a well in north central Nebraska) to a maximum of 316 m in the Alluvial Basins groundwater region (a well on the south rim of the Grand Canyon), with an average depth to groundwater of 22 m for the continental U.S. Table 6.39 lists the water-level depths at the grid locations. The proposed empirical probability distribution and cumulative probability distribution of unsaturated zone thickness, H_2, are shown in Figures 6.21 and 6.22, respectively. An empirical distribution was chosen due to lack of a basis for choosing a specific distributional form.

6.4.2.5 Parameter Uncertainty

The distribution is based on the assumption that licensed sites are uniformly distributed in space throughout the United States. Instead, sites are expected to be concentrated near population centers; however, the effect of this concentration on the distribution is unclear. Water table depth is also a function of time, responding to seasonally variable recharge rates and pumping rates.

6.4.2.6 Alternative Parameter Values

Information on water table depth is often available from state and city government agencies because this data is important for public water resource management and planning. It is expected that a licensee would easily be able to define a site-specific range or distribution from this information, considering uncertainties created by the 1000 year time-frame considered in the dose assessment.

6.4.3 Hydrologic Parameters: Soil Texture, Porosities (n_1, n_2), Relative Saturation (f_1,f_2), Infiltration (I), Bulk Densities (ρ_1, ρ_2) and Soil Areal Density (Ps)

6.4.3.1 Hydrologic Parameter Descriptions

Several input parameters represent characteristics of the surface soil or the soil of the unsaturated layer. These parameters include porosity and saturation ratio. Rather than sample independently from distributions of these parameters, the dependence of these parameters is represented by first sampling soil texture then selecting an appropriate distribution for porosity and saturation ratio for the sampled texture. Soil densities are tied to the soil texture by a functional relationship to porosity.

A common method of describing and quantifying soil texture is the USDA soil textural classification (Soil Survey Staff, 1997). This classification was used by Meyer and others (1997) to represent the variability of a number of soil hydrologic properties that are related to porosity and saturation ratio. The USDA soil textural classification is also reported in a variety of available electronic data bases for the United States.

Porosity (n) is a measure of the relative pore volume in the soil. It is the ratio of the volume of the voids to the total volume:

$$n = \frac{V_{voids}}{V_{total}} = \frac{V_{air} + V_{water}}{V_{air} + V_{water} + V_{soil}} \qquad (6.46)$$

Soil bulk density (ρ)represents the ratio of the mass of dried soil to its total volume (solids and pores together):

$$\rho = \frac{M_{soil}}{V_{total}} = \frac{M_{soil}}{V_{air} + V_{water} + V_{soil}} \qquad (6.47)$$

It is assumed that for each realization the porosities in the surface soil layer and in the unsaturated layer will be equivalent. The same holds true for the bulk densities. That is:

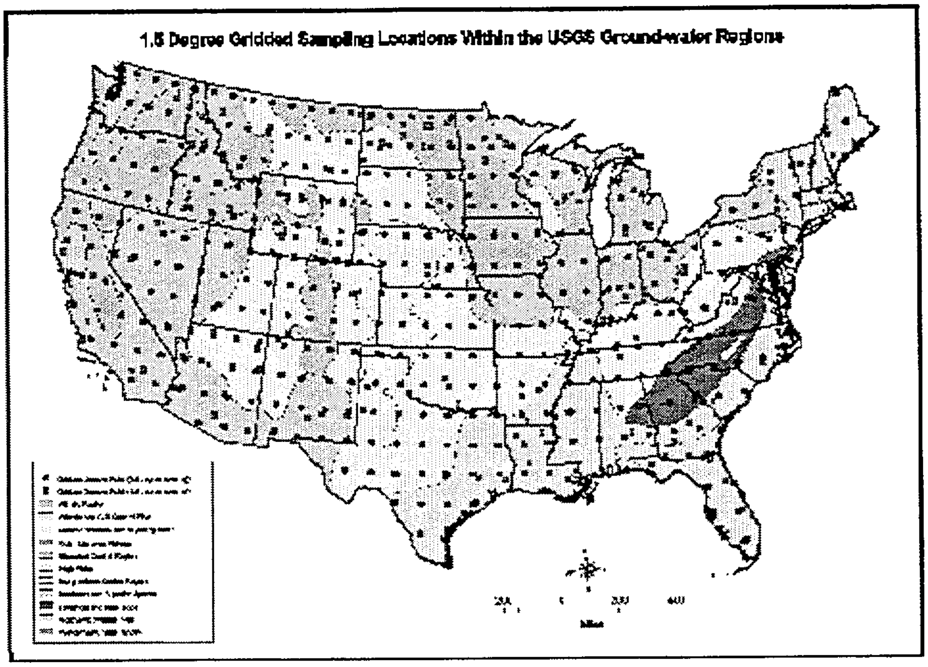

Figure 6.20 Gridded sampling and well locations within the USGS groundwater regions

Table 6.39 Estimated depth-to-water at gridded sampling locations

Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)
1	0.30	54	3.88	107	8.99	160	27.22
2	0.67	55	4.17	108	9.00	161	27.30
3	0.81	56	4.25	109	9.13	162	27.57
4	0.92	57	4.44	110	9.14	163	27.73
5	0.99	58	4.44	111	9.20	164	27.78
6	1.03	59	4.63	112	9.31	165	27.99
7	1.07	60	4.87	113	9.55	166	28.60
8	1.14	61	5.13	114	9.59	167	29.44
9	1.21	62	5.18	115	9.63	168	30.06
10	1.30	63	5.54	116	9.86	169	30.34
11	1.31	64	5.83	117	10.47	170	30.34
12	1.32	65	5.85	118	10.71	171	30.55
13	1.56	66	5.86	119	11.31	172	30.75
14	1.58	67	5.90	120	11.54	173	31.12
15	1.61	68	6.06	121	11.67	174	31.69
16	1.69	69	6.13	122	11.97	175	31.70
17	1.69	70	6.17	123	12.57	176	31.74
18	1.69	71	6.22	124	12.63	177	32.23
19	1.78	72	6.31	125	12.79	178	33.87
20	1.80	73	6.36	126	13.15	179	34.82
21	1.81	74	6.40	127	13.24	180	35.44
22	1.84	75	6.46	128	13.35	181	36.04
23	1.87	76	6.51	129	13.37	182	36.77

Table 6.39 Estimated depth-to-water at gridded sampling locations (continued)

Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)	Observation	Thickness (meters)
24	1.92	77	6.55	130	13.62	183	40.30
25	2.04	78	6.60	131	13.68	184	40.72
26	2.10	79	6.86	132	13.75	185	42.37
27	2.11	80	6.92	133	14.09	186	42.88
28	2.32	81	6.92	134	14.49	187	44.18
29	2.36	82	6.95	135	15.05	188	47.17
30	2.37	83	6.97	136	15.23	189	49.66
31	2.39	84	7.09	137	16.08	190	51.15
32	2.44	85	7.18	138	16.22	191	61.31
33	2.44	86	7.35	139	16.49	192	61.90
34	2.45	87	7.36	140	16.56	193	62.28
35	2.59	88	7.40	141	16.85	194	63.15
36	2.63	89	7.43	142	17.38	195	65.87
37	2.69	90	7.46	143	18.17	196	67.33
38	2.79	91	7.59	144	18.42	197	74.67
39	2.81	92	7.60	145	18.43	198	79.24
40	2.90	93	7.64	146	18.66	199	81.17
41	2.95	94	7.87	147	19.45	200	82.81
42	3.07	95	8.10	148	20.05	201	84.72
43	3.18	96	8.28	149	20.68	202	89.58
44	3.22	97	8.35	150	20.76	203	94.68
45	3.29	98	8.70	151	21.69	204	107.60
46	3.34	99	8.71	152	22.37	205	113.13
47	3.37	100	8.73	153	22.73	206	114.78
48	3.44	101	8.79	154	22.86	207	141.71
49	3.58	102	8.80	155	22.94	208	176.91
50	3.61	103	8.82	156	24.01	209	177.99
51	3.66	104	8.85	157	24.66	210	180.25
52	3.74	105	8.89	158	25.96	211	315.85
53	3.86	106	8.90	159	26.47		

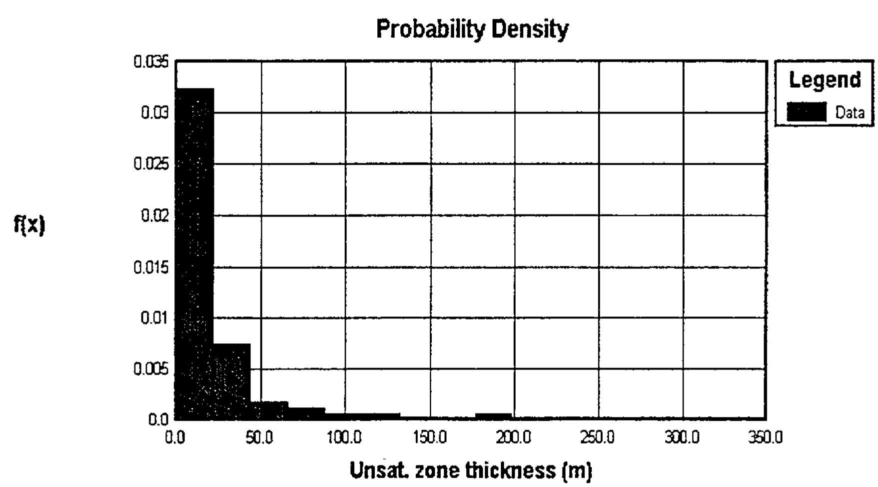

Figure 6.21 Empirical probability distribution for H_2

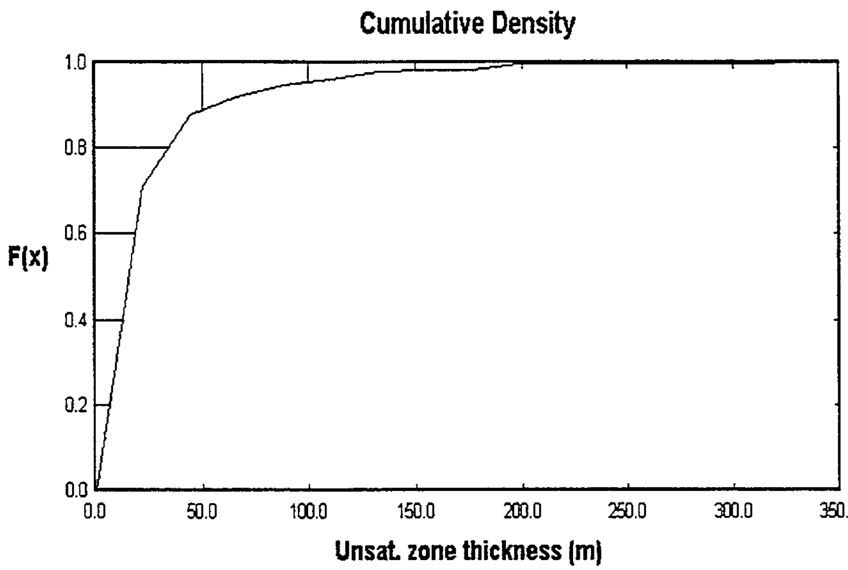

Figure 6.22 Empirical cumulative distribution function for H_2

$$n_1 = n_2 \tag{6.48}$$

$$\rho_1 = \rho_2 \tag{6.49}$$

Soil areal density of the surface plow layer is a measure of the mass of soil per square meter in the surface layer. The depth of this layer is assumed to be 0.15 m in the DandD model.

The infiltration rate is measured as the volume of water per unit area per unit time that percolates deeply beneath the root zone and becomes infiltration. It is the effective rate at which water moves through the surface soil layer and through the unsaturated layer, as well as the rate at which the aquifer receives recharge water. Its units are given as length/time.

The saturation ratio (f) expresses the volume of water relative to the volume of the pore space.

$$f = \frac{V_{water}}{V_{air} + V_{water}} \tag{6.50}$$

It is also a ratio of the moisture content (θ) to the porosity.

$$f = \theta / n \tag{6.51}$$

It is assumed that for each realization the saturation ratios in the surface soil layer and in the unsaturated layer will be equivalent. That is:

$$f_1 = f_2 \tag{6.52}$$

6.4.3.2 Use of the Hydrologic Parameters in Modeling

The hydrologic parameters control the rate at which the contaminant is leached out of each layer and is transported into the next layer. Soil texture is not used directly in the modeling; it is used to determine the active distribution for the directly related parameters; porosity and saturation ratio. The following equation is a generic representation of the leaching model (NUREG/CR 5512, Vol. 1, Equations 4.7–4.12, pp. 4.8–4.9).

$$L_{kj} = \frac{I}{H_k \theta_k Rt_k 365.25} \tag{6.53}$$

Where L is the leach rate for layer k and contaminant j, H is the layer thickness, θ_k is volumetric moisture content, Rt_k is the retardation factor, 365.25 is a time unit conversion factor and I is the infiltration rate (m/y). The retardation coefficient is a function of the partition coefficient (Kd), porosity (n) and bulk density (ρ) and the volumetric moisture content (θ_k) is a function of the sampled relative saturation and the porosity:

$$Rt_k = 1 + \frac{K_{d\rho}}{n} \tag{6.54}$$

$$\theta_R = fn \tag{6.55}$$

The effect of the hydrologic parameters on the dose is uncertain due to uncertainty in the dominant exposure pathway.

6.4.3.3 Information Reviewed to Define the Distribution of Soil Texture

The CONUS-SOIL database created and electronically 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 United States. This CONUS-SOIL database generalizes a variety of soils data, including the USDA soil texture, on a 1 km grid with constant layering. The layering consists of two 5 cm. thick layers near the land surface followed by three 10 cm. layers, three 20 cm. layers and finally three 50 cm. layers.

In general, the total area of each texture class is fairly consistent from layer to layer with the clay content tending to increase slightly with depth. Since the uppermost soil layer in the DandD conceptualization is 15 cm. thick, the three uppermost CONUS-SOIL layers were examined for uniformity and consistency. Approximately 85% of the area covered by materials with USDA classified soil textures is a consistent texture for the three uppermost layers. Table 6.40 summarizes the areal distributions of textures for the three upper layers individually and the volume weighted distribution of textures for the three layers combined.

6.4.3.4 Parameter Distributions

6.4.3.4.1 Soil Texture

The proposed probability distribution for soil texture is related to the volume weighted distribution of soil texture for the first three layers of the CONUS-SOIL database. The probability of encountering a specific soil texture is equal to the percentage of the volume occupied by a this soil texture. For example, the probability of the site having a silt loam soil texture is 24.881%.

Normal distributions of porosities (assumed to be equivalent to saturated water content) are given in Carsel and Parrish (1988). They are reported based on the 12 Soil Conservation Service textural classifications and a compilation of data for each of the textural classes. These distributions are used in the parameter analysis. The means and standard deviations for these normal distributions are given in Table 6.41.

6.4.3.4.2 Soil Bulk Density and Areal Density

Bulk density is functionally related to porosity:

$$\rho = (1 - n)\rho_p \tag{6.56}$$

where ρ is the soil bulk density (g/cm^3), n is the porosity, and ρ_p is the particle density (g/cm^3). In most soils the mean particle density is very close to the density of quartz (2.65 g/cm^3), typically the main component of sandy soils. Clay minerals have a similar density. While the presence of heavy minerals such as iron oxides 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/cm^3 (Hillel, 1980) and can be represented as a constant of 2.65 g/cm^3. With that, the bulk density becomes:

$$\rho = (1 - n)\cdot 2.65 \tag{6.57}$$

Table 6.40 CONUS-SOIL texture summary

USDA soil texture	Layer 1 (0–5cm) (% of area)	Layer 2 (5–10cm) (% of area)	Layer 3 (10–20cm) (% of area)	Volume weighted % of 0–20 cm
silt	0.005	0.005	0.015	0.01
sandy clay	0.000	0.065	0.216	0.124
sandy clay loam	0.398	0.650	1.323	0.923
silty clay	1.569	1.623	1.316	1.456
loamy sand	3.822	3.719	3.540	3.655
clay	3.525	3.845	5.766	4.726
clay loam	4.385	4.706	6.003	5.274
silty clay loam	4.578	4.734	5.407	5.032
sand	7.267	7.188	7.385	7.306
sandy loam	23.541	22.673	21.792	22.450
silt loam	25.339	25.336	24.424	24.881
loam	25.571	25.456	22.813	24.163

Table 6.41 Distributions for porosity based on soil texture (after Carsel and Parrish, 1988)

Soil type	Mean	Standard deviation	Number of samples
sand	0.43	0.06	246
loamy sand	0.41	0.09	315
sandy loam	0.41	0.09	1183
sandy clay loam	0.39	0.07	214
loam	0.43	0.10	735
silt loam	0.45	0.08	1093
silt	0.46	0.11	82
clay loam	0.41	0.09	364
silty clay loam	0.43	0.07	641
sandy clay	0.38	0.05	46
silty clay	0.36	0.07	374
clay	0.38	0.09	400

The soil areal density of the surface plow layer, P_s (kg/m^2), is a function of the bulk density (and hence the porosity). Actually, it amounts to nothing more than a conversion of units from the bulk density along with an assumption of a 0.15 m plowing depth. Mass is converted from grams to kilograms. Volume is converted from cubic centimeters to an area (in square meters) times an (implicit) depth of 0.15 meters:

$$P_s = 150 \cdot \rho \tag{6.58}$$

$$P_s = 397.5(1-n) \tag{6.59}$$

6.4.3.4.3 Infiltration Rate

Infiltration rate is a function of the amount of water applied to the land surface (either by precipitation or irrigation) and the soil hydraulic conductivity which controls the rate at which the soil is able to drain. To determine infiltration rate (I) we assume a model in which the infiltration rate is the product of the application rate (AR) and the fraction of the applied water that will percolate deeply beneath the root zone and become infiltration. (The infiltration fraction is designated as IF.) The infiltration fraction is a function of the saturated hydraulic conductivity (K_{sat}).

$$I = AR \cdot IF\left(K_{sat}\right) \tag{6.60}$$

Distributions of saturated hydraulic conductivity are given in Carsel and Parrish (1988). They are reported based on the 12 Soil Conservation Service textural classifications. Carsel and Parrish (1988) fitted distributions from a class of transformed normal distributions. Meyer et al. (1997) refitted the distributions of Carsell and Parrish (1988) to distributional forms that are more commonly used and more easily constructed— either lognormal or beta. The lognormal distribution is completely specified by the mean and standard deviation while the beta distribution is completely specified by mean, standard deviation, and range (upper and lower limits of the distribution). The distribution type and parameters for these distributions for each of the 12 soil types are given in Table 6.42.

The U.S. Bureau of Reclamation (USBR) has developed an empirical relationship between soil permeability and the proportion of water that percolates beneath the root zone (USBR, 1993) (shown in Figure 6.23 and in Table 6.43).

Having now developed a relationship for the propensity of soil to drain based on its ability to transmit water, we now consider water application rates.

Total water application at a particular site must equal or exceed the annual precipitation (assuming negligible runoff). The distribution for precipitation is given in Figure 6.24. This distribution was derived by interpolating a precipitation surface using average precipitation data obtained from weather stations across the conterminous United States (France, 1992; Owenby and Ezell, 1992). In humid regions of the country, precipitation supplies sufficient moisture to grow garden crops. In semi-arid or arid regions however, precipitation alone does not supply sufficient moisture to meet the requirements of garden crops. This water deficit must be met through the application of irrigation water. In determining minimum water requirements, we considered crops grown in arid regions because data are available for irrigation rates and obtaining data for total application of water (irrigation plus precipitation) is more problematic. Under arid conditions, irrigation water alone is sufficient to meet or nearly meet the crop

Table 6.42 Saturated hydraulic conductivity distributions

Soil type	Distribution type	Mean (cm/s)	Standard deviation	Lower limit	Upper limit	Number of samples
sand	beta	8.22E-03	4.49E-03	3.50E-04	1.86E-02	246
loamy sand	beta	3.99E-03	3.17E-03	3.90E-05	1.34E-02	315
sandy loam	lognormal	1.17E-03	1.37E-03			1183
sandy clay loam	lognormal	3.23E-04	5.98E-04			214
loam	lognormal	2.92E-04	4.91E-04			735
silt loam	lognormal	9.33E-05	2.24E-04			1093
silt	lognormal	4.89E-05	2.76E-05			88
clay loam	lognormal	9.93E-05	2.51E-04			345
silty clay loam	lognormal	1.54E-05	3.38E-05			592
sandy clay	lognormal	3.55E-05	1.48E-04			46
silty clay	lognormal	2.19E-06	4.08E-06			126
clay	lognormal	3.65E-05	1.08E-04			114

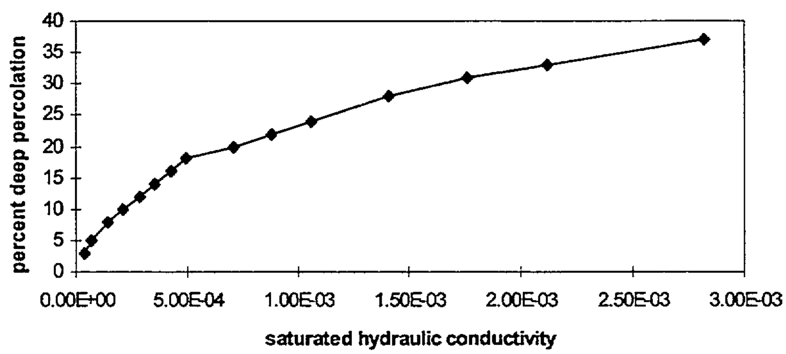

Figure 6.23 Percent percolation as a function of K_{sat}

Table 6.43 USBR relationship between soil permeability and infiltration fraction

Saturated hydraulic conductivity (inches/hr)	Saturated hydraulic conductivity (cm/sec)	Deep percolation (%)
0.05	**3.53E-05**	3
0.10	**7.06E-05**	5
0.20	**1.41E-04**	8
0.30	**2.12E-04**	10
0.40	**2.82E-04**	12
0.50	**3.53E-04**	14
0.60	**4.23E-04**	16
0.70	**4.94E-04**	18
1.00	**7.06E-04**	20
1.25	**8.82E-04**	22
1.50	**1.06E-03**	24
2.00	**1.41E-03**	28
2.50	**1.76E-03**	31
3.00	**2.12E-03**	33
4.00	**2.82E-03**	37

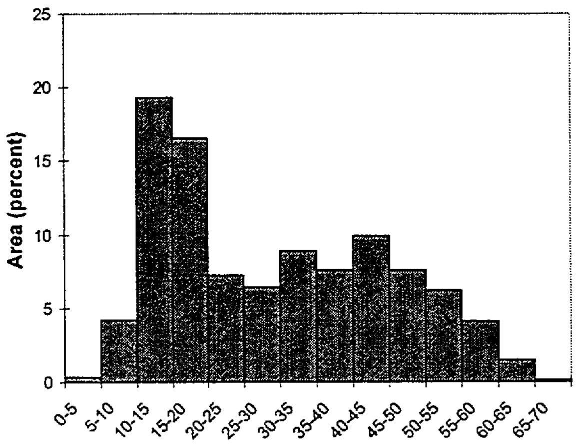

Figure 6.24 PDF for precipitation

water requirements since the contribution of precipitation in meeting the crop water requirements will be small to negligible. For this exercise, we considered irrigation rates for Idaho (USDC, 1994). Idaho data was used for several reasons. Its main commercial crop, potatoes, has similar water requirements to small vegetables typically grown in a home garden. (In fact, potatoes are commonly grown in home gardens.) Its climate is arid such that the vast majority of water for crops is supplied by irrigation. And its position along the Northern border of the country give it a single-crop growing season. Idaho applies just under 2 acre-feet of irrigation water per acre per year. As a comparison, water requirements for small vegetables, melons, and corn in New Mexico were also considered (USBR, 1997). These requirements range from 17 to 30 in. of water depending on the crop and the soil type, with an average requirement of about 24 in. of water, equivalent to the Idaho data.

Based on this data, a cumulative distribution for application rate is presented in Figure 6.25 and Table 6.44. For all precipitation rates at or above the minimum crop requirement of 2 ft of water, the application rate is considered to be equal to the precipitation rate. For all arid and semi-arid regions having precipitation rates of less than 24 in., water application rates are assumed to be equal to 24 in.

An additional logical condition is that the sampled water application rate at a particular site should never be less than the irrigation rate. If the sampled application is less than the irrigation rate, then the application rate is set equal to the irrigation rate.

$$\text{if } AP<IR, \text{ then } AP=IR \qquad (6.61)$$

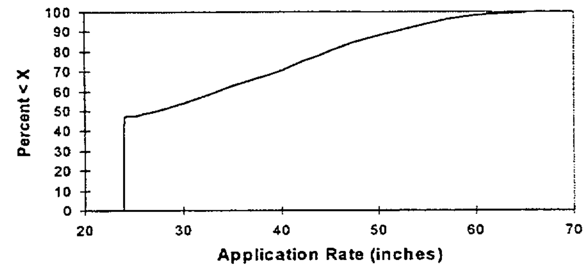

Figure 6.25 CDF for application rates

Table 6.44 CDF for application rates

Annual precipitation (inches)	% < X
<24	0.00
24	46.24
25	47.63
30	54.04
35	62.94
40	70.51
45	80.39
50	87.94
55	94.14
60	98.24
65	99.76
>65	100.00

Based on the preceding discussion, the steps to determining infiltration rate are as follows:

2. Sample soil type, using the volume-weighted percentages in Table 6.40.

2. Sample a saturated hydraulic conductivity for that soil type (Table 6.42).

3. Given the sampled hydraulic conductivity, use the USBR relationship relating soil conductivity to the infiltration fraction to determine the infiltration fraction. (Some interpolation or extrapolation may be required.) (Table 6.43)

4. Sample an application rate from the distribution in Table 6.44. (If AR < IR, then AR = IR.)

5. Calculate infiltration rate from the relationship, I = AR * IF. In some cases, the presence of low permeability soils will prevent infiltration at the calculated infiltration rate. The rate of water infiltration can be limited by the soil's ability to transmit water. The most favorable conditions for transmitting water through soils occur under

saturated conditions and a unit gradient. In this case, the rate at which water can be transmitted is equal to the soil's saturated hydraulic conductivity.

6. Compare (in consistent units) the infiltration rate to the saturated hydraulic conductivity. Use the lesser of the two as the infiltration rate.

7. Report infiltration rate in units of meters/year.

6.4.3.4.4 Saturation Ratios

Campbell (1974) derived a relationship between unsaturated hydraulic conductivity, K(θ) and saturation ratio, f:

$$K(\theta) = K_{sat} f^{2b+3} \qquad (6.62)$$

where b is a curve fitting parameter related to pore size distribution.

Under unit gradient, steady state conditions such as are assumed in the DandD model, the unsaturated hydraulic conductivity is equivalent to the infiltration rate determined above. Substituting infiltration rate for unsaturated hydraulic conductivity and rearranging to solve for the saturation ratio, results in:

$$f = \left[\frac{I}{K_{sat}}\right]^{\frac{1}{2b+3}} \qquad (6.63)$$

Since infiltration rate and saturated hydraulic conductivity are known from Steps 2 and 6 above, all that remains is to determine a value for b. Meyer et al. (1997) derived a relationship for b using soil water retention parameters considered in Carsel and Parrish (1988). Using this relationship, Meyer et al. (1997) constructed distributions for b. They are reported based on the 12 Soil Conservation Service textural classifications. The distribution type and parameters for these distributions for each of the 12 soil types are given in Table 6.45.

Meyer et al. (1997) also developed correlation matrices for parameters for each of the 12 soil types. There exists a moderate negative correlation between b and porosity as well as between b and saturated hydraulic conductivity. These correlations persist across all soil types. Summarizing the correlation matrices given for all soils, a correlation of −0.35 for both relationships is a reasonable approximation.

Once a b value is sampled, the saturation ratio can be calculated using the above equation.

The steps to calculate saturation ratio are:

1. Sample a value for the parameter b using the sampled soil type from Step 1 of the above procedure, then

2. Calculate "f" from Equation 6.63 using the sampled values for b, I, and Ksat.

6.4.3.5 Uncertainty in Hydrologic Parameters

The distribution for the soil texture was based on generalized soil textures throughout the continental U.S. These textures omit bedrock, highly organic soils (peat, muck, etc.), water, and "other" textures and should be representative of soil textures in most regions of the country. The distribution was selected to be most

Table 6.45 Distributions for the parameter *b*

Soil type	Distribution type	Mean	Standard deviation	Lower limit	Upper limit
sand	lognormal	0.998	0.226		
loamy sand	lognormal	1.40	0.397		
sandy loam	lognormal	1.96	0.579		
sandy clay loam	lognormal	4.27	1.39		
loam	lognormal	3.07	0.900		
silt loam	lognormal	3.80	1.42		
silt	lognormal	3.21	0.465		
clay loam	lognormal	5.97	2.37		
silty clay loam	lognormal	7.13	2.34		
sandy clay	lognormal	6.90	2.27		
silty clay	lognormal	10.2	2.96		
clay	beta	14.1	6.24	4.93	75.0

representative of surface soils (the upper 15 cm.). While deeper soils might tend to be slightly more clayey, this uncertainty is not expected to significantly affect the results of this analysis.

The distribution of soil types across sites is uncertain. Sites were assumed to be uniformly distributed over the area described in the CONUS-SOIL database.

6.4.3.6 Alternative Values for Hydrologic Parameters

Soil texture will vary from site to site and may vary over a site. While soil texture is not an explicit parameter in the DandD analysis, knowing it for a site may enable the licensee to refine the distributions of related parameters such as porosity and saturation ratio. For many sites, soil texture can be evaluated by reviewing existing soil surveys available from state agencies or the USDA. For sites located in regions with highly variable soils, site data on soil texture are easily collected by routine sampling and particle-size analysis.

6.4.4 Dust-Loading: Air Dust-Loading Outdoors, CDO and Indoors CDI (g/m^3); Floor Dust-Loading Pd (g/m^2) and Resuspension Rfr (m^{-1})

6.4.4.1 Parameter Descriptions

The dust-loading factors are used to calculate the average annual dose resulting from inhalation of airborne contaminants. The dust-loading factors, CDO and CDG, are used to calculate the inhalation dose due to activities occurring outdoors. CDO (g/m^3) represents the mass concentration of contaminated airborne particles in air outdoors, as defined in the exposure model, and corresponds to the long-term average quantity of respirable particulate material in outdoor air. CDG (g/m^3) represents the higher average mass loading of contaminated airborne particles in air while the individual is gardening. The default values for these parameters defined in Volume 1, are 1×10^{-4} g/m^3 for CDO and 5×10^{-4} g/m^3 for CDG. These values were defined based on the review of literature from outdoor air pollution studies from the National Air Sampling Network and studies on suspended particles in the atmosphere in communities across the United States.

The indoor dust-loading factor, CDI, represents the process of infiltration of contaminated airborne particles into the house (mass-loading) as the mass of infiltrating particles per unit volume of air. These particulates are distinguished from contaminated soil that is tracked indoors and subsequently released into the air by resuspension. Since the source of contamination is the surface soil layer, CDI becomes a function of the outdoor dust loading factor (CDO). CDI is used to calculate the average annual dose resulting from inhalation of airborne contaminants that are represented by parent and daughter radionuclides. The default value for this parameter as defined in Volume 1 (p. 6.10–6.11), is 5×10^{-5} g/m^3. This value was selected based on a fraction (1/100th) of the regulatory limit for total dust loading of respirable particulates in industrial settings (29 CFR 1910.1000, 1990), considered representative of the long-term average concentration of contaminated respirable dust, and is equivalent to 0.5 times the default CDO value.

P_d is a physical parameter that represents the long-term average mass of contaminated soil per unit area of floor inside the residence. Since it is a single parameter value for the entire time spent indoors, it is an average value for the entire house. The dust-loading on floors is used to estimate the airborne particulate concentration due to resuspension of soil tracked into the house. The default value for this parameter defined in NUREG/CR-5512, Vol. 1, is 0.4 g/m^2.

The resuspension factor, RF_r, defined for the NUREG/CR-5512 dose modeling, defines the ratio of the long-term average respirable contaminant concentration in air to the long-term average floor surface contaminant concentration due to contaminated soil tracked indoors. The default value for the resuspension factor recommended in NUREG/CR-5512, Vol. 1, is 5×10^{-5} m^{-1}, based on recommendations from IAEA (IAEA, 1970). The overall range of values obtained from literature published from 1964 to 1990 is 2×10^{-11} to 4×10^{-2} m^{-1}. However, most data referenced are for outdoor conditions (wind stress and vegetation). Only two of the references cited in Volume 1 provide data for indoor resuspension. The first of these, an IAEA technical report (1970), reports a value of 5×10^{-5} m^{-1}, which has been obtained for operating nuclear facilities and may not provide a representative value for resuspension in a residential setting. The second of these two references, a review by Sehmel (1980), provides different resuspension factors depending on the type of activity conducted within the rooms of the building (walking, vigorous sweeping, and fan) but does not differentiate between the resuspension of respirable and non-respirable particle sizes. The overall range cited by Sehmel is from 1×10^{-6} to 4×10^{-2} m^{-1} which may over estimate the resuspension factor used in this model because the data include non-respirable particles.

6.4.4.2 Use of Dust Loading Parameters in Modeling

CDO, CDG, CDI, P_d and Rf_r are important to dose because, the higher the mass loading in air, the higher the total annual dose during the first year of the residential scenario. CDO also influences the dust mass loading indoors (CDI). As described below, the dose for the inhalation pathway is directly proportional to each of these parameters.

These parameters are used for calculating the inhalation committed effective dose equivalent, DHR_i, from contaminated indoor and outdoor air as described in the following formula (NUREG/CR 5512, Vol. 1, p. 5.55, Equation 5.70):

$$\begin{aligned} DHR_i = & \left[24\, V_g (t_g / t_{tg}) CDG\ C_{si} \sum_{(j=1,Ji)} S\{A_{sij}, t_{tg}\} DFH_j\right] \\ & + \left[24\, V_x (t_x / t_{tr})\ CDO\ C_{si} \sum_{(j=1,Ji)} S\{A_{sij}, t_{tr}\}\ DFH_j\right] \\ & + \left[24\, V_r (t_i / t_{tr})\ (CDI + P_d RF_r)\ C_{si} \sum_{(j=1,Ji)} S\{A_{sij}, t_{tr}\}\ DFH_j\right] \end{aligned} \tag{6.64}$$

where V_g, V_r, and V_x correspond to the volumetric breathing rates for time spent gardening, indoors, and outdoors (m^3/h), respectively; t_g is the time during the one-year exposure period that the individual spends outdoors gardening (d); t_{tg} is the total time in one gardening period (d); t_i and t_x are the times in the one-year exposure period that the individual spends indoors and outdoors (excluding gardening), respectively; t_{tr} is the total time in the residential exposure period (d); CDI, CDO, and CDG are dust loading factors for indoor, outdoor, and gardening activities (g/m^3), respectively; C_{si} is the concentration of parent radionuclide i in soil at time of site release (pCi/g dry-weight soil); J_i corresponds to the number of explicit members of the decay chain for parent radionuclide i; $S\{A_{sij}, t_{tr}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over a one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); $S\{A_{sij}, t_{tg}\}$ is a time-integral operator used to develop the concentration time integral of radionuclide j for exposure over one gardening season during one-year period per unit initial concentration of parent radionuclide i in soil (pCi*d/g per pCi/g dry-weight soil); DFH_j is the inhalation committed effective dose equivalent factor for radionuclide j for exposure to contaminated air (in units of mrem per pCi inhaled); P_d is the indoor dust-loading on floors (g/m^2); and RF_r is the indoor resuspension factor (m^{-1}). The higher the value for each of the dust-loading and resupension factors, the higher the dose.

The concentration of contaminated particles in air indoors due to infiltration was assumed to be a fraction (PF) of the outdoor air concentration. The long-term average outdoor air concentration (C_{Oai}) is estimated as the product of CDO and the contaminant concentration in soil (C_{si}).

$$C_{Oai} = CDO\ C_{si} \tag{6.65}$$

Resulting in the following model of the concentration of contaminant i in indoor air due to infiltration:

$$C_{Iai} = CDI * C_{si} = PF * CDO * C_{si} \tag{6.66}$$

The factor PF represents the fraction of airborne particulates that infiltrate the house and remain airborne. This factor will be a function of the ability of the particulate matter to enter the house (generally reported as a penetration factor) and remain suspended. There will be less suspension of particles indoors (due to cleaning, static electricity and lower wind speed (air disturbance)) which will lead to a net deposition or loss.

6.4.4.3 Information Reviewed to Define Distributions for CDO and CDG

Air concentrations are determined using mass-loading factors and are converted to units of activity from the concentration of the source material. Thirteen references are listed in NUREG/CR 5512, Vol. 1, for this data (Hinton et al., 1986; Stern, 1968; HEW, 1969; MaGill et al., 1956; Shinn et al., 1989; Sehmel, 1975; Sehmel, 1977a; Sehmel, 1984; Sehmel, 1977b; Stewart, 1964; Sinclair, 1976; Soldat et al., 1973; Anspaugh et al., 1975). The outdoor air dust-loading factors range from 1×10^{-5} to 2.3×10^{-1} g/m^3 for all airborne particles. Under extreme conditions, air dust-loading can be as high as 5 g/m^3; however, these conditions persist for only very short periods of time. For particles less than 10 μm diameter (the respirable fraction), air dust-loading factors range from 1×10^{-5} to 7×10^{-4} g/m^3. Table 6.46 summarizes the experimental results on dust loading studies.

Additional information was reviewed to determine if other data or approaches, preferably more recent than those cited in NUREG/CR-5512, Vol. 1, were available to provide a defensible basis for constructing PDFs for CDO and CDG for use in this analysis. The outdoor dust-loading factor, CDO (g/m^3), represents the long-term average quantity of respirable outdoor dust, as defined in the exposure model. In order to define the parameter distribution, a detailed analysis of the factors that contribute to outdoor air-dust loading along with supporting experimental data on outdoor dust-loading measurements is needed.

Table 6.46 Total dust loading

Reference	Dust Loading
Anspaugh et al. (1975)	$9 \times 10^{-6} - 7 \times 10^{-5}$ g/m^3
Soldat et al. (1973)	1×10^{-4} g/m^3
Shinn et al. (1989)	2.1×10^{-5} g/m^3 (background)
	3.4×10^{-5} g/m^3 (sea spray)
MaGill et al. (1956)	$1 \times 10^{-4} - 2 \times 10^{-3}$ g/m^3
HEW (1969)	1×10^{-5} g/m^3 (rural areas)
	$6 \times 10^{-5} - 2.2 \times 10^{-4}$ g/m^3 (urban)
Stern (1968)	9.8×10^{-5} g/m^3 (geometric mean) with maximum of 1.7×10^{-3} g/m^3
Sehmel (1975; 1977a;1984)	upper limit of 7×10^{-4} g/m^3 (<10 μm diameter)
	upper limit of 2.3×10^{-1} g/m^3 (>10μm diameter)

In the absence of human activities that create or suspend airborne particulates, the major factor controlling the suspension and resulting particle concentration in air is wind speed. Higher dust loading due to human activity is represented by gardening. As shown by a number of authors, the particle concentration is an exponential function of the wind speed (e.g., Sehmel, 1977b). Unfortunately, there is no reliable analytical relationship between the wind speed and dust loading factor that could be used in defining dust loading from the average wind speed. Moreover, it is not clear how to specify the function and determine the proportionality coefficient between the wind speed and dust loading under different conditions.

Another important factor influencing dust loading is soil moisture. As discussed in (Tegen and Fung, 1994), suspension of soil particles in air is only possible when the soil matric potential[2] is greater than 10^4 J/kg. In other cases, no suspension will occur even under strong wind conditions. Moreover, suspension is also influenced to a great extent by vegetation cover. High resuspension is common for areas without vegetation or with sparse vegetation, and low resuspension is common for areas of dense vegetative cover. Finally, dust loading is affected by soil type (composition). Some soils are easily eroded, while other soil types are resistant to erosion. Other less significant factors are: topography (surface roughness) and snow cover/surface soil freezing.

Since the wind speed, soil moisture (or amount of precipitation), and vegetation cover are factors related to the climate, different categories could be defined based on different climatic conditions. More generally (including the other factors, such as soil types, topography, and etc.), categories could be defined based on different environmental conditions. The usefulness of one or another category definition depends on the availability of information on dust loading factors measured under different climatic or environmental settings. A second, and equally important factor, is estimating the probability that a particular site is in a specific category.

An extensive literature review was conducted to identify different categories of environmental conditions that could be reasonably defined based on published data. A summary of this review is presented in Table 6.47. The information allows us to evaluate single dust loading measurements and average values from a number of measurements, to distinguish between extreme conditions (dust loading during a dust storm) and normal conditions (dust loading under average wind conditions), and to compare environmental conditions specific to different sites.

Most of the dust loading values available from the literature (Table 6.47) represent the total amount of dust resuspended in air. The dust loading factor, as defined in NUREG/CR-5512, corresponds to the quantity of contaminated, respirable airborne particulates. According to the EPA, the respirable particles are particles smaller than 10 µm. Various studies have been conducted to determine the relationship between the mass loading and particle sizes. Data from Hinton et al. (1986) indicate the mass of respirable particles is 0.5 to 2.5 orders of magnitude less than the total mass of airborne particles. These data are supported by other observations (Sehmel, 1975; 1977a; 1984).

Another factor that influences the way experimental data should be interpreted in defining CDO is the difference in the particle mass suspended in air at different heights above the land surface. The dust loading factor defined in NUREG/CR-5512 should represent the air concentration at the respirable height. As discussed in (Sehmel, 1977a), the air concentration depends on the height. In some cases, the concentrations near the land surface can be lower than at some distance from the surface (usually, below the respirable height) where it reaches a maximum value. In other cases, the functional relationship is monotonic with higher concentrations near the land surface. However, the concentrations of suspended particles in the air vary by about 20% for a height between 0.5 and 2.0 m. Since particles are measured near the land surface or at the reference height of 1 m, these small variations can be neglected when defining the dust loading factor ranges.

[2]A measure of the surface tension of moisture in the soil.

Table 6.47 Outdoor dust loading

Reference	Dust loading (g/m^3)	Site description
Sehmel (1977b)	$7.7 \times 10^{-6} - 7.1 \times 10^{-4}$	Hanford Site, arid climate, sparse vegetation, average annual wind 3.4 m/s, 0.16 - 10 μm particles (numerous long-term average values over a 4 year period)
Sehmel (1977b)*	$2 \times 10^{-5} - 2.3 \times 10^{-1}$	Hanford Site, 10 - 230 μm particles (non-respirable, not included in data to support pdfs)
Prospero (1981)	2×10^{-5}	Near large body of water (Spring)
Pye (1992)	$1 \times 10^{-7} - 6 \times 10^{-5}$	Near large body of water
Hartmann et al. (1989)	$4.5 \times 10^{-5} - 1.3 \times 10^{-4}$	Humid climate, forest
Gao (1992)	4×10^{-6}	Near large body of water (Spring)
Rognon (1991)	$1.6 \times 10^{-6} - 1.3 \times 10^{-5}$	Desert region
Zier (1991)	$2.3 \times 10^{-5} - 1.2 \times 10^{-4}$	Near-surface air
Friedrichs (1993)	8×10^{-5} - 1.6×10^{-4}	Small industrial city
Tegen and Fung (1994)	1×10^{-4}	Areas of high dust loading (deserts, eroding cultivated areas)
Tegen and Fung (1994)	$5 \times 10^{-6} - 2.5 \times 10^{-5}$	Tropical climate, dense vegetation cover
Tegen and Fung (1994)	6×10^{-5}	Pacific Northwest
Clausnitzer and Singer (1996)*	$3 \times 10^{-4} - 1 \times 10^{-2}$	Dust collector mounted 94 cm above disturbed soil on agricultural implement (<4 μm diameter particles). (Respirable fraction, but not representative of average conditions for exposure due to measurement conditions)
Moulin et al. (1997)	1×10^{-5}	Tropical climate, dense vegetation cover (average over 30 year period)
NYS DEC (1981)	6.6×10^{-5}	Annual average over 4-year period

* Shaded rows are not included in the distribution; see text.

The outdoor air-dust loading, CDO, varies with the particle size of the contaminant, quantity of loose particulate contaminants at the surface, and magnitude and types of external stresses. The concentration of dust in the atmosphere has been measured and modeled under a wide range of conditions. Rognon (1991) conducted field measurements near the ground and correlated the dust content with surrounding soils based on the composition of the soil, state of the plant surface and ground cover, surface roughness, drag velocity, turbulence, wind velocity, and the atmospheric dust load and composition. The particle concentration varied from 1.6×10^{-6} to 1.25×10^{-5} g/m^3. Tegen and Fung (1994) applied a model that takes into account the size distribution of the dust particles to estimate the distribution of atmospheric mineral dust. Tegen extended the model to calculate the atmospheric mineral aerosol load under conditions in which the soil surface is disrupted by agricultural activities or the soil surface is exposed to wind erosion through deforestation and shifting desert boundaries. Suspended particulate matter was monitored by the New York State Department of Environmental Conservation in residential and industrial sections of a small city. The concentration of particulate matter averaged 6.6×10^{-5} g/m^3 over a four-year period (NYS DEC, 1982).

These data are not specific to human activities. The residential farmer is likely to work under more extreme dust-loading conditions for short periods of time; however, dust loadings greater than 4×10^{-3} g/m^3 for an extended period of time has resulted in a significant increase in death rates (MaGill et al., 1956). This information can be used to provide an upper bound on CDG if the time spent gardening is representative of the "extended periods of time" in the MaGill study.

6.4.4.4 Distribution for CDO

The potential variability in site-specific conditions and the large variability in the measured mass loading (orders of magnitude) indicate a wide range for the potential values of this parameter. The distribution of the dust loading is best represented by a log-uniform distribution with a lower limit of 1×10^{-7} g/m^3 and an upper limit of 1×10^{-4} g/m^3. The range of values is defined by the range of average values for dust loading of respirable particles (<10 μm in size) in arid and humid climates. The use of a log-uniform distribution ensures that the selection of a particular magnitude of CDO will be equally likely.

In the absence of information on the fraction of sites in each of the two climatic categories, due to unknown location of future sites and the indistinct categories of arid and humid, an equal probability has been assumed.

6.4.4.5 Distribution for CDG

Short-term gardening activities are expected to produce localized, elevated levels of dust loadings. Based on the data presented in Tables 6.46 and 6.47, the upper limit on dust loading for respirable particles is approximately 7×10^{-4} g/m^3 (Sehmel, 1975; 1977a; 1984). Higher dust loading of respirable particles has been measured (Clausnitzer and Singer, 1996) but not under conditions reasonable for human exposure and at levels that would cause physical harm. For this analysis the gardening dust-loading factor is assigned a uniform distribution with a lower limit of 1×10^{-4} g/m^3 and an upper limit of 7×10^{-4} g/m^3, based on the range of values from the literature for particulates less than 10 µm in diameter for higher dust loading activities (as cited in NUREG/CR-5512, Vol. 1). The lower limit for CDG corresponding to the upper limit of CDO, based on the intent of the gardening scenario to represent a higher level of activity while outdoors. This distribution for CDG will result in higher dust-loading during the time spent gardening.

6.4.4.6 Review of Information to Define CDI

Additional information was reviewed to determine data in addition to that presented in NUREG/CR-5512, Vol. 1, were available to provide a defensible basis for constructing a PDF to represent the variability of CDI for residential settings over all current and future sites.

The ratio of indoor to outdoor suspended particle matter has been reported from a number of studies. Whitby et al. (1957) studied the properties of airborne dust indoors and outdoors at various locations and reported values ranging from 65 µg/m^3 indoors to 93µg/m^3 outdoors (a ratio of 0.70). Total suspended particulate concentrations were monitored outdoors over a period of about four years near an industrial site. Sterling and Kobayoshi (1977) compared indoor and outdoor suspended particulate concentrations and observed that the concentration of suspended particles indoors is 77 to 85% of the corresponding concentration outdoors. However these studies did not distinguish between infiltration of airborne particles and resuspension of contaminated soil tracked indoors. As a result, these studies can only provide an upper bound on the potential CDI for the specific conditions evaluated (i.e., by assuming the floor dust loading or resuspension factor indoors are negligible).

A more recent study by Thatcher and Layton (1995) uses experimental data, modeling and evaluation of other published studies, to discriminate between resuspension and infiltration of particles. In their analysis, Thatcher and Layton's measurements and modeling support their conclusion that the difference in the indoor and outdoor air concentration due solely to infiltration (i.e., excluding resuspension) is a function of deposition indoors rather than the ability of the house to limit infiltration of particles. CDI represents the mass loading indoors of infiltrated particles and combines the effects of penetration and net deposition. As a result, studies that neglect deposition can be used to estimate the variability in PF (which is the ratio of CDI to CDO). The studies cited by Thatcher and Layton and the results of Thatcher and Layton's studies are summarized in Table 6.48.

6.4.4.7 Values for Parameter Analysis

Based the studies summarized in Table 6.48 it can be concluded that PF ranges from 0.2 to 0.7. This variability is due to a number of factors including the measurement technique, location within the house, and variability in the airborne particle size distribution. Given the limited number of studies and measurements to support a generic parameter value and the uncertainty in the particle size distribution of the contaminated soil, the variability in PF is best represented by a uniform distribution between the values of 0.2 and 0.7.

A separate PDF was not defined for CDI. Instead, CDI was calculated from values sampled for CDO and PF (see Equation 6.66).

6.4.4.8 Review of Additional Information to Define PDF for P_d

Solomon (1976) measured floor dust in a number of residential settings. The floor dust loading ranged from 0.11 to 0.59 g/m^2 based on 239 samples from 12

Table 6.48 Reported values for the ratio of indoor to outdoor dust loading

PF	Reference	Notes
0.2 – 0.6	Thatcher and Layton, 1995	3-10 µm particle size range, assuming deposition negligible
0.4 – 0.6	Thatcher and Layton, 1995	1-3 µm particle size range, assuming deposition negligible
0.7	Dockery and Spengler, 1981	respirable particles and sulfates
0.4	Freed et al., 1983	sub-micron particles
0.2	Freed et al., 1983	super-micron particles
0.3	Alzona et al., 1979	reported typical for Fe, Zn, Pb,Br and Ca
0.45	Cohen and Cohen, 1980	sub-micron particles, reported average for Fe, Zn, Pb,Br and Ca in residential and industrial settings
0.2	Cohen and Cohen, 1980	super-micron particles, reported average for Fe, Zn, Pb,Br and Ca in residential and industrial settings
0.7	Colome et al., 1992	<10 µm particle size, average for 35 California homes (range 0.4 to 1.5, may neglect resuspension)
0.77–0.85	Sterling and Kobayoshi, 1977	unknown size distribution, includes resuspension therefore not used to establish the pdf.

different dwellings. Similar results were reported from studies conducted by the New York State Department of Environmental Conservation (NYS DEC, 1982). In the absence of additional information, a uniform distribution is proposed. However, the results of these two studies are for total dust loading which may include non-soil components and soil from remote locations. As a result, these studies can be used to estimate an upper bound on P_d.

Thatcher and Layton (1995) performed a detailed modeling and experimental study to quantify the sources of indoor air contamination. They report that the major component of floor dust is soil, but they do not present the results. Total dust loading in the two houses in the Thatcher and Layton study ranged from 0.06 g/m^2 on linoleum to 43.4 g/m^2 on a rug by the door. Dust loading on carpeted floors was significantly higher than on linoleum (0.58 to 2.2 g/m^2) with the higher values in high-traffic areas. Information on the area of floor carpeted and the area covered with linoleum is not provided. If it is assumed that the floors are covered in equal parts linoleum and carpet and the area covered by the rug near the front door is negligible, then the average total dust load is on the order of 0.6 g/m^2.

A recent study by Rutz et al. (1997) evaluated the average total dust loading on floors in two separate homes and estimated the fraction of dust that is from contaminated soil. The results of this analysis provide information necessary to estimate P_d for those two homes if it is assumed that the floors are covered in equal parts linoleum and carpet and that the dust loading in the rug by the door is negligible when the dust density is averaged over the entire house. One house had an average total dust density of 0.4 g/m^2 and an average of 30% of that dust is contaminated soil resulting in a P_d of 0.12 g/m^2. The other home had a lower average total dust density (0.1 g/m^2) and an average of 20% of that dust is contaminated soil resulting in a P_d of 0.02 g/m^2.

Other studies on floor dust loading with contaminated soil cited by Rutz et al. (1997) indicate the dust is comprised of 31 to 50% contaminated soil (Calebrese and Stanek (1992) and Fergusson et al. (1986)).

6.4.4.8.1 PDF for P_d

Given this limited amount of information, the range of P_d values is 0.02 to 0.3 g/m^2 and all values in that range are equally likely. A uniform distribution between 0.02 and 0.3 g/m^2 was used to represent the uncertainty in this parameter.

6.4.4.9 Review of Additional Information to Define PDF for RF_r

An extensive literature review was conducted to identify any developments in the understanding of the resuspension process since the review reported in NUREG/CR-5512 in 1992, and to identify data or approaches that could be used to develop a probability distribution function for the indoor resuspension factor in the residential and occupancy scenarios. The general findings from the literature review are discussed in Section 5.4.4.3.

The published data indicate that resuspension factor values vary over orders of magnitude depending on site specific conditions which include the nature and intensity of mechanical disturbance associated with activities in the home.

The Thatcher and Layton (1995) study indicates that resuspension indoors is a function of the time individuals spend inside the home and that the two parameters are linearly correlated for the particular set of conditions analyzed. Variability from site to site in surface conditions, humidity, human activities and particle size distributions produces order-of-magnitude variations in RF_r. As a result, the uncertainty in the appropriate effective parameter value overwhelms the linear relationship between time spent indoors and RF_r.

6.4.4.9.1 Grouping of Reported Resuspension Factors based on Experimental Conditions

Table 6.49 summarizes the resuspension factors reported for experimental studies for various conditions (Jones and Pond, 1964; and Fish et al., 1964). The experiments by Jones and Pond (1964) provide average resuspension factors for a range of activities that are common in occupational settings. The measured resuspension factors reported by Jones and Pond (1964) are for four levels of activities conducted for 60 minute periods in a laboratory setting with different floor surfaces, using $Pu(NO_3)_4$ and PuO_2-contaminated particles (0.4–60 μm diameter) and particulate air samplers positioned at 14–175 cm above the surface. The particle size distribution includes non-respirable components and the height above the floor surface is not necessarily representative of the exposure scenario. Fish et al. (1964) provides average resuspension factors for a range of vigorous mechanical disturbances of contamination on a tile floor based on 10 minutes of the reported activity. The values in Table 6.49 for this study are reported for four levels of disturbances.

In order to develop a distribution that represents the average conditions in the residence, the average or effective activity level must be determined. Robinson and Thomas (1991) summarize the results of a national survey on time spent in activities. This survey, conducted in 1985, is based on averages from diaries kept by 1,980 adults (921 men) over a two month period. In this survey, adult men spent an average of 886 minutes per day at home, 6 minutes per day cleaning the house (vigorous activity) and 486 minutes sleeping. Some of this time at home was spent in the yard or garage, using the data presented for California, the time spent at home outside is approximately 37 minutes per day, leaving approximately 849 minutes per day indoors. Of the time at home spent indoors approximately 0.7% is vigorous activity, 57.2% sleeping (no activity), and the remaining 42.1% is spent in moderate to low activity. Given this estimate of how all adult males time is spent indoors, the effective parameter value should be a time weighted average of the Rf_r for each activity category. As can be seen in Table 6.50 the contribution from low to moderate activities while awake will dominate the time-weighted average.

PDF for Rf_r

The variability and uncertainty in the resuspension factor is best represented by a log-uniform distribution with a lower limit of 1×10^{-7}/m and an upper limit of 8×10^{-5} 1/m. These limits are based on the moderate waking activity range from Table 6.50, which dominates the time-weighted sum. The range of values is defined by the time weighted minimum and maximums of measured values for resuspension under low to moderate activities. The use of a log-uniform distribution ensures that the selection of a particular magnitude of RF_r within this range will be equally likely. This distribution reflects the uncertainty in the effective model parameter value given limited data on the relative amount of time spent at different activity levels by adult males indoors at home.

6.4.4.10 Uncertainty in RF_r

The proposed distributions describing the variability in the parameters representing indoor and outdoor dust-loading are determined by the following assumptions that introduce uncertainty in the distributions:

- Respirable particles are less than 10 μm in diameter, as defined in the NUREG/CR-5512 exposure model;
- there are an equal number of sites in each of the two climate categories (arid and humid).
- airborne contaminated particles will have a distribution of sizes such that there is net deposition indoors, and
- the long-term average PF is in the range 0.2 to 0.7 for all sites, indoor activities, outdoor activities and future houses,
- resuspension of loose particles indoors occurs by a combination of wind stress from normal building ventilation and mechanical disturbances from walking and other activities (e.g., cooking, sweeping, running, playing, exercising, working, reading, watching television; and

Table 6.49 Resuspension factors measured under various conditions

Experimental condition	RF_r (m^{-1})
Reported by Jones and Pond (1964)	
Air circulation (no mechanical disturbance)	7.7×10^{-10} to 1.5×10^{-7}
Walking (14 steps/min)	3×10^{-7} to 2×10^{-5}
Walking (36 steps/min)	9.7×10^{-7} to 1.8×10^{-4}
Walking (200 steps/min) with wind stress (hair dryer directed toward floor)	8×10^{-6} to 1.5×10^{-4}
Reported by Fish et al. (1964)	
Vigorous work activity, including sweeping	1.9×10^{-4}
Vigorous walking	3.9×10^{-5}
Light work activity	9.4×10^{-6}

Table 6.50 Time weighted resuspension factors

Activity	Range of Rf_r (m^{-1})	Reference	Fraction of time	Time weighted range RF_r
Sleeping	7.7×10^{-10} to 1.5×10^{-7}	Jones and Pond (1964); Air circulation	0.572	4.4×10^{-10} to 8.6×10^{-8}
Awake (not sweeping)	3×10^{-7} to 1.8×10^{-4}	Jones and Pond (1964); Walking (14 steps/min)	0.421	1.3×10^{-7} to 7.6×10^{-5}
Awake (vigorous, sweeping)	9.4×10^{-6} to 1.9×10^{-4}	Fish et al. (1964); Light to vigorous work activity	0.007	6.6×10^{-8} to 1.3×10^{-6}

- resuspension factor values are reported to depend to some extent on a number of other factors, including surface texture and roughness (in this case the type of floor covering), particle size distribution, type of deposition, and chemical properties of the contaminant and surface. These factors are assumed to produce site-to-site variations in resuspension factor values.

6.4.4.11 Alternative Values for RF_r

Several of the physical factors influencing dust loading and resuspension may be plausibly bounded by characteristics of the site, or controlled by the licensee in an effort to support a site-specific values for these parameters. These parameters may also change if the licensee defines a site-specific critical group.

The outdoor dust-loading factor would be expected to vary from site to site due to local climatic conditions, differences in the activities at the site, use of the property and activities that are likely to occur. The indoor dust-loading factor would be expected to vary from site to site due to differences in the activities at the site resulting in an uncertain distribution of the airborne particle sizes and, to a lesser degree, to the ability of the house to filter and prevent infiltration. The average floor dust loading for an entire house will depend on the relative amount of smooth (wood, tile or linoleum) verses rough (carpet) floor covering, the construction style (number of stories) and to a lesser degree the cleaning habits of the occupant. There may be regional differences in the indoor dust-loading factors due to construction styles and climatic differences. The resuspension factor will vary across sites due to differences in the use of the properties, and due to factors unrelated to the use of the property such as surface chemistry and topography.

6.4.5 Crop Yields for Vegetables, Fruits, and Grains Consumed by Humans, Y_v, and Forage, Y_f, Stored Grain, Y_g, and Stored Hay, Y_h, Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens (kg/m²)

6.4.5.1 Description of Crop Yields

The crop yields represent the average annual yields of garden produce (vegetables, fruit, grain) and livestock feed (hay, forage, and grain) that are grown on contaminated land and consumed by individuals and livestock at the site.

The crop yields are needed for determining the uptake and transport of radionuclides in: 1) irrigation water-plant-human pathway; 2) irrigation water-forage-animal-human pathway; 3) irrigation water-stored grain-animal-human pathway; and 4) irrigation water-stored hay-animal-human pathway, and the parameters are used to calculate the cultivated area, A_r (see Section 6.2.2).

6.4.5.2 Crop Yields for Vegetables, Fruits, and Grains, Y_v (kg/m^2)

Crop yields for vegetables, fruits, and grains, Y_v, describe the amounts of garden produce grown per unit area of cultivated land at the site. The model allows different values of Y_v for vegetables (leafy), vegetables (other than leafy), fruits, and grains. The default values of 2.0 kg/m^2 (leafy vegetables), 4.0 kg/m^2 (other vegetables), 2.0 kg/m^2 (fruits), and 1.0 kg/m^2 (grains) were adopted as the default values in NUREG/CR-5512, Vol. 1, and are based on information published by Shor et al. (1982), Strenge (1987), and Napier et al. (1988).

6.4.5.2.1 Use of Y_v in Modeling

Y_v is used in determining the average deposition rate of radionuclide j to edible parts of plant v from application of irrigation water per unit average concentration of parent radionuclide i in water (pCi/d·kg wet-weight plant per pCi/L water), R_{wvjg}, as shown by the following (Equation 5.22, p. 5.27 of NUREG/CR-5512, Vol. 1):

$$R_{wvjg} = IR\ r_v\ T_v / Y_v \left[C_{wj}/C_{wi}\right] \qquad (6.67)$$

where IR is the average annual application rate of irrigation water (L/m^2·d); r_v is the fraction of initial deposition (in water) retained on the plant (pCi retained per pCi deposited); T_v is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant part per pCi retained); Y_v is the yield of plant v (kg wet-weight plant/m^2); C_{wj} is the average annual concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average annual concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.2.2 Additional Information Reviewed to Define Revised Values for Y_v

Estimates of the yields for vegetables, fruits, and grains were obtained from USDA crop reports collected during the period from 1994 to 1996. Distributions for the individual crops for the residential scenario were determined from the annual average yields and the fraction of total crop area that is devoted to each crop. Tables 6.51 through 6.54 list the individual crops in each of the four categories (vegetables (leafy), vegetables (other), fruits, and grains), the total land area (averaged over three years) for production of each crop, and the average annual yield (kg/m^2).

6.4.5.2.3 Distribution for Crop Yields for Vegetables, Fruit, and Grain

The resident farmer is assumed to cultivate a mix of crops based on the reported fraction of cultivated area for each crop type. The yield for each crop type was assumed to be independent of the yield for other crops, and was assumed to follow a normal distribution with the reported average and standard deviation.

Distributions for crop yields were determined from the annual average yields for individual crops and the fraction of land for production of these crops using the following equation:

$$Y_c = \sum_{(j=1,n)} F_j * Y_j \qquad (6.68)$$

where Y_c is the total crop yield for a classification of produce (i.e., leafy vegetables, other vegetables, fruits, or grains), j corresponds to a particular crop, F_j is the fraction of the total land area for production of crop j, and Y_j is the reported yield of crop j. Figures 6.26 through 6.33 show the PDFs and CDFs for each of the edible crops identified in NUREG/CR-5512. The mean and range of crop yields for vegetable, fruit, and grain crops are summarized in Table 6.55.

6.4.5.3 Crop Yield for Forage, Y_f (kg/m^2)

Crop yield for forage, Y_f, represents the quantity of forage produced per unit area of cultivated land. The model accepts different values of Y_f for forage crops grown for consumption by beef cattle, poultry, milk cows, and layer hens. The crop yields are defined by standing biomass. Volume 1 proposes the following values: beef cattle, 1.5 kg/m^2; poultry, 1.0 kg/m^2; milk cows, 1.5 kg/m^2; layer hens, 1.0 kg/m^2. These value were based on information published by Shor (1982), Strenge (1987), and Napier et al. (1988).

Table 6.51 Production of vegetable crops (leafy) in 1994–1996*

Crop	Area (acres)	Fraction	Std Dev	Yield (kg/m^2)	Std dev
Artichokes	8633	0.0143	0.0005	1.182	0.240
Broccoli	119333	0.1978	0.0045	1.355	0.039
Brussel sprouts	3400	0.0056	0.0001	1.926	0.086
Cabbage	81273	0.1348	0.0022	3.811	0.211
Cauliflower	50317	0.0834	0.0057	1.500	0.085
Celery	27833	0.0461	0.0010	7.401	0.527
Head lettuce	204237	0.3385	0.0095	3.582	0.056
Leaf lettuce	39300	0.0652	0.0038	2.546	0.014
Romaine lettuce	30813	0.0511	0.0080	3.116	0.015
Spinach	38030	0.0630	0.0011	1.543	0.048

*Source: "Crop Production Annual Survey," National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture, January 1997.

Table 6.52 Production of vegetable crops (other than leafy vegetables) in 1994–1996*

Crop	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Asparagus	74217	0.02675	0.00087	0.31278	0.00895
Beans, Lima	53767	0.01937	0.00093	0.31310	0.00687
Beans, snap	294280	0.10599	0.00266	0.73221	0.04381
Beets	10217	0.00368	0.00015	3.11675	0.32048
Cantaloups	103447	0.03729	0.00113	2.15530	0.20594
Carrots	108323	0.03909	0.00437	3.71015	0.12441
Corn	713270	0.25701	0.00669	1.43156	0.02909
Cucumbers	171103	0.06163	0.00146	1.44046	0.03415
Eggplant	3067	0.00110	0.00015	2.46063	0.27061
Escarole	3613	0.00130	0.00007	1.72619	0.01439
Garlic	28667	0.01035	0.00101	1.90709	0.05609
Honeydews	26000	0.00938	0.00068	1.98313	0.18518
Onions	161653	0.05826	0.00130	4.37844	0.07288
Peas	280203	0.10084	0.00844	0.37263	0.00802
Bell peppers	66700	0.02405	0.00133	2.60024	0.17790
Tomatoes	470387	0.16949	0.00043	6.26320	0.12603
Watermelon	206423	0.07441	0.00224	2.25624	0.11714

*Source: "Crop Production Annual Survey," National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture, January 1997.

Table 6.53 Production of fruit crops in 1994–1996*

Crop	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Apples	459703	0.1540	0.00312	2.6400	0.1442
Apricots	21423	0.0072	0.00009	1.0261	0.5190
Avocados	67670	0.0227	0.00221	0.6163	0.0718

Table 6.53 Production of fruit crops in 1994–1996* (continued)

Crop	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Cherries, sweet	47347	0.0159	0.00011	0.8339	0.1438
Cherries, tart	44950	0.0151	0.00132	0.8062	0.1452
Cranberries	32467	0.0109	0.00020	1.5563	0.1282
Dates	5127	0.0017	0.00017	1.0553	0.1678
Figs	14767	0.0049	0.00004	0.7606	0.1160
grapes	759833	0.2545	0.00521	1.7269	0.0965
guaves	733	0.0002	0.00001	2.5727	0.1236
Kiwifruit	6700	0.0022	0.00010	1.2146	0.1251
Nectarines	31633	0.0106	0.00065	1.5735	0.3354
Olives	33133	0.0111	0.00016	0.7374	0.3214
Papayas	2157	0.0007	0.00011	2.6849	0.4294
Peaches	173072	0.0580	0.00132	1.4875	0.1403
Pears	70510	0.0236	0.00047	2.9766	0.3599
Plums	41633	0.0139	0.00034	1.0672	0.3566
Prunes	79300	0.0266	0.00037	1.7867	0.1588
Strawberries	48610	0.0163	0.00044	3.7544	0.0259
Oranges	763757	0.2556	0.01114	3.2780	0.0408
Grapefruit	165297	0.0553	0.00218	3.7573	0.2316
Lemons	61133	0.0205	0.00054	3.5158	0.2279
Limes	1933	0.0006	0.00001	1.2714	0.2656
Tangelos	12133	0.0041	0.00017	2.4964	0.5210
Tangerines	34300	0.0115	0.00124	2.0941	0.2632
Temples	6700	0.0022	0.00007	3.4799	0.2464

*Source: http://mannlib.cornell.edu

Table 6.54 Production of grain crops in 1994–1996*

Grain	Area (acres)	Fraction	Std dev	Yield (kg/m^2)	Std dev
Corn	66,434,000	0.3092	0.0136	0.7282	0.0976
Sorghum	9,960,000	0.0464	0.0056	0.4021	0.0401
Oats	4,802,000	0.0225	0.0073	0.1967	0.0243
Barley	7,562,000	0.0354	0.0059	0.2927	0.0370
Rye	443,000	0.0021	0.0006	0.1697	0.0103
Wheat	60,927,000	0.2838	0.0140	0.2460	0.0155
Rice	2,870,000	0.0134	0.0012	0.6398	0.0230
Flax	221,000	0.0011	0.0005	0.0952	0.0276
Sunflowers	2,385,000	0.0111	0.0028	0.1379	0.0216
Soybeans	59,008,000	0.2752	0.0111	0.2329	0.0258

*Source: "Crop Production Annual Survey," National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture, January 1997.

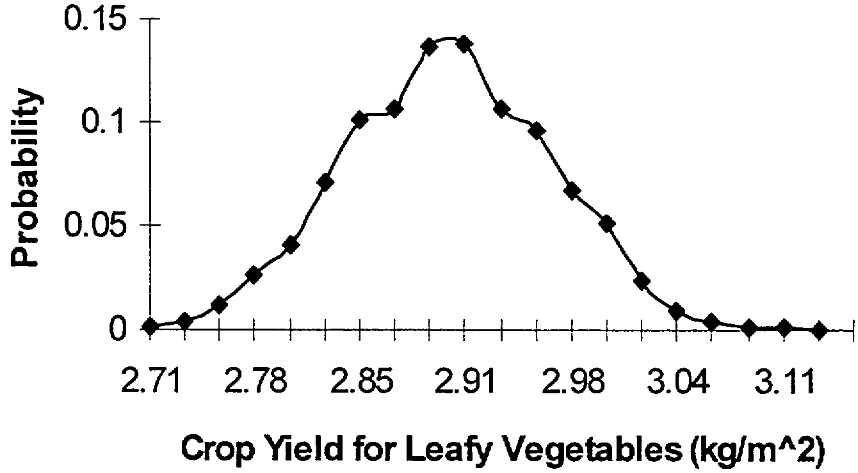

Figure 6.26 PDF for crop yields for vegetables (leafy)

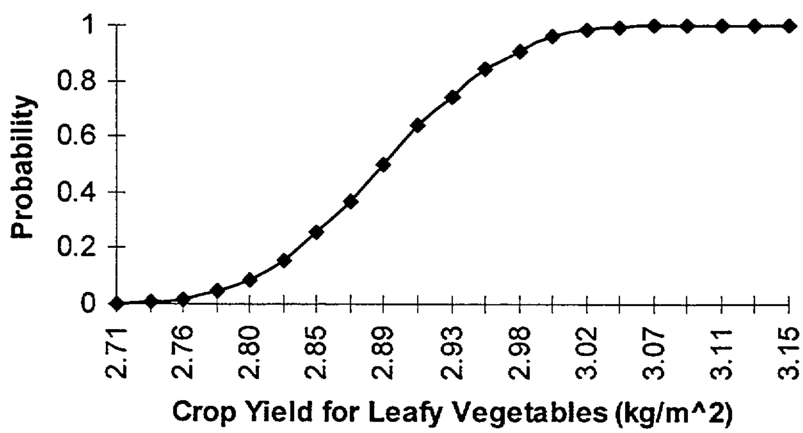

Figure 6.27 Cumulative distribution for Y_v (leafy vegetables)

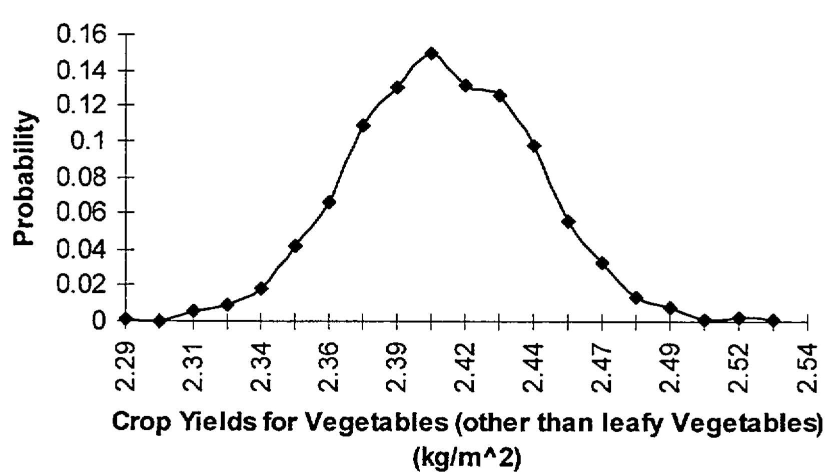

Figure 6.28 PDF for crop yields for vegetables (other)

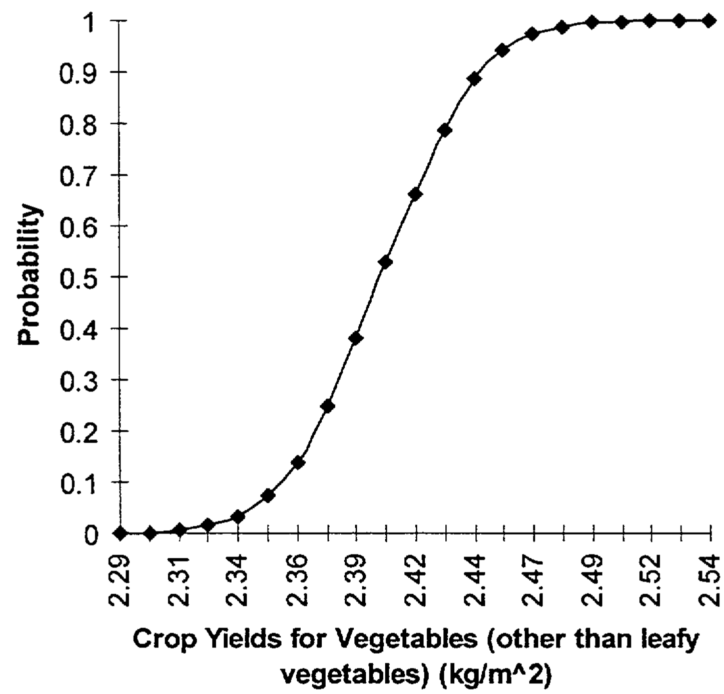

Figure 6.29 Cumulative distribution for Y_v (other vegetables)

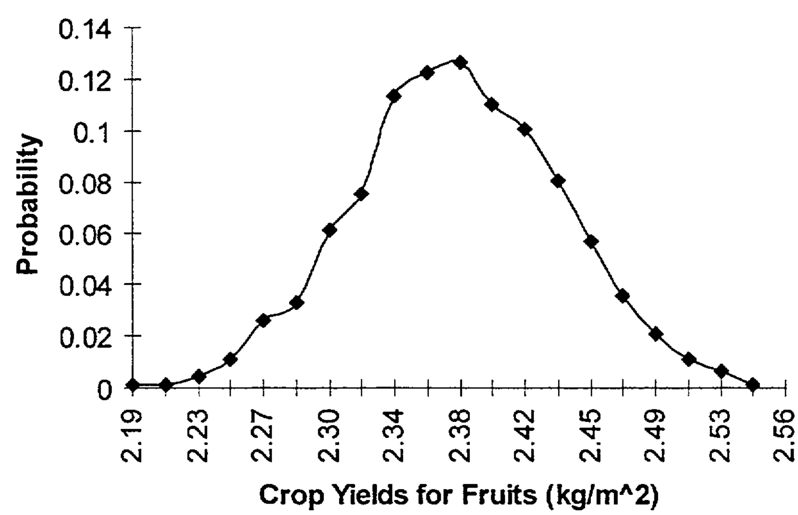

Figure 6.30 PDF for crop yields for fruit

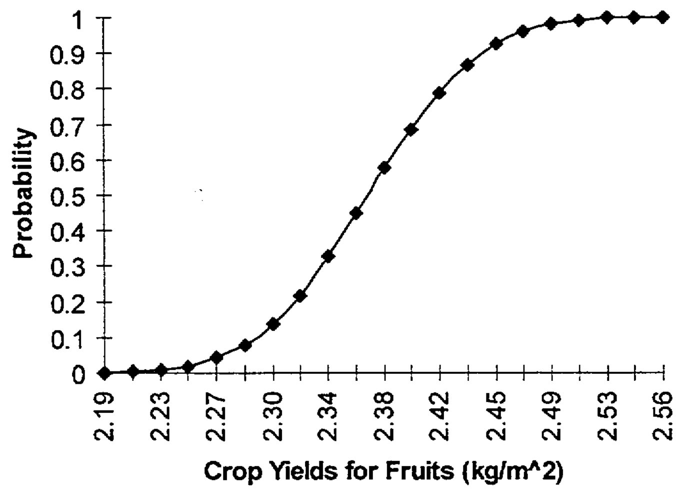

Figure 6.31 Cumulative distribution for Y_v (fruit)

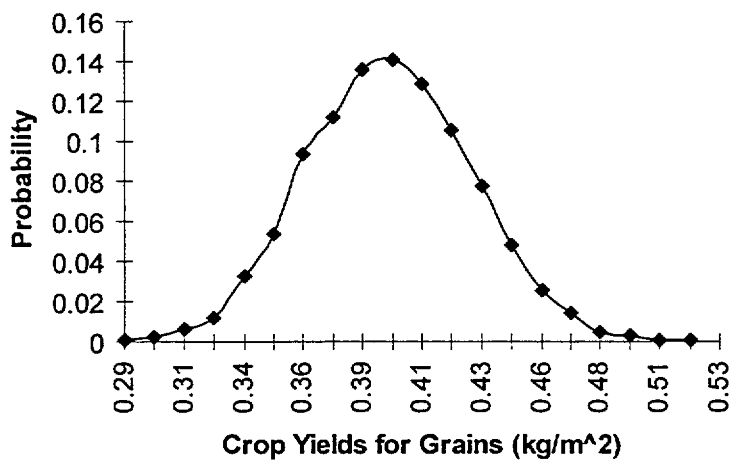

Figure 6.32 PDF for crop yields for grain

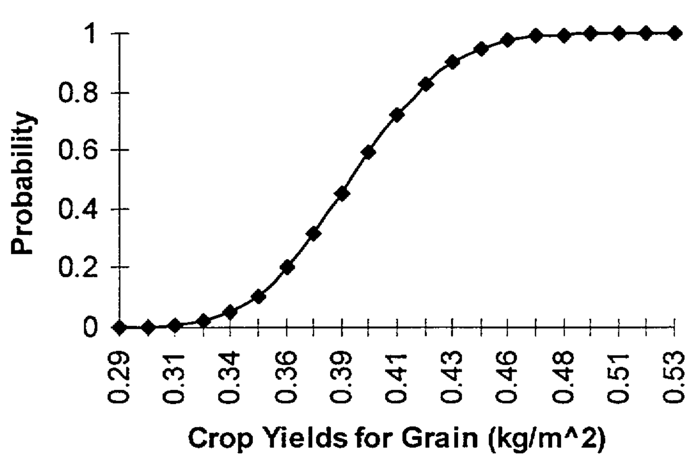

Figure 6.33 Cumulative distribution for Y_v (grain)

Table 6.55 Average yields and distribution for edible crops

Crop	Average yield (kg/m^2)	Range (kg/m^2)
Vegetables (leafy)	2.9	2.7 – 3.2
Vegetables (other)	2.4	2.3 – 2.5
Fruits	2.4	2.2 – 2.6
Grains	0.40	0.28 – 0.52

6.4.5.3.1 Use of Y_f in Modeling

Y_f is used to calculate the average deposition rate of radionuclide j to forage crop f from application of irrigation water during the feeding period for an average unit concentration of parent radionuclide i in water (pCi/d kg wet-weight plant per pCi/L water), R_{wfjf}. The relationship between Y_f and R_{wfjf} is described by the following:

$$R_{wfjf} = IRr_f \; T_f / Y_f \left[C_{wij} / C_{wi} \right] \qquad (6.69)$$

where IR is the annual average application rate of irrigation water (L/m^2 d); r_f is the fraction of initial deposition of radionuclides in water retained on plant h (pCi retained per pCi deposited); T_f is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant parts per pCi retained); Y_f is the yield of the forage crop f (kg wet-weight plant/m^2); C_{wj} is the average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.3.2 Additional Information Reviewed to Define Revised Values for Y_f.

Estimates of the crop yields for forage were obtained from information compiled by the USDA (USDA, 1997b,c). These data are summarized in Table 6.56.

The frequency distribution and fitted data PDF for average annual yield of forage crops in Table 6.56 are shown in Figure 6.34. The corresponding calculated and observed cumulative distributions are shown in Figure 6.35.

6.4.5.3.3 Proposed Distribution for Crop Yields for Forage

The distribution for Y_f was based on the average annual yield of forage crops. The binned data from Table 6.56 were fit to several functions and evaluated. The best fit was obtained with a beta function. The distribution parameters are shown in Table 6.57.

Table 6.56 Crop yields for forage crops (USDA, 1997c)

Year	Yield (kg dry-weight/m^2)
1987	0.484
1988	0.383
1989	0.456
1990	0.473
1991	0.486
1992	0.492
1993	0.486
1994	0.503
1995	0.511
1996	0.484

Table 6.57 Distribution parameters for crop yields for forage

Parameter	Value
a_1	2.36
a_2	1.26
δ_1	0.370
δ_2	0.524

6.4.5.4 Crop Yield for Stored Grain, Y_g (kg/m^2)

Crop yield for stored grain, Y_g, is the quantity of grain produced per unit area of cultivated land. The model uses a single, constant value for the yield of grain crops grown for consumption by beef cattle, poultry, milk cows, and layer hens. NUREG/CR-5512, Vol. 1, proposed the following values: beef cattle, 1.0 kg/m^2; poultry, 1.0 kg/m^2; milk cows, 1.0 kg/m^2; layer hens, 1.0 kg/m^2. These values were based on information published by (Shor, 1982), (Strenge et al., 1987), and (Napier et al., 1988).

6.4.5.4.1 Use of Parameter in Modeling

Y_g is used to calculate the average deposition rate of radionuclide j to stored grain from applying irrigation water with a unit concentration of parent radionuclide i (pCi/d kg wet-weight plant per pCi/L water), R_{wgjg}. The relationship between Y_g and R_{wgjg} is described by the following (Equation 5.53, p. 5,46 if NUREG/CR-5512, Vol. 1):

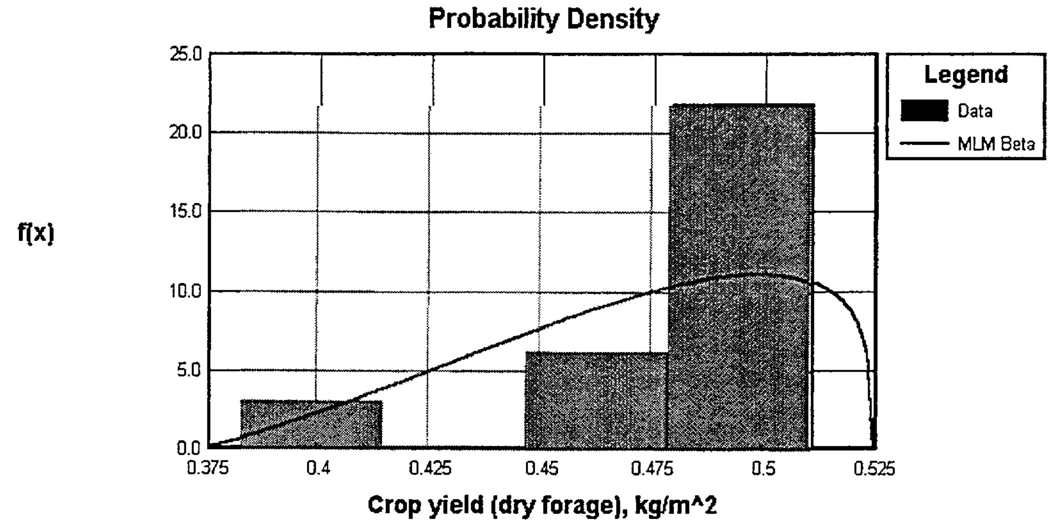

Figure 6.34 Frequency distribution and proposed PDF for Y_f

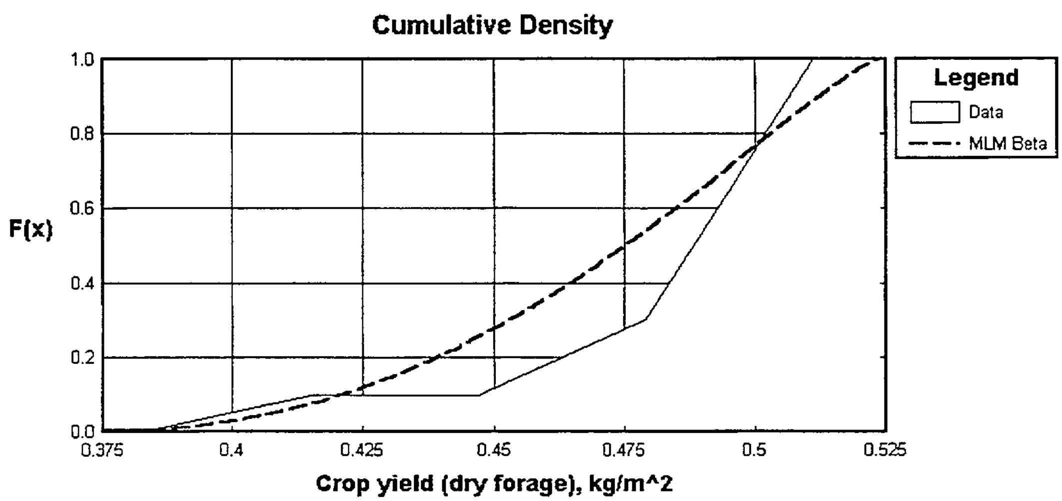

Figure 6.35 Cumulative distribution for Y_f

$$R_{wgjg} = IR\ r_g T_g / Y_g \left[C_{wj}/C_{wi}\right] \qquad (6.70)$$

where IR is the annual average application rate of irrigation water (L/m^2 d); r_g is the fraction of initial deposition of radionuclides in water retained on grain (pCi retained per pCi deposited); T_g is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant parts per pCi retained); Y_g is the yield of stored grain g (kg wet-weight plant/m^2 of land); C_{wj} is the average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.4.2 Additional Information Reviewed to Define Revised Values for Y_g

An estimate of the crop yield for grain was obtained from USDA crop reports collected across the United States. Tables 6.58 through 6.60 show the total acres harvested and the quantities and yields of corn, sorghum, and oats during the ten-year period beginning in 1987 (USDA, 1997b,c).

6.4.5.4.3 Proposed Distribution for Crop Yields for Grain

The distribution for Y_g was the value determined from the average annual yields of grain crops in Table 6.61. The resident farmer is assumed to cultivate a mix of grains that matches the fraction of the total cultivated area devoted to the three major grains. Table 6.61 shows the effective yield for this mixture calculated from the annual data in Tables 6.58 through 6.60. Annual variations in this yield were assumed to approximate the potential variations among sites. The binned data from Table 6.61 were fit to several functions and evaluated. The best fit was obtained with a normal function. The distribution parameters are shown in Table 6.62.

The frequency distribution and fitted PDF for average annual yield of grain crops in Table 6.61 are shown in Figure 6.36. The corresponding calculated and observed cumulative distributions are shown in Figure 6.37.

Table 6.58 Annual production of corn in the United States

Year	Acres	Fraction	Bushels	Yield (kg/m^2)
1987	59,505,000	0.773556	7,131,300,000	0.753
1988	58,250,000	0.799896	4,928,681,000	0.532
1989	64,783,000	0.782706	7,531,953,000	0.730
1990	66,952,000	0.816607	7,934,028,000	0.744
1991	68,822,000	0.824137	7,474,765,000	0.682
1992	72,077,000	0.813299	9,476,698,000	0.826
1993	62,921,000	0.831848	6,336,470,000	0.633
1994	72,917,000	0.84936	10,102,735,000	0.871
1995	64,995,000	0.853681	7,373,876,000	0.713
1996	73,147,000	0.833727	9,293,435,000	0.798
Mean		0.817882		0.728
Std. Dev.		0.02647		0.098

Table 6.59 Annual production of sorghum in the United States

Year	Acres	Fraction	Bushels/1000	Yield (kg/m^2)
1987	10,531,000	0.136901	730,809,000	0.436
1988	9,042,000	0.124166	576,686,000	0.401
1989	11,103,000	0.134146	615,420,000	0.348
1990	9,089,000	0.110858	573,303,000	0.396
1991	9,870,000	0.118192	584,860,000	0.372
1992	12,050,000	0.135969	875,022,000	0.456
1993	8,916,000	0.117874	534,172,000	0.376
1994	8,917,000	0.103911	649,206,000	0.457
1995	8,178,000	0.107414	460,373,000	0.354
1996	11,901,000	0.135647	802,974,000	0.424
Mean		0.122508		0.402
Std. Dev.		0.012687		0.0401

Table 6.60 Annual production of oats in the United States

Year	Acres	Fraction	Bushels	Yield (kg/m^2)
1987	6,888,000	0.089543	373,713,000	0.195
1988	5,530,000	0.075939	217,375,000	0.141
1989	6,882,000	0.083148	373,587,000	0.195
1990	5,947,000	0.072535	357,654,000	0.216
1991	4,816,000	0.057671	243,851,000	0.182
1992	4,496,000	0.050732	294,229,000	0.235

Table 6.60 Annual production of oats in the United States (continued)

Year	Acres	Fraction	Bushels	Yield (kg/m^2)
1993	3,803,000	0.050278	206,770,000	0.195
1994	4,010,000	0.046729	229,008,000	0.205
1995	2,962,000	0.038905	162,027,000	0.196
1996	2,687,000	0.030626	155,225,000	0.207
Mean		0.05961		0.197
Std. Dev.		0.019687		0.0243

Table 6.61 Weighted average annual yield of grain crops

Year	Yield (kg dry-weight/m^2)
1987	0.581
1988	0.428
1989	0.559
1990	0.588
1991	0.543
1992	0.657
1993	0.510
1994	0.701
1995	0.576
1996	0.642

Table 6.62 Distribution parameters for crop yields for grain

Parameter	Value
μ	0.5781
σ	0.0777

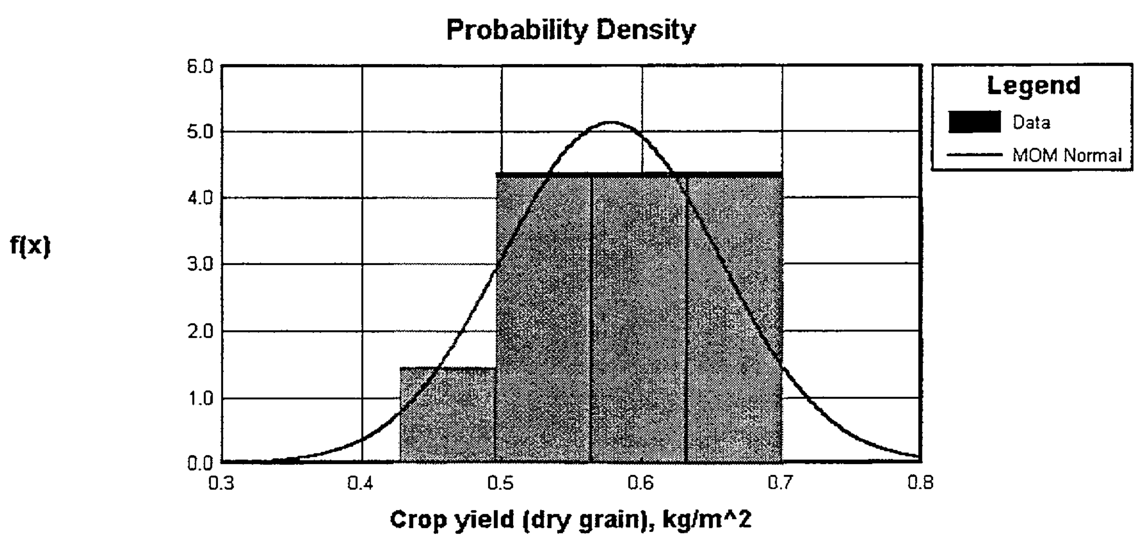

Figure 6.36 Frequency distribution and proposed PDF for Y_g

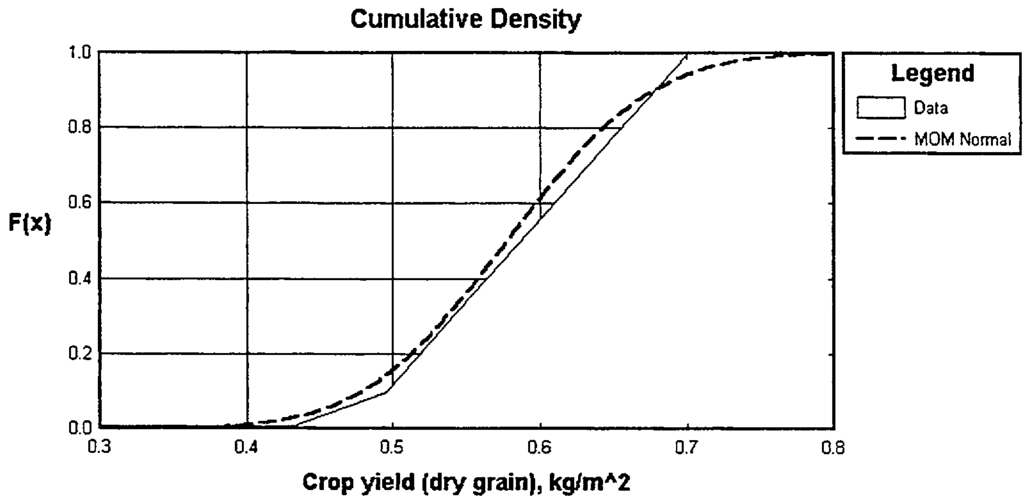

Figure 6.37 Cumulative distribution for Y_g

6.4.5.5 Crop Yield for Stored Hay, Y_h (kg/m^2)

Crop yield for stored hay, Y_h, represents the quantity of hay produced per unit area of cultivated land. The model accepts different values of Y_h for hay crops grown for consumption by beef cattle, poultry, milk cows, and layer hens. The crop yields are defined by standing biomass. Volume 1 proposes the following default values: beef cattle, 1.5 kg/m^2; poultry, 1.0 kg/m^2; milk cows, 1.5 kg/m^2; layer hens, 1.0 kg/m^2. These values were based on information published by Shor (1982), Strenge (1987), and Napier et al. (1988).

6.4.5.5.1 Use of Y_h in Modeling

The average deposition rate of radionuclide j to the stored hay crop from irrigation water, R_{whjg}, is calculated as follows (Equation 5.48, p. 5.41 of NUREG/CR-5512, Vol. 1):

$$R_{whjg} = IR\ r_h T_h / Y_h [C_{wj} / C_{wi}] \qquad (6.71)$$

where IR is the annual average application rate of irrigation water (L/m^2-d); r_h is the fraction of initial deposition of radionuclides in water retained on plant h (pCi retained per pCi deposited); T_h is the translocation factor for transfer of radionuclides from plant surfaces to edible parts of the plant (pCi in edible plant parts per pCi retained); Y_h is the yield of the stored hay crop h (kg wet-weight plant/m^2); C_{wj} is the average concentration of radionuclide j in irrigation water over the current annual period (pCi/L water); and C_{wi} is the average concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water).

6.4.5.5.2 Additional Information Reviewed to Define Revised Values for Y_h

Estimates of the crop yields for hay were obtained from data compiled by the USDA (USDA, 1997b,c). These values are listed in Table 6.63.

6.4.5.5.3 Proposed Distribution for Crop Yields for Stored Hay

The distribution for Y_h was determined from the average annual yields of hay crops. The binned data from Table 6.63 were fit to several functions and evaluated. The best fit was obtained with a beta function. The distribution parameters are shown in Table 6.64.

The frequency distribution and fitted PDF for average annual yield of hay crops in Table 6.63 are shown in Figure 6.38. The corresponding calculated and observed cumulative distributions are shown in Figure 6.39.

Table 6.63 Crop yields for hay crops (USDA, 1997b)

Year	Yield (kg dry-weight/m^2)
1987	0.484
1988	0.383
1989	0.456
1990	0.473
1991	0.486
1992	0.492
1993	0.486
1994	0.503
1995	0.511
1996	0.484

Table 6.64 Distribution parameters for crop yields for hay

Parameter	Value
a_1	2.36
a_2	1.26
δ_1	0.370
δ_2	0.524

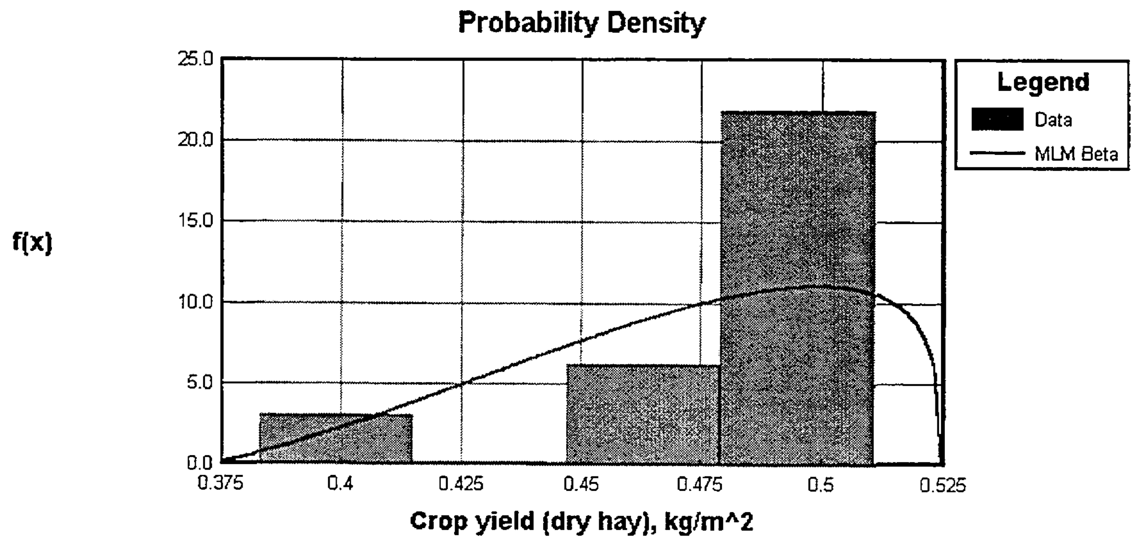

Figure 6.38 Frequency distribution and proposed PDF for Y_h

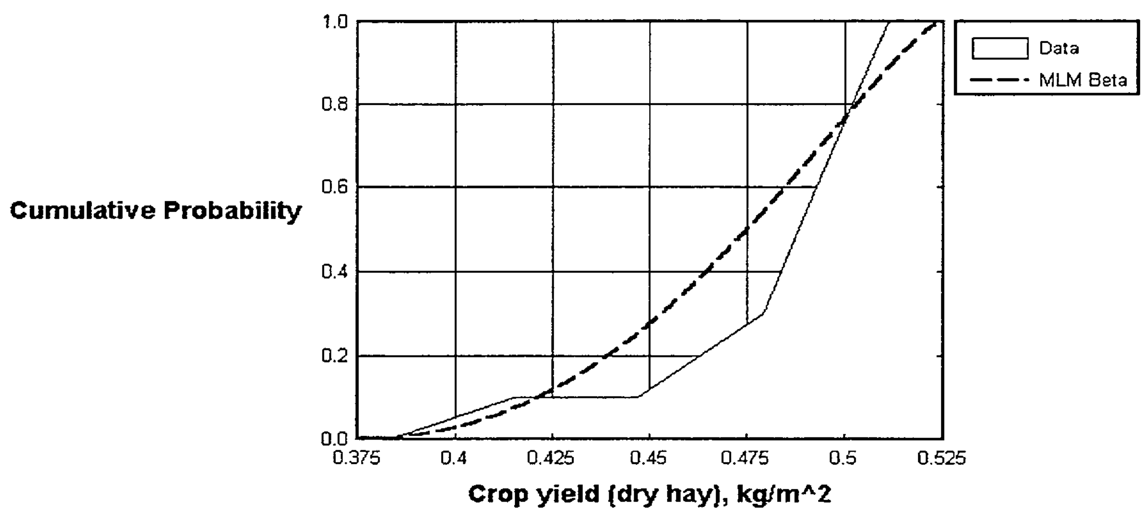

Figure 6.39 Cumulative distribution for Y_h

6.4.5.6 Uncertainty in Y_h

The distributions for each of the individual crops are based on the assumption that the resident farmer produces crops in direct proportion to the production across the United States. This assumption is not intended to describe any individual farmer, but corresponds to the conception of the receptor as the average member of the screening group of resident farmers. The average member of this group grows the average amount of each crop type.

The effective yield for this mixture is expected to vary from site to site because of variations in climate, soil conditions, and farming practice. Data on variations on the effective yield was not found. Instead, the distributions that describe this variability were estimated from other information on crop yields, including:

- Summary statistics for annual yields of individual vegetables, fruits, and grains from 1994 to 1996;
- Annual national average yields for forage, grain, and hay from 1987 to 1996.

Estimating the parameter distributions from this data requires assumptions about the independence of yield variations for different crop types, and about the similarity of site-to-site variations in yield to year-to-year variations in yield for hay, forage, and grain. These assumptions introduce uncertainty in the resulting distributions.

6.4.5.7 Alternative Y_h Values

Crop yields can vary from site to site depending on the location, climatic conditions, and soil type.

6.4.6 Animal Feed Intake Rates for Forage (Q_f), Stored Grain (Q_g), and Stored Hay (Q_h) Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens (kg/d)

6.4.6.1 Description of Animal Feed Intake Rates

The animal feed intake rates represent the average daily quantities of on-site produced foods consumed by livestock in the residential scenario. The feed intake rates for beef cattle, poultry, milk cows, and layer hens are used in the agricultural pathway to determine the total dose due to consumption of animal products. The animal feed consumption rates are combined with the fraction of food consumed that is contaminated and plant concentration factors to determine animal product concentration factors of radionuclides in a given quantity of product consumed by humans over the time period of interest.

6.4.6.2 Use of Animal Feed Intake Rates in Modeling

The animal feed intakes rates are used in the calculation of partial pathway transfer factors, PPTFs, for plant and animal products contaminated by soil. For a given concentration of contaminants in foods consumed by animals, the greater the animal feed intake rate, the higher the dose to humans via consumption of animal products.

The animal feed intake rates, Q_f, Q_g, and Q_h, are used to calculate the concentrations of radionuclides in beef, milk-producing cows, egg-laying hens, and meat-producing poultry that consume fresh forage, grain, or hay raised in contaminated soil irrigated with contaminated water. Those contaminated animal products are assumed to be raised and consumed on site by humans. While grazing fresh forage, the transfer of contaminants from soil to animal products occurs by two different processes: 1) ingestion of contaminated plant matter (through resuspension and root uptake from soil to plants) by animals, and 2) ingestion of contaminated soil by animals during grazing. For ingestion of stored grain or stored hay, the transfer of contaminants from soil to stored grain occurs by resuspension and root uptake from soil to the grain crop. Animals consume the contaminated plant matter which is then converted to animal products consumed by humans.

The following equations taken from NUREG/CR-5512, Vol. 1, are those for fresh forage and therefore include the subscript 'f'. Unless noted, identical equations are used for stored grain (subscript 'g') and stored hay (subscript 'h'). Note that some of the parameters in the equations have somewhat different definitions, primarily with respect to the timing of events. The references to the equations for stored hay and stored grain are also given in the following discussion.

The concentration of radionuclides in fresh forage consumed by the animal (at any time) is evaluated as follows (Equation 5.13, p. 5.19, NUREG/CR-5512, Vol. 1):

$$C_{sfjt} = 1000\left(ML_f + B_{jf}\right) W_f \, A\left\{C_{sj}, t\right\} / C_{si}(0) \qquad (6.72)$$

where C_{sfjt} is the concentration factor for radionuclide j in fresh forage crop f at time t, from an initial unit concentration of parent radionuclide i in soil; ML_f is the plant soil mass-loading factor for resuspension of soil onto the forage plant f; B_{jf} is the concentration factor for uptake of radionuclide j from the soil in fresh forage crop f; W_f is the dry-weight-to-wet-weight conversion factor for fresh forage crop f; $A\{C_{sj}, t\}$ denotes concentration of radionuclide j in soil at time t during the feeding period for fresh forage crop f; t is any point in time during the fresh forage feeding period; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period. For stored grain and stored hay, the NUREG/CR-5512, Vol. 1, references are Equations 5.12 and 5.11, respectively.

For fresh forage only, the average concentration of radionuclides in forage over the feeding period, t_{ff}, is evaluated as (from Equation 5.15, p. 5.21, NUREG/ CR-5512, Vol. 1):

$$C_{sfjc} = 1000\left(ML_f + B_{jf}\right) W_f \, A\left\{C_{sj}, t_{ff}\right\} / \left[t_{ff} C_{si}(0)\right] \quad (6.73)$$

where C_{sfjc} is the average concentration factor for radionuclide j in fresh forage crop f over the feeding period at time of animal consumption of forage from an initial unit concentration of parent radionuclide i in soil, $S\{C_{sj}, t_{ff}\}$ is the concentration time integral factor for radionuclide j in soil over the feeding period, and t_{ff} is the feeding period for forage crop f.

The concentration factor for animal product *a*, over the time period of feeding on fresh forage for radionuclide j for an initial unit concentration of parent radionuclide in soil, C_{sajf}, is given by (Equation 5.18, p. 5.22 of NUREG/CR-5512, Vol. 1):

$$C_{sajf} = F_{aj} \, Q_f \, x_f \, C_{sfjc} \quad (6.74)$$

where F_{aj} is the transfer coefficient that relates daily intake in animal feed and ingested soil to the concentration of radionuclide j in an animal product *a*, Q_f is the consumption rate of fresh forage by the animal, x_f is the fraction of animal forage intake that is contaminated, and C_{sfjc} is the average concentration factor for radionuclide j in fresh forage crop f, over the feeding period, at the time of animal consumption of forage from an initial unit concentration of parent radionuclide i in soil. For stored grain and stored hay, the NUREG/CR-5512, Vol. 1, references are Equations 5.17 and 5.16, respectively.

While ingesting fresh forage only, the amount of soil ingested while grazing is a function of the fresh forage intake rate. The average concentration factor for animal product *a*, over the fresh forage feeding period for radionuclide j for initial unit concentration of parent radionuclide i in soil, C_{sajd}, is given by the following (Equation 5.19, p. 5.22 of NUREG/CR-5512, Vol. 1):

$$C_{sajd} = 1000 \; F_{aj} \, Q_d \, W_f \, Q_f \, x_f \, S\left\{C_{sj}, t_{ff}\right\} / \left[t_{ff} C_{si}(0)\right] \quad (6.75)$$

where Q_d is the soil intake as a fraction of forage intake for the animal; W_f is the dry to wet-weight conversion factor for fresh forage; $S\{C_{sj}, t_{ff}\}$ is the concentration time-integral factor for radionuclide j in fresh forage crop f over the feeding period, t_{ff}; t_{ff} is the feeding period for the forage crop; and $C_{si}(0)$ is the initial concentration of parent radionuclide in soil at the start of the growing period.

Finally, the ingestion dose from agricultural products grown in contaminated soil, secondary ingestion of soil, and ingestion of animal products is given by the following (Equation 5.71, p. 5.56, NUREG/CR-5512, Vol. 1):

$$DGR_i = C_{si} \; DIET \sum_{j=1}^{J_i} A_{stj} \, AF_{sj} \quad (6.76)$$

where DGR_i is the annual dose from intake of home-grown food and animal products, C_{si} is the initial concentration of parent radionuclide in soil at the time of release of the site (i.e., the start of the growing season for the first year), DIET is no longer used (see Section 6.2.1), A_{stj} is the concentration factor for radionuclide j in soil at the beginning of the current annual exposure period per initial unit concentration of parent radionuclide i is soil at time of site release, and AF_{sj} is the dose factor for ingestion of agricultural product per unit concentration of radionuclide j in soil at the beginning of the growing season.

6.4.6.3 Information Reviewed to Define Animal Feed Intake Rate Distributions

The values proposed in NUREG/CR-5512, Vol. 1 (Table 6.8, p. 6.19), for foods consumed by beef cattle, poultry, milk cows, and layer hens are shown in Table 6.65. Rates are specified for each of the animal product consumed by humans: dairy cattle produce contaminated milk; laying hens produce contaminated eggs.

The transfer of radionuclides to humans from animal products also includes the direct ingestion of soil by animals while consuming fresh forage. The default value for intake rate of soil for cattle (beef and milk cows) was set to 2% of dry-matter forage intake. For poultry and egg-laying hens, the default intake value of soil was set to 10% of dry-matter forage intake. As discussed in Section 6.4.1 on the soil intake fraction, Q_d, these default values will continue to be used in the models.

Table 6.65 Animal feed intake rates from NUREG/CR-5512, Vol. 1

Intake medium	Beef	Intake rate (kg wet-weight/d)		
		Poultry	Milk	Eggs
Fresh forage (Q_f)	27 (14)	0.13	36	0.13
Stored hay (Q_h)	14 (27)	0	29	0
Stored grain (Q_g)	3	0.09	2	0.09

* Corrected values in parenthesis - see text.

Determination of the wet-weight intake rates reported in Table 6.65 was performed using the dry-weight intake rate, the percent intake by feed type, and the percent water content in the feed of interest for the animal type (from NUREG/CR-5512, Vol. 1, Equation 6.12, p. 6.19) as follows:

$$\text{(Wet Weight Intake Rate)} = \frac{\text{(Dry Weight Intake Rate)}\,\text{(Percent Intake)}}{\text{(100-Percent Water Content)}} \tag{6.77}$$

Derivation of the default values in Table 6.65 assumed that the intake rate for beef cattle is based on a total daily intake of 12 kg (dry-weight), with 25% in the form of fresh forage, 50% as stored hay, and 25% as stored grain. A water content of 78% was used in converting stored hay and forage (dry weight) to a corresponding wet-weight basis. The stored grain has a water content of 9%. When the default values were calculated for fresh forage and stored hay for beef using Equation 6.72, we found the corresponding values were transposed in Table 6.8 of NUREG/CR-5512, Vol. 1. The corrected values are shown in parenthesis in Table 6.65.

The intake rate for milk cows was based on a total daily intake of 16 kg (dry-weight), with 50% in the form of fresh forage, 40% as stored hay, and 10% as stored grain. For poultry, the intake rates were based on a total daily intake of 0.11 kg, with 25% as fresh forage and 75% as stored grain. It is assumed that poultry do not consume stored hay or any products made from stored hay in the residential scenario.

Information on the consumption of forage, grain and hay crops by beef and dairy cattle, poultry, and layer hens was obtained from National Research Council publications on the nutrient requirements of livestock (National Research Council, 1996a, and references cited therein). This new information includes and supercedes the original references (such as IAEA, 1982 and Till and Meyer, 1983) provided in NUREG/CR-5512, Vol. 1, for determining the default values for animal food intake.

6.4.6.4 Animal Feed Intake Rate Distributions

In the following four subsections summarizing food consumption by livestock, a consistent approach was followed for developing distributions of dry- and wet-weight matter intake for animals. The NRC publications provide average values from a number of studies for "dry matter intake" (DMI). Those reported averages include a 12% moisture content.

In the following subsections, the DMI values are provided in tables and reduced to actual dry matter by backing out the 12% moisture content as reported. The actual dry matter data, Q_{dry}, are then used to develop distributions for the respective animal feed intake rates as dry matter. The distributions are corrected (shifted) to account for the percentage intake of food products by each animal as originally reported in NUREG/CR-5512 and as summarized above in the discussion of the default values.

In Section 6.4.9, the distributions for W_f, W_g, and W_h, the wet-to-dry-weight conversion factors for forage, stored grain, and stored hay, are determined based on the following equation (using fresh forage as an example):

$$W_f = (100 - \%\ \text{Moisture, Forage})/100 \tag{6.78}$$

The dry intake rate distributions, Q_{dry}, are sampled along with samples of the wet-to-dry conversion factor, to derive the distributions for Q_f, Q_g, and Q_h on a wet-weight basis. These calculations are based on the following (again, using the example for fresh forage):

$$Q_f = \frac{Q_{dry} \times \text{Fraction of Intake}}{W_f} \tag{6.78}$$

where Fraction of Intake is the Percent Intake divided by 100. Therefore,

$$Q_f = \frac{Q_{dry} \times \text{Percent Intake}}{100 - \text{Percent Moisture of Forage}} \tag{6.79}$$

6.4.6.4.1 Fresh Forage, Stored Grain, and Stored Hay Consumed by Beef Cattle

The dominant factors that determine DMI of beef cattle are physiological demand (based on body weight and age), differences among breeds of beef cattle, and gastrointestinal capacity limits. In this analysis, we assume that the nutrient value of fresh forage (as well as stored grain and stored hay) is the same as the dry matter documented here. We also assume, consistent with NUREG/CR-5512, Vol. 1, that fresh forage provides

25% of the total nutrient requirements for beef cattle, and stored grain and stored hay provide 25% and 50%, respectively, of total intake requirements. Researchers referenced by the National Research Council (National Research Council, 1996) developed equations and relationships to predict and estimate DMI requirements for beef cattle.

One of these, Thornton et al. (1985) reported results on 119,482 yearling British breed cattle over a 12-month period. The data in Table 6.66 show 14-day averages for actual daily intake of dry matter as fed to cattle (includes 12% moisture assumed by Thornton). The daily intake for cattle is a function of size and weight. The distribution for dry forage, stored grain, or stored hay, Q_{dry}, consumed by beef cattle was developed from data in Table 6.66 by backing out the moisture content and equally weighting the average daily dry intake rate for each age category. This distribution represents the variability of the daily intake of food.

Table 6.66 DMI for beef cattle (Wernig et al., 1999)

Age (days)	Weight (kg)	Actual average intake (kg/d) - DMI	Dry matter (no moisture)
0 – 14	321	7.91	6.96
15 – 28	329	9.91	8.72
29 – 42	352	9.96	8.76
43 – 56	374	10.04	8.84
57 – 70	394	10.13	8.91
71 – 84	415	10.18	8.96
85 – 98	433	10.13	8.91
99 – 112	451	9.95	8.76
113 – 126	468	9.50	8.36
127 – 140	485	8.95	7.88

The binned data were fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit was obtained with a beta distribution. Table 6.67 provides the beta distribution parameters for fresh forage, stored grain, and stored hay consumed by beef cattle. The frequency distribution and the corresponding PDF for the intake rate for forage by beef cattle, Q_{dry}, is shown in Figure 6.40. Similar PDFs for stored grain and stored hay are represented in Figures 6.41 and 6.42. The corresponding cumulative distributions for Q_{dry} for fresh forage, stored grain, and stored hay are shown in Figures 6.43, 6.44, and 6.45.

Table 6.67 Beta distribution parameters for fresh forage, stored grain, and stored hay

Parameter	Fresh forage	Stored grain	Stored hay
a_1	1.99	1.99	1.99
a_2	0.911	0.911	0.911
δ_1	1.69	1.69	3.38
δ_2	2.29	2.29	4.58

6.4.6.4.2 Forage, Stored Grain, and Stored Hay Consumed by Dairy Cattle

Table 6.68 shows DMI for dairy cattle by body weight and milk production (NRC, 1996). Estimates of DMI for dairy cattle are complicated by milk production rates, lactation periods, environmental factors, feed quality, body weight, and other physiological factors. Many researchers quoted in the NRC reports have proposed equations and approaches for predicting and estimating feeding rates. Odwongo and Conrad (1983) developed equations for predicting daily DMI for dairy cattle as shown in Table 6.68.

As noted above, these DMI values were corrected to actual DMI, Q_{dry}, by backing out the 12% moisture content that was reported and correcting for the percentage of forage, stored grain, or stored hay intake for dairy cattle. Dairy cattle are assumed to derive 50% of total nutrient requirements from fresh forage, 40% from stored hay, and 10% from stored grain. This allocation is consistent with the allocation assumed in NUREG/CR-5512, Vol. 1.

The binned data from Table 6.68 were then fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit for fresh forage and stored hay was obtained with a gamma distribution. For stored grain, the best fit was represented by a normal distribution. Table 6.69 provides the gamma and normal distribution parameters for fresh forage, stored grain, and stored hay consumed by dairy cattle. The frequency distribution and the fitted PDF for the intake rate for forage for dairy cattle, Q_{dry}, is shown in Figure 6.46. Similar PDFs for stored grain and stored hay are represented in Figures 6.47 and 6.48. The corresponding cumulative distributions for Q_{dry} for fresh forage, stored grain, and stored hay for dairy cattle are shown in Figures 6.49, 6.50, and 6.51.

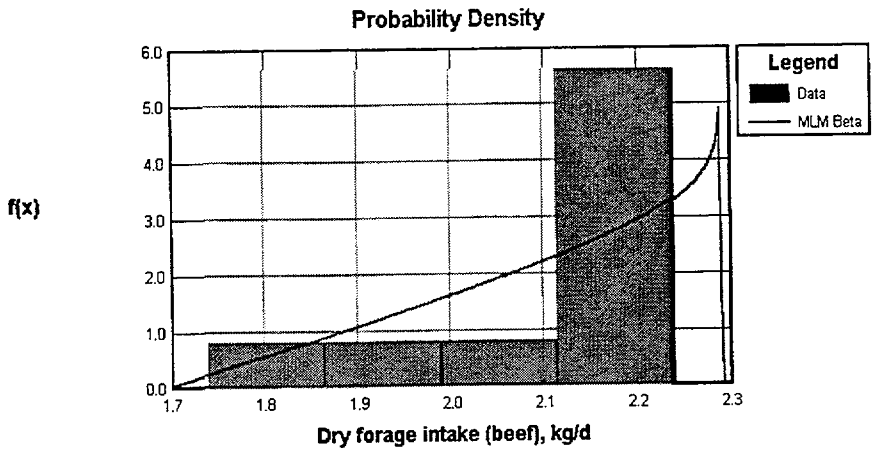

Figure 6.40 Calculated probability distribution for forage consumed by beef cattle

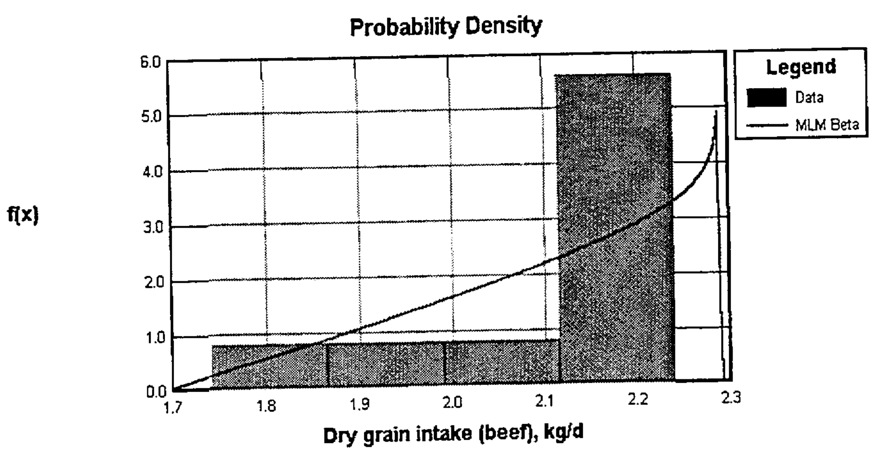

Figure 6.41 Calculated probability distribution for stored grain consumed by beef cattle

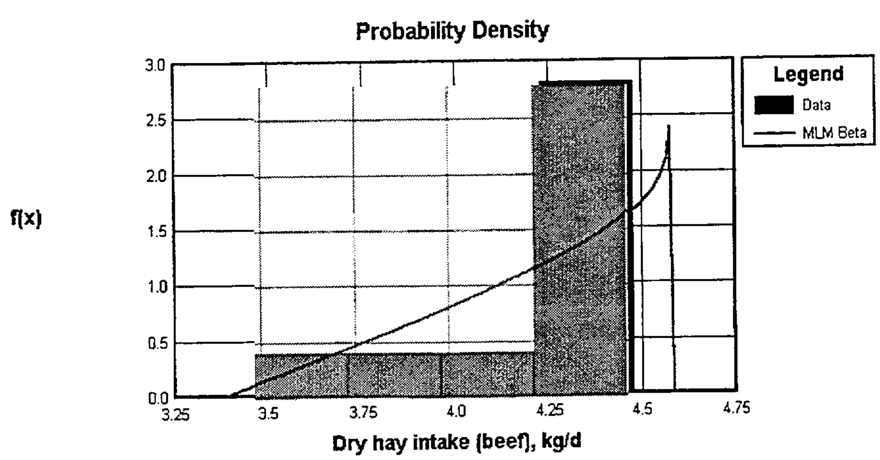

Figure 6.42 Calculated probability distribution for stored hay consumed by beef cattle

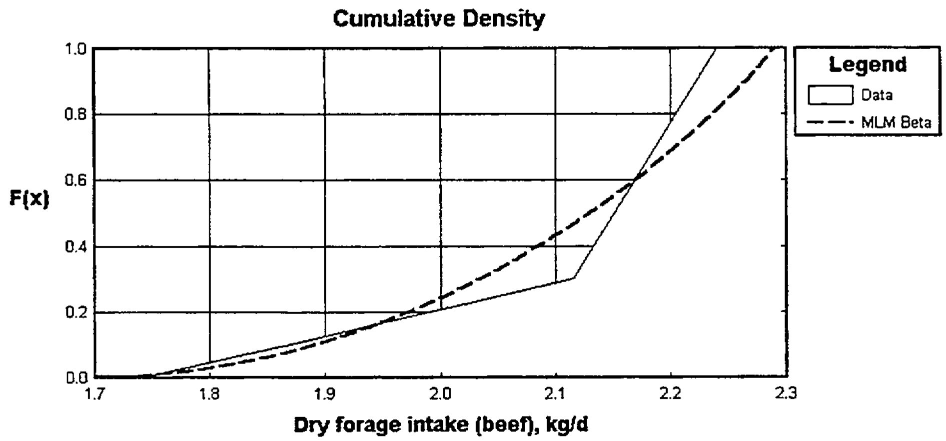

Figure 6.43 Cumulative distribution for forage consumed by beef cattle

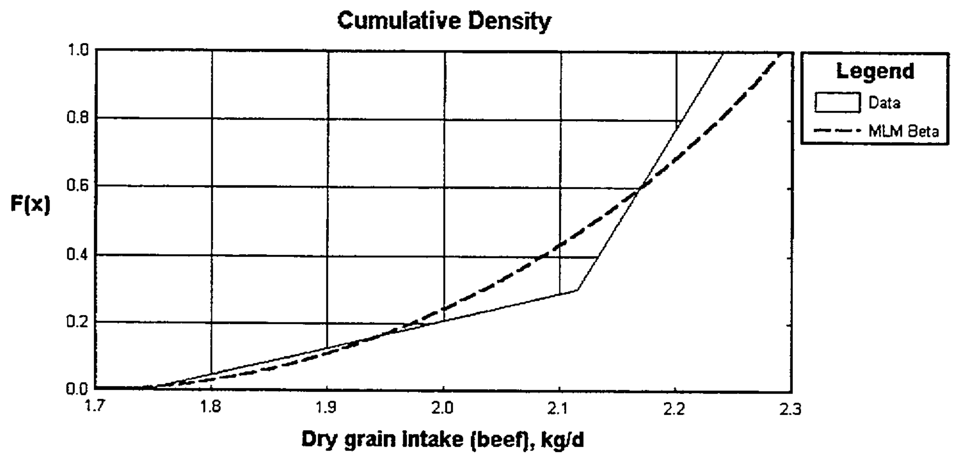

Figure 6.44 Cumulative distribution for stored grain consumed by beef cattle

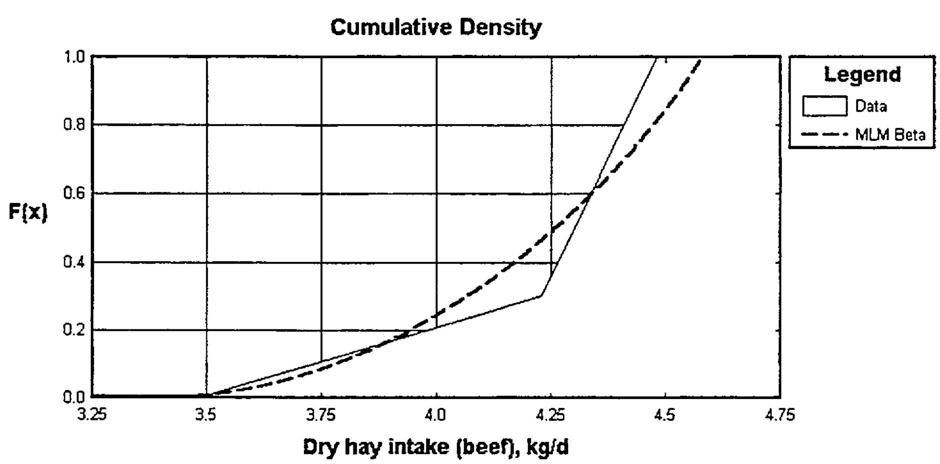

Figure 6.45 Cumulative distribution for stored hay consumed by beef cattle

Table 6.68 Predicted DMI in dairy cattle (kg/d) (NRC, 1996)

Milk production (Kg/d)	Body weight (kg)							
	400	450	500	550	600	650	700	800
	DMI (kg/d)							
15	14.7	15.7	16.8	17.7	18.7	19.6	20.5	22.1
20	14.9	16.0	17.1	18.0	19.0	20.0	20.9	20.5
25	14.7	15.8	16.8	17.8	18.8	19.7	20.5	22.7
30	14.5	15.6	16.6	17.6	18.5	19.4	20.3	22.2
35	*	16.4	17.5	18.5	19.5	20.4	21.3	22.0
40	*	*	18.3	19.4	20.4	21.4	22.4	28.6
45	*	*	*	20.2	21.2	22.2	23.2	29.0
55	*	*	*	19.9	21.0	22.0	23.0	29.7

* amount of feed computed was in excess of the amount that cows would be expected to eat

Table 6.69 Distribution parameters for forage, stored grain, and stored hay

Parameter	Fresh forage	Stored grain	Stored hay
Gamma			
κ	2.74		2.743
λ	1.15		1.43
ϵ	6.26		5.00
Normal			
μ		1.71	
σ		0.262	

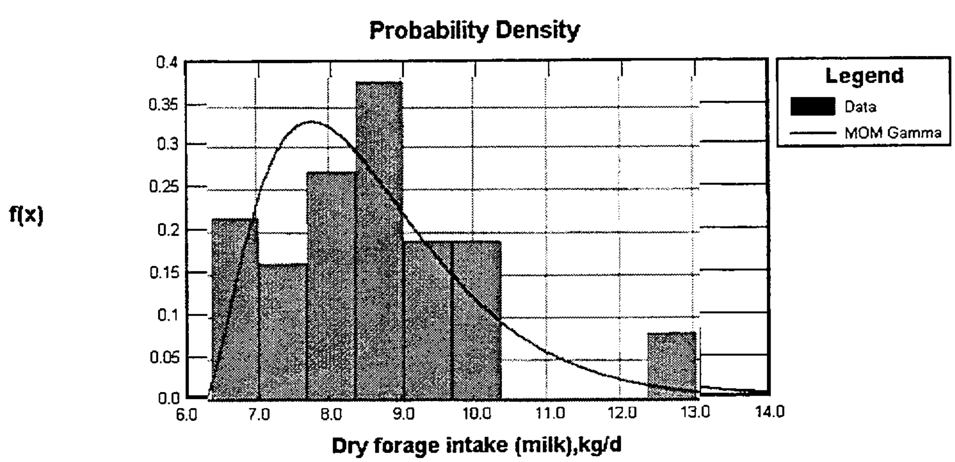

Figure 6.46 Calculated probability distribution for forage consumed by dairy cattle

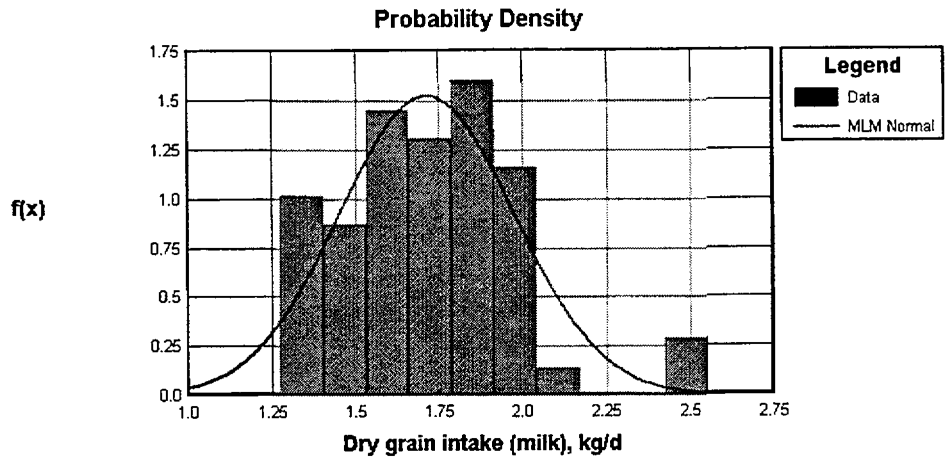

Figure 6.47 Calculated probability distribution for stored grain consumed by dairy cattle

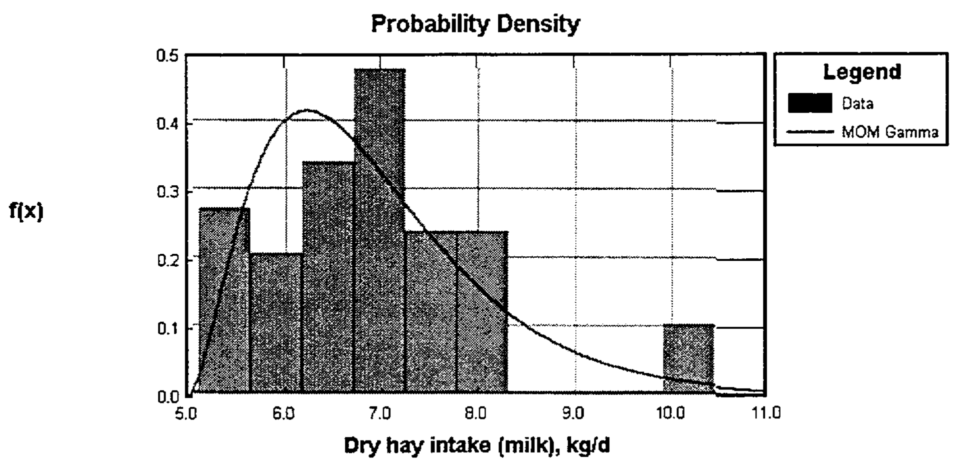

Figure 6.48 Calculated probability distribution for stored hay consumed by dairy cattle

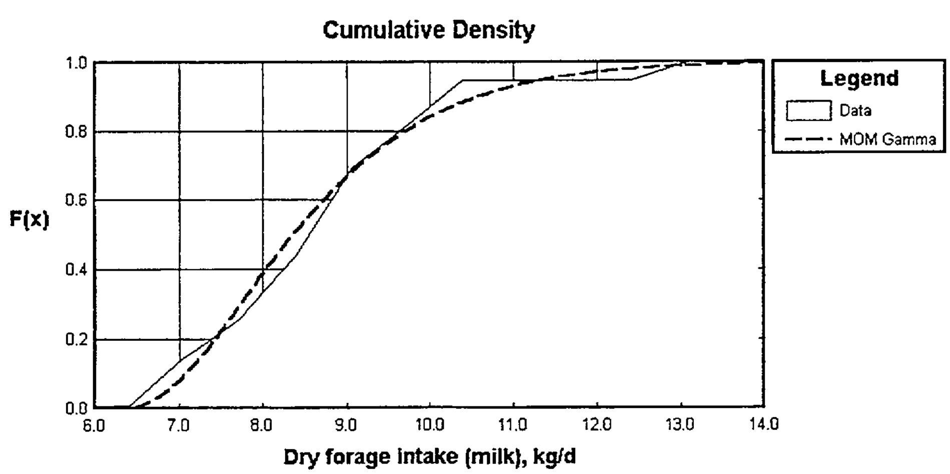

Figure 6.49 Cumulative distribution for forage consumed by dairy cattle

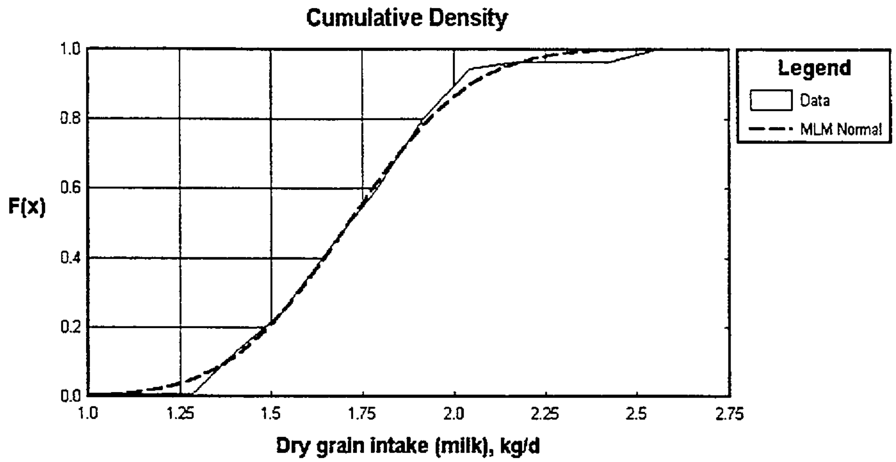

Figure 6.50 Cumulative distribution for stored grain consumed by dairy cattle

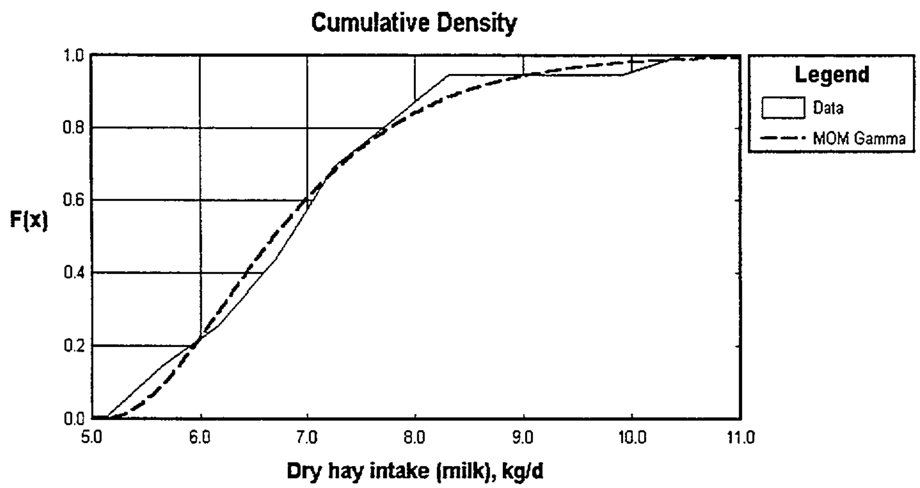

Figure 6.51 Cumulative distribution for stored hay consumed by dairy cattle

6.4.6.4.3 Fresh Forage and Stored Grain Consumed by Poultry

Waldroup et al. (1976), Hurwitz et al. (1978), and the NRC (1981) derived equations and estimates of DMI based on energy needs of a growing broiler chick. Table 6.70 summarizes these estimates in terms of the estimated average daily DMI rate for poultry derived from their estimated energy needs based on age. In poultry (broilers), feeding rate generally increases with age and body weight. The published values included a 12% moisture content which was factored into the DMI values given in the table. As above, this moisture content was then backed out to derive the intake of actual dry matter in broilers. Consistent with NUREG/CR-5512, Vol. 1, poultry are assumed to derive 25% of their total nutrient requirements from fresh forage and 75% from stored grain.

The binned data from the table were converted to consistent units (kg/d), multiplied by the assumed fractions for forage and grain intake for poultry, and were then fit to several distributions. The fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit was obtained with a beta distribution. Table 6.71 provides the beta distribution parameters for fresh forage and stored grain consumed by poultry. The frequency distribution and the fitted PDF for the intake rates for forage and store grain for poultry, Q_{dry}, are shown in Figures 6.52 and 6.53. The corresponding cumulative distributions for poultry are shown in Figures 6.54 and 6.55.

Table 6.70 Predicted DMI for broilers at different ages (NRC, 1996)

Age (days)	BW (g)	Daily gain (g)	Est. energy needs (kcal/d)	DMI (g/d)	Dry matter (no moisture)
7	130	27	102.7	28.3	24.9
14	320	34	155.6	42.8	37.7
21	560	43	212.5	58.4	51.4
28	860	56	279.9	77.0	67.8
35	1250	63	340.5	93.6	82.4
42	1690	59	378.8	104.2	91.7
49	2100	60	420.6	115.6	101.7

Table 6.71 Beta distribution parameters for fresh forage and stored grain - poultry

Parameter	Fresh forage	Stored grain
a_1	1.51	1.52
a_2	1.41	1.41
δ_1	0.00348	0.0104
δ_2	0.0282	0.0845

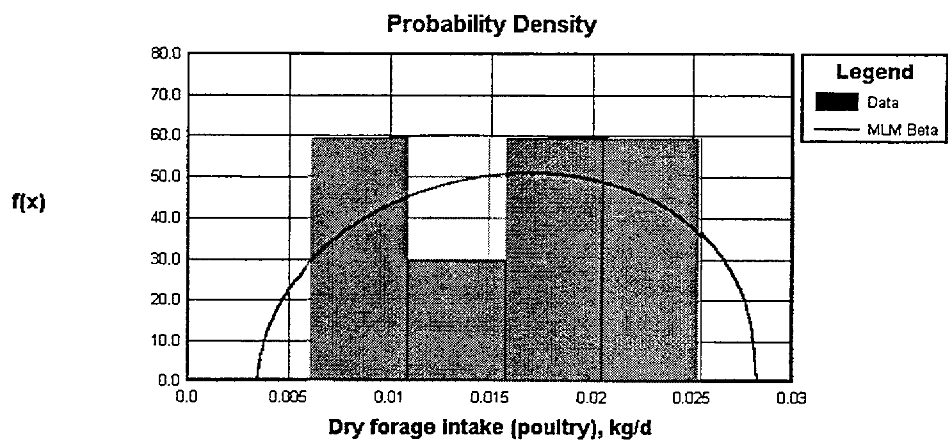

Figure 6.52 Calculated probability distribution for forage consumed by poultry

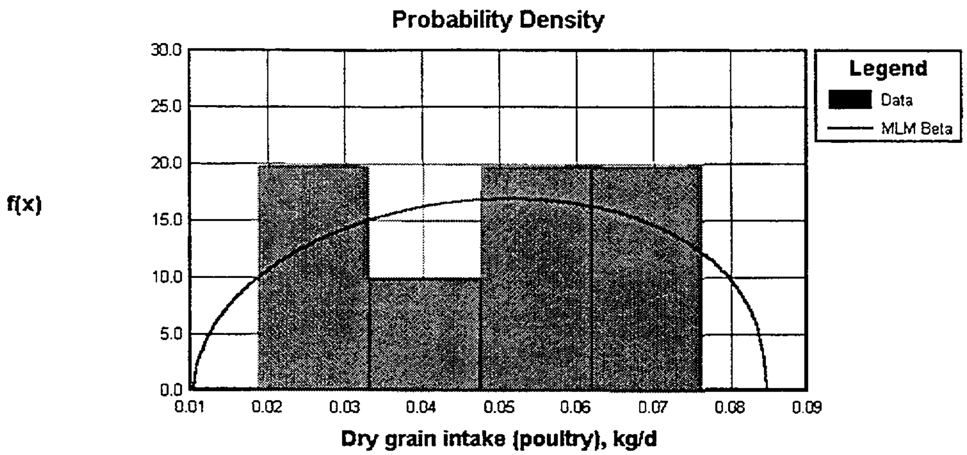

Figure 6.53 Calculated probability distribution for stored grain consumed by poultry

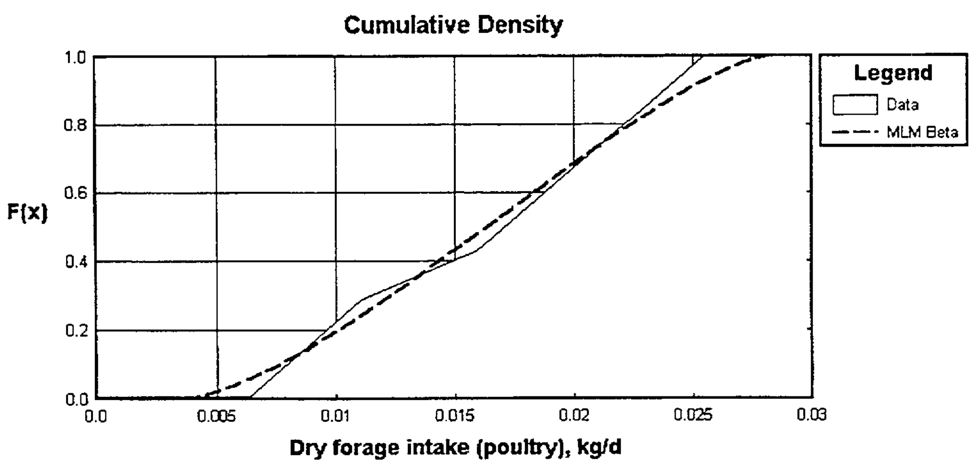

Figure 6.54 Cumulative distribution for forage consumed by poultry

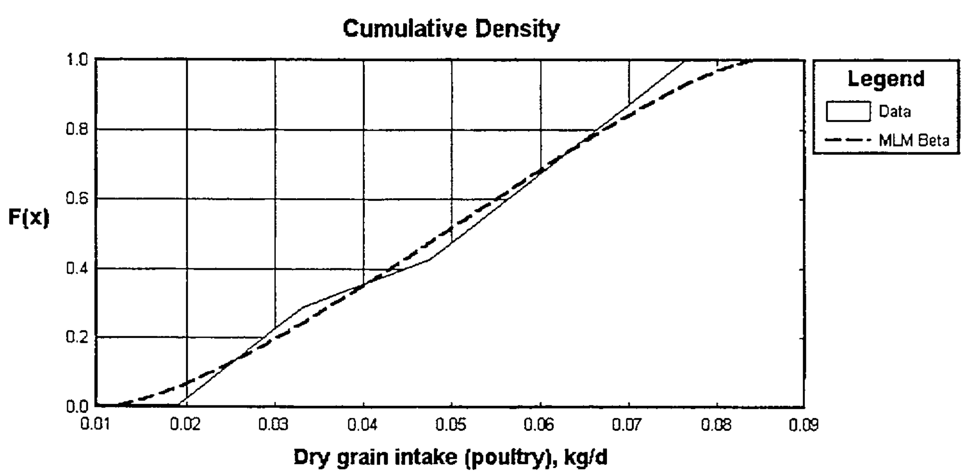

Figure 6.55 Cumulative distribution for stored grain consumed by poultry

6.4.6.4.4 Fresh Forage and Stored Grain Consumed by Layer Hens

Table 6.72 provides estimates of the average daily DMI rate for egg laying hens at different times in the egg production process. Laying hens generally attain a steady state of feed consumption once peak egg production has occurred. Byerly et al. (1980) and Hurwitz et al. (1978) developed equations that characterized observed feeding behavior of laying hens. Those equations were used to derive the DMI rates given in Table 6.72 which confirm the steady state feeding rate when egg production stabilizes in mature hens. The published values included a 12% moisture content which was included in the DMI values given in the table. Once again, this moisture content was used to calculate the intake of actual dry matter by laying hens. As with poultry, layer hens were assumed to derive 25% of their total nutrient requirements from fresh forage and 75% from stored grain.

Based on the average steady state DMI rate for mature hens, the data were converted to consistent units (kg/d) and multiplied by the assumed fractions for forage and grain intake for laying hens. The data were then binned and fit to several distributions and the fitness to each distribution was evaluated with a Kolmogorov-Smirnov test. The best fit was obtained with a beta distribution. Table 6.73 provides the beta distribution parameters for fresh forage and stored grain consumed by laying hens. The frequency distribution and the fitted PDF for the intake rates for forage and store grain for laying hens, Q_{dry}, are shown in Figures 6.56 and 6.57. The corresponding cumulative distributions for laying hens are shown in Figures 6.58 and 6.59.

Table 6.72 Predicted DMI for laying hens at different stages of egg production (NRC, 1996)

Age (weeks)	Egg production (%)	BW (g)	DMI (g/d)	Dry matter (no moisture)
20	5	1317	60.2	53.0
			56.0	49.3
			59.7	52.5
			61.9	54.5
24	62	1513	82.2	72.3
			78.2	68.8
			81.5	71.7
			83.9	73.8
28	91	1663	98.0	86.2
			94.1	82.8
			96.7	85.1
			99.3	87.4
32	89	1737	93.2	82.0
			89.4	78.7
			94.6	83.2
			97.2	85.5
36	87	1821	92.6	81.5
			88.8	78.1
			95.1	83.7
			97.9	86.2
40	85	1877	88.5	77.9
			84.9	74.7
			98.0	86.2
			95.8	84.3

Table 6.73 Beta distribution parameters for fresh forage and stored grain - laying hens

Parameter	Fresh forage	Stored grain
a_1	1.43	1.43
a_2	0.792	0.792
δ_1	0.0119	0.0358
δ_2	0.0222	0.0667

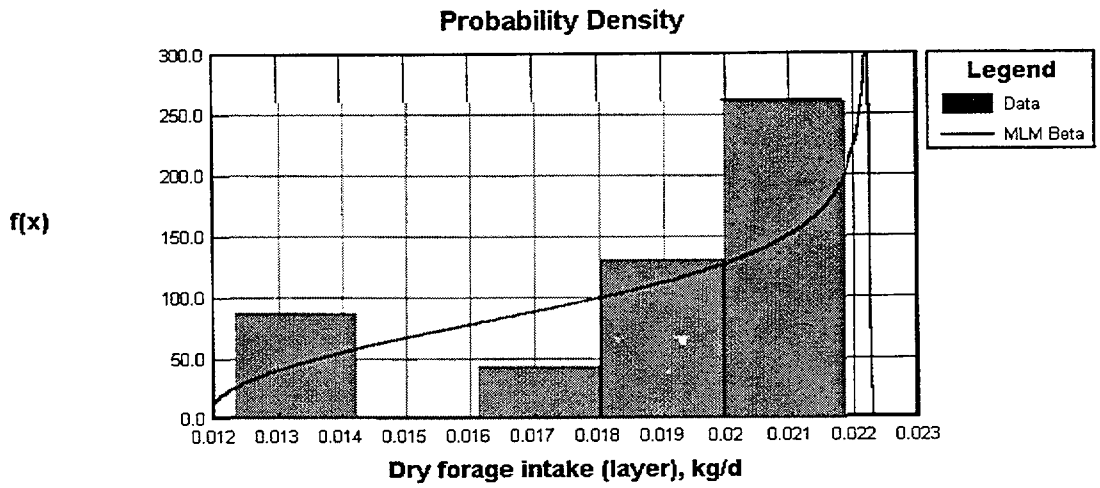

Figure 6.56 Calculated probability distribution for forage consumed by layer hens

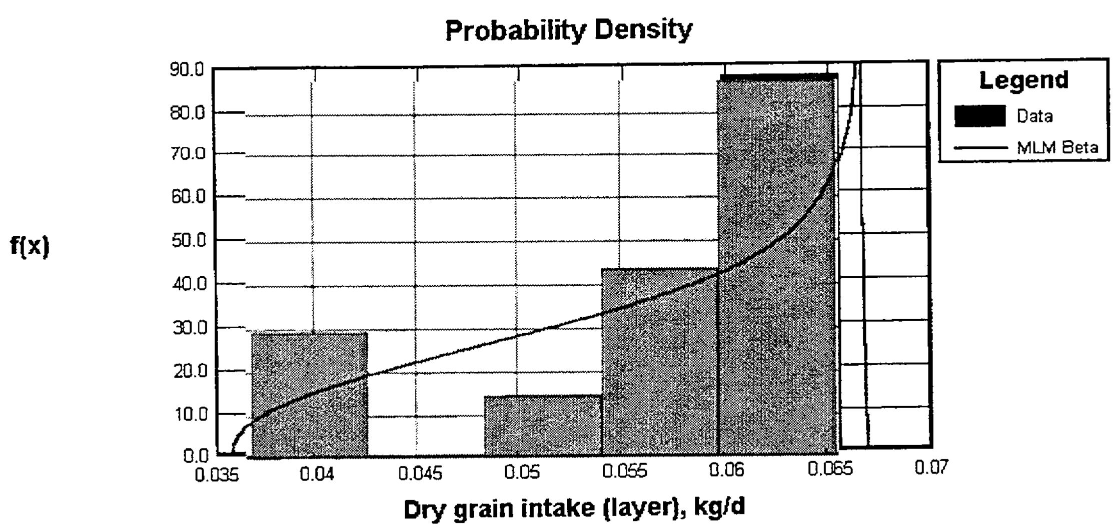

Figure 6.57 Calculated probability distribution for stored grain consumed by layer hens

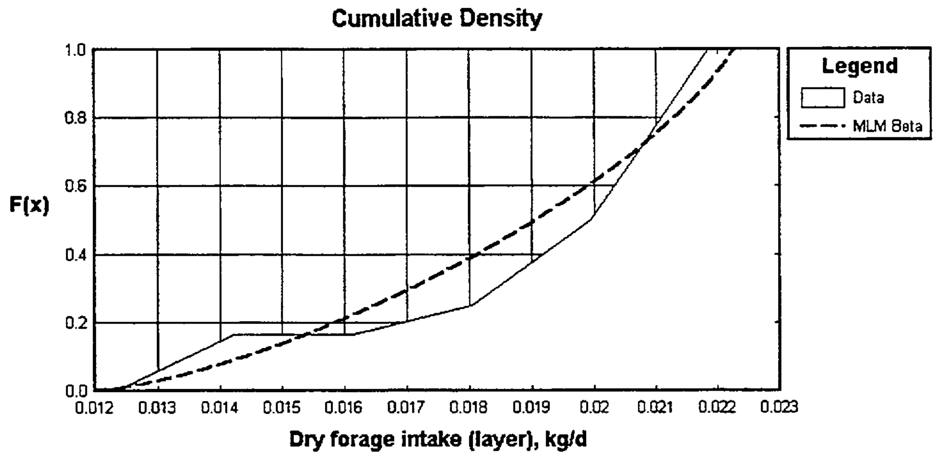

Figure 6.58 Cumulative distribution for forage consumed by layer hens

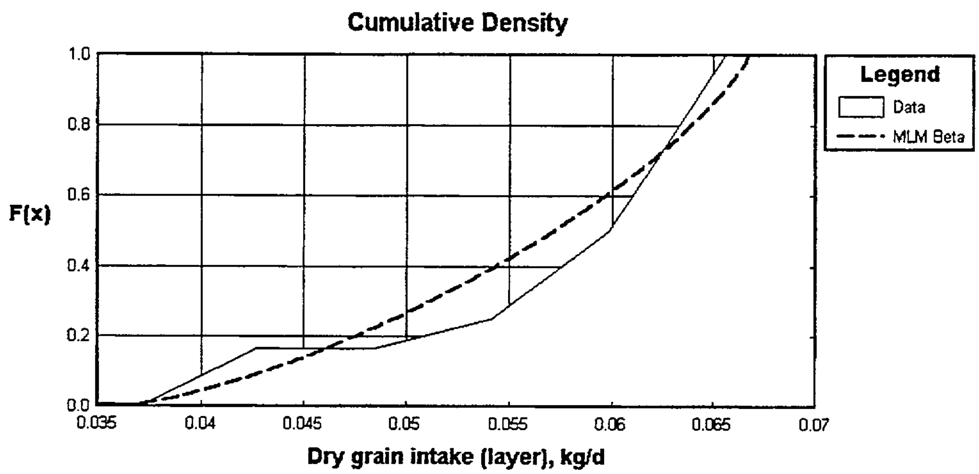

Figure 6.59 Cumulative distribution for stored grain consumed by layer hens

6.4.6.5 Uncertainty in Animal Feed Intake Rates

Distributions describing site-to-site variability in animal feed rates were derived from models developed by the NRC which predict total intake requirements as a function of the animal's age and, for cattle, weight. Variations among sites were assumed to be primarily due to variations in these physiological parameters, and each reporting category was assumed to be equally likely. These assumptions create uncertainty in the parameter distributions. The relative contributions of fresh forage, grain, and hay to each animal's diet were also uncertain. The proportions proposed in NUREG/ CR-5512, Vol. 1, were retained for this analysis.

6.4.6.6 Alternative Values for Animal Feed Intake Rates

These parameters are expected to vary to a small degree from site to site. The distributions for animal feed intake rates are established based on average daily intake rates that depend on factors such as the breed of animal, the age and size of the animal, physiological response, environmental factors (particularly temperature and humidity), diet water content, quantity and quality of food stocks fed to the animals, feed processing methods, use of anabolic stimulants and other feed additives, timing of feeding, and production rates. These factors introduce variability that is captured in the data and proposed parameter distributions.

Applicants may attempt to support alternative values for animal feed intake rates based on regional/seasonal variations in food availability, animal breeds, different varieties of forage and feeds available and intended for animal consumption, and intended production and use of the animal products for human consumption.

6.4.7 Vegetation Concentration Factors For Uptake, B_{jv} (unitless)

6.4.7.1 Description of B_{jv}

The concentration factors for uptake by vegetation, B_{jv}, as defined for NUREG/CR-5512, Vol. 1, dose modeling, estimate the amount of radionuclide uptake by plants grown in contaminated soil for both human consumption and as forage and feed for animals. The model uses a single, constant value for each chemical element for each of the following plant types: vegetables ("leafy" and "root"), fruits, and grains. Each value represents the average uptake for each of these cultivar groups.

6.4.7.2 Use of B_{jv} in Modeling

The concentration factor for uptake is important to modeling dose since the higher the value for B_{jv}, the higher the CEDE value for ingestion via the agricultural pathway (i.e., soil-plant-human and soil-plant-animal-human).

The concentration factor for uptake (B_{jv}) is used to calculate the concentration factor (C_{svjh}) for a radionuclide in a plant at harvest from an initial soil concentration of parent radionuclide. The mathematical relation between B_{jv} and C_{svjh} is given in NUREG/CR-5512, Vol. 1 (Equation 5.5, p. 5.12):

$$C_{svjh} = 1000\left(ML_v + B_{jv}\right)W_v \; A\{C_{sj}, t_{gv}\}/C_{si}(0), \qquad (6.80)$$

where:

C_{svjh} = concentration factor for radionuclide j in plant v at harvest from an initial unit concentration of parent radionuclide i in soil (pCi/kg wet-weight plant per pCi/kg dry-weight soil),

B_{jv} = concentration factor for uptake of radionuclide j from the soil in plant v (pCi/kg dry-weight plant per pCi/kg dry-weight soil),

ML_v = plant soil mass-loading factor for resuspension of soil to plant type v (pCi/kg dry-weight plant per pCi/kg dry-weight soil),

W_v = dry-weight-to-wet-weight conversion factor for plant v (kg dry-weight plant per kg wet-weight plant),

$A\{C_{sj}, t_{gv}\}$ = decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing period, t_{gv} (pCi/g dry-weight soil),

C_{sj} = concentration of radionuclide j in soil during the growing period (pCi/g dry-weight soil),

$C_{si}(0)$ = initial concentration of parent radionuclide i in soil (pCi/g dry-weight soil),

t_{gv} = growing period for food crop v (d), and

1000 = unit conversion factor (g/kg).

The units of radionuclide activity are not always in pCi. However, as long as the units of activity for the plant and the soil are the same, the ratio of plant to soil concentration is preserved and can be used to compare data from different sources.

6.4.7.3 Information Reviewed to Define B_{jv} Distributions

Soil-to-plant concentration factors are given for leafy vegetables, root vegetables, fruits, and grains in NUREG/CR-5512, Table 6.16, repeated here as Table 6.74. Leafy vegetables are part of the "vegetative" portion of plants, while all the other categories are considered "reproductive" portions of plants. Therefore, there are values for B_{jv} for four vegetation categories and 82 elements, for a total of 328 values. However, for nearly all the elements, there is one value given for leafy vegetables and one value that is given for all the reproductive crop types, reducing the number of distinct values for B_{jv} from 328 to approximately 164.

All but a few of the values given in Volume 1 were obtained from Baes et al. (1984). The remainder come from a compilation of the International Union of Radioecologists (IUR 1989), except for the element californium, for which default values were taken from Strenge et al. (1987). Most of the values taken from Baes et al. (1984) are the geometric means of data distributions. For many elements Baes et al. (1984) also provide the geometric standard deviation. The range between two standard deviations from the mean for a single element often exceeds two orders of magnitude.

Soil-to-plant concentration factor distributions with ranges of several orders of magnitude are not uncommon (Arkhipov et al., 1975, Dahlman et al., 1976, Whicker 1978, and Sheppard and Evenden, 1988). The variability in concentration factors is the result of numerous and complex underlying processes such as climate, growing conditions, plant metabolism, plant rooting traits, soil type, soil moisture, soil texture, and soil pH.

A lognormal distribution is consistently proposed as the most appropriate distribution for concentration factors (Gilbert and Simpson, 1985, Sheppard and Evenden, 1988, Sheppard and Evenden, 1990, and Murphy and

Table 6.74 Soil-to-plant concentration factors from NUREG/CR-5512 (Table 6.16, pages 6.25-6.27), pCi/kg dry weight per pCi/kg soil

Element	Leafy vegetables	Root vegetables	Fruit	Grain
H	*	*	*	*
Be	1.0E-2	1.5E-3	1.5E-3	1.5E-3
C	7.0E-1	7.0E-1	7.0E-1	7.0E-1
N	3.0E+1	3.0E+1	3.0E+1	3.0E+1
F	6.0E-2	6.0E-3	6.0E-3	6.0E-3
Na	7.5E-2	5.5E-2	5.5E-2	5.5E-2
Mg	1.0E+0	5.5E-1	5.5E-1	5.5E-1
Si	3.5E-1	7.0E-2	7.0E-2	7.0E-2
P	3.5E+0	3.5E+0	3.5E+0	3.5E+0
S	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Cl	7.0E+1	7.0E+1	7.0E+1	7.0E+1
Ar	**	**	**	**
K	1.0E+0	5.5E-1	5.5E-1	5.5E-1
Ca	3.5E+0	3.5E-1	3.5E-1	3.5E-1
Sc	6.0E-3	1.0E-3	1.0E-3	1.0E-3
Cr	7.5E-3	4.5E-3	4.5E-3	4.5E-3
Mn	5.6E-1	1.5E-1	5.0E-2	2.9E-1
Fe	4.0E-3	1.0E-3	1.0E-3	1.0E-3
Co	8.1E-2	4.0E-2	7.0E-3	3.7E-3
Ni	2.8E-1	6.0E-2	6.0E-2	3.0E-2
Cu	4.0E-1	2.5E-1	2.5E-1	2.5E-1
Zn	1.4E+0	5.9E-1	9.0E-1	1.3E+0
Ga	4.0E-3	4.0E-4	4.0E-4	4.0E-4
As	4.0E-2	6.0E-3	6.0E-3	6.0E-3
Se	2.5E-2	2.5E-2	2.5E-2	2.5E-2
Br	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Kr	**	**	**	**
Rb	1.5E-1	7.0E-2	7.0E-2	7.0E-2
Sr	1.6E+0	8.1E-1	1.7E-1	1.3E-1
Y	1.5E-2	6.0E-3	6.0E-3	6.0E-3
Zr	2.0E-3	5.0E-4	5.0E-4	5.0E-4
Nb	2.0E-2	5.0E-3	5.0E-3	5.0E-3
Mo	2.5E-1	6.0E-2	6.0E-2	6.0E-2
Tc	4.4E+1	1.1E+0	1.5E+0	7.3E-1
Ru	5.2E-1	2.0E-2	2.0E-2	5.0E-3
Rh	1.5E-1	4.0E-2	4.0E-2	4.0E-2
Pd	1.5E-1	4.0E-2	4.0E-2	4.0E-2
Ag	2.7E-4	1.3E-3	8.0E-4	1.0E-1
Cd	5.5E-1	1.5E-1	1.5E-1	1.5E-1
In	4.0E-3	4.0E-4	4.0E-4	4.0E-4
Sn	3.0E-2	6.0E-3	6.0E-3	6.0E-3
Sb	1.3E-4	5.6E-4	8.0E-5	3.0E-2
Te	2.5E-2	4.0E-3	4.0E-3	4.0E-3

Table 6.74 Soil-to-plant concentration factors from NUREG/CR-5512 (Table 6.16, pages 6.25–6.27), pCi/kg dry weight per pCi/kg soil (continued)

Element	Leafy vegetables	Root vegetables	Fruit	Grain
I	3.4E-3	5.0E-2	5.0E-2	5.0E-2
Xe	**	**	**	**
Cs	1.3E-1	4.9E-2	2.2E-1	2.6E-2
Ba	1.5E-1	1.5E-2	1.5E-2	1.5E-2
La	5.7E-4	6.4E-4	4.0E-3	4.0E-3
Ce	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Pr	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Nd	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Pm	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Sm	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Eu	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Gd	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Tb	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Dy	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Ho	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Er	1.0E-2	4.0E-3	4.0E-3	4.0E-3
Hf	3.5E-3	8.5E-4	8.5E-4	8.5E-4
Ta	1.0E-2	2.5E-3	2.5E-3	2.5E-3
W	4.5E-2	1.0E-2	1.0E-2	1.0E-2
Re	1.5E+0	3.5E-1	3.5E-1	3.5E-1
Os	1.5E-2	3.5E-3	3.5E-3	3.5E-3
Ir	5.5E-2	1.5E-2	1.5E-2	1.5E-2
Au	4.0E-1	1.0E-1	1.0E-1	1.0E-1
Hg	9.0E-1	2.0E-1	2.0E-1	2.0E-1
Tl	4.0E-3	4.0E-4	4.0E-4	4.0E-4
Pb	5.8E-3	3.2E-3	9.0E-3	4.7E-3
Bi	3.5E-2	5.0E-3	5.0E-3	5.0E-3
Po	2.5E-3	9.0E-3	4.0E-4	4.0E-4
Rn	**	**	**	**
Ra	7.5E-2	3.2E-3	6.1E-3	1.2E-3
Ac	3.5E-3	3.5E-4	3.5E-4	3.5E-4
Th	6.6E-3	1.2E-4	8.5E-5	3.4E-5
Pa	2.5E-3	2.5E-4	2.5E-4	2.5E-4
U	1.7E-2	1.4E-2	4.0E-3	1.3E-3
Np	1.3E-2	9.4E-3	1.0E-2	2.7E-3
Pu	3.9E-4	2.0E-4	4.5E-5	2.6E-5
Am	5.8E-4	4.1E-4	2.5E-4	5.9E-5
Cm	3.0E-4	2.4E-4	1.5E-5	2.1E-5
Cf	1.0E-2	1.0E-2	1.0E-2	1.0E-2

* Concentration factors for tritium are not needed because a special model is used to determine tritium uptake in plants.
**Noble gases are not assumed to be taken up by plants.

Tuckfield, 1992). Because B_{jv} is the product of several variables, a lognormal distribution for B_{jv} is expected from the central limit theorem (Sheppard and Evenden, 1988).

The lognormal distribution bounds B_{jv} by zero and allows B_{jv} to go to infinity at probabilities approaching zero. At some level of contaminant concentration for each plant and each element, B_{jv} is bound by a toxicity limit. Rarely are these limits observed experimentally.

6.4.7.4 B_{jv} Probability Distributions

Distribution parameters were taken from Ng et al. (1982) and Baes et al. (1984) (Table 6.75). For the elements reported in Ng et al. (1982), the geometric means and geometric standard deviations (GSD) were taken directly from the text. For data given in Baes et al. (1984) geometric means are provided in the text, but the GSDs are provided only graphically and only for some elements. In lieu of visual estimation of the GSD for an element, a "generic" GSD proposed by Sheppard and Evenden (1990) was used. This GSD (2.47) was determined from a pool of 23 elements and more than 1,250 values for B_{jv}. Sheppard and Evenden (1990) demonstrate that the variance of B_{jv} is unrelated to site or element characteristics, suggesting that a generic GSD is appropriate for stochastic modeling of plant uptake. Because Ng et al. (1982) includes more detailed information on distribution parameters of B_{jv} than Baes et al. (1984), Ng et al. (1982) was used as the primary source for B_{jv} values. No revisions were required to the distributions of B_{jv} as they encompassed concentration factors found in other reports.

All the data from Baes et al. (1984) are given in units of pCi plant dry-weight per pCi soil dry-weight. Ng et al. (1982) give the data for leafy vegetation in units of pCi plant dry-weight per pCi soil dry-weight and for reproductive vegetation in units of pCi plant wet-weight per pCi soil dry-weight. To calculate the input value for the DandD code, the sampled values of dry-to-wet weight conversion factors were used to convert the B_{jv} values where required.

Table 6.75 Distribution properties for soil-to-plant concentration factors

Element	Leafy (non-reproductive) vegetation (pCi dry plant mass/pCi dry soil mass)			Reproductive vegetation[a]		
	Geometric mean	Geometric standard deviation	Data source[b]	Geometric mean	Geometric standard deviation	Data source[b]
H	*	*	*	*	*	*
Be	1.0E-2	2.47E+0	2	1.5E-3	2.47E+0	2
C	7.0E-1	2.47E+0	3	7.0E-1	2.47E+0	3
N	3.0E+1	2.47E+0	2	3.0E+1	2.47E+0	2
F	6.0E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Na	7.4E-2	2.47E+0	1	4.6E-3	4.10E+0	1
Mg	1.0E+0	2.47E+0	2	5.5E-1	2.47E+0	2
Si	3.5E-1	2.47E+0	2	7.0E-2	2.47E+0	2
P	3.5E+0	2.47E+0	2	3.5E+0	2.47E+0	2
S	1.5E+0	2.47E+0	2	1.5E+0	2.47E+0	2
Cl	7.0E+1	2.47E+0	2	7.0E+1	2.47E+0	2
Ar	**	**	**	**	**	**
K	1.0E+0	2.47E+0	2	5.5E-1	2.47E+0	2
Ca	3.5E+0	2.47E+0	2	3.5E-1	2.47E+0	2
Sc	6.0E-3	2.47E+0	2	1.0E-3	2.47E+0	2
Cr	2.2E-2	2.20E+0	1	1.3E-2	2.00E+0	1
Mn	3.3E-1	7.60E+0	1	1.2E-1	4.90E+0	1
Fe	5.6E-3	3.80E+0	1	4.2E-4	3.50E+0	1
Co	8.8E-2	4.70E+0	1	1.5E-2	3.30E+0	1
Ni	3.4E-2	3.20E+0	1	2.1E-2	2.50E+0	1
Cu	4.9E-1	2.60E+0	1	4.3E-2	1.00E+1	1
Zn	5.8E-1	2.60E+0	1	1.1E-1	3.90E+0	1
Ga	4.0E-3	2.47E+0	2	4.0E-4	2.47E+0	2

Table 6.75 Distribution properties for soil-to-plant concentration factors (continued)

Element	Leafy (non-reproductive) vegetation (pCi dry plant mass/pCi dry soil mass)			Reproductive vegetation[a]		
	Geometric mean	Geometric standard deviation	Data source[b]	Geometric mean	Geometric standard deviation	Data source[b]
As	4.0E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Se	2.5E-2	2.47E+0	2	2.5E-2	2.47E+0	2
Br	1.5E+0	2.47E+0	2	1.5E+0	2.47E+0	2
Kr	**	**	**	**	**	**
Rb	8.1E-1	3.60E+0	1	7.0E-2	2.47E+0	2
Sr	1.8E+0	3.80E+0	1	7.5E-2	3.80E+0	1
Y	1.5E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Zr	7.2E-2	2.00E+0	1	7.7E-4	9.50E+0	1
Nb	2.0E-2	2.47E+0	2	5.0E-3	2.47E+0	2
Mo	2.2E+0	3.30E+0	1	6.0E-2	2.47E+0	2
Tc	9.5E+0	2.47E+0	2	1.5E+0	2.47E+0	2
Ru	6.2E-2	4.80E+0	1	1.4E-3	4.90E+0	1
Rh	1.5E-1	2.47E+0	2	4.0E-2	2.47E+0	2
Pd	1.5E-1	2.47E+0	2	4.0E-2	2.47E+0	2
Ag	4.0E-1	2.47E+0	2	1.0E-1	2.47E+0	2
Cd	5.5E-1	2.47E+0	2	1.5E-1	2.47E+0	2
In	4.0E-3	2.47E+0	2	4.0E-4	2.47E+0	2
Sn	3.0E-2	2.47E+0	2	6.0E-3	2.47E+0	2
Sb	2.0E-1	2.47E+0	2	3.0E-2	2.47E+0	2
Te	2.5E-2	2.47E+0	2	4.0E-3	2.47E+0	2
I	1.6E-1	3.50E+0	1	4.5E-3	4.90E+0	1
Xe	**	**	**	**	**	**
Cs	4.1E-2	3.50E+0	1	5.0E-3	4.10E+0	1
Ba	3.9E-2	2.90E+0	1	1.3E-3	3.10E+0	1
La	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Ce	2.1E-2	4.30E+0	1	7.3E-4	6.20E+0	1
Pr	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Nd	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Pm	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Sm	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Eu	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Gd	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Tb	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Dy	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Ho	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Er	1.0E-2	2.47E+0	2	4.0E-3	2.47E+0	2
Hf	3.5E-3	2.47E+0	2	8.5E-4	2.47E+0	2
Ta	1.0E-2	2.47E+0	2	2.5E-3	2.47E+0	2
W	4.5E-2	2.47E+0	2	1.0E-2	2.47E+0	2
Re	1.5E+0	2.47E+0	2	3.5E-1	2.47E+0	2
Os	1.5E-2	2.47E+0	2	3.5E-3	2.47E+0	2
Ir	5.5E-2	2.47E+0	2	1.5E-2	2.47E+0	2
Au	4.0E-1	2.47E+0	2	1.0E-1	2.47E+0	2
Hg	9.0E-1	2.47E+0	2	2.0E-1	2.47E+0	2

Table 6.75 Distribution properties for soil-to-plant concentration factors (continued)

Element	Leafy (non-reproductive) vegetation (pCi dry plant mass/pCi dry soil mass)			Reproductive vegetation[a]		
	Geometric mean	Geometric standard deviation	Data source[b]	Geometric mean	Geometric standard deviation	Data source[b]
Tl	4.0E-3	2.47E+0	2	4.0E-4	2.47E+0	2
Pb	4.5E-2	2.47E+0	2	9.0E-3	2.47E+0	2
Bi	3.5E-2	2.47E+0	2	5.0E-3	2.47E+0	2
Po	2.5E-3	2.47E+0	2	4.0E-4	2.47E+0	2
Rn	**	**	**	**	**	**
Ra	1.5E-2	2.47E+0	2	1.5E-3	2.47E+0	2
Ac	3.5E-3	2.47E+0	2	3.5E-4	2.47E+0	2
Th	8.5E-4	2.47E+0	2	8.5E-5	2.47E+0	2
Pa	2.5E-3	2.47E+0	2	2.5E-4	2.47E+0	2
U	8.5E-3	2.47E+0	2	4.0E-3	2.47E+0	2
Np	1.1E+0	4.90E+0	1	**6.0E-2**	**3.00E+0**	**1**
Pu	4.5E-4	2.47E+0	2	4.5E-5	2.47E+0	2
Am	5.5E-3	2.47E+0	2	2.5E-4	2.47E+0	2
Cm	8.5E-4	2.47E+0	2	1.5E-5	2.47E+0	2
Cf	1.0E-2	2.47E+0	3	1.0E-2	2.47E+0	3

*Concentration factors for tritium are not needed because a special model is used to determine tritium uptake in plants.
**Noble gases are not assumed to be taken up by plants.
[a]Data Source 1 (pCi wet plant mass/pCi dry soil mass), indicated with bold font; Data Sources 2 and 3 (pCi dry plant mass/pCi dry soil mass).
[b] 1 = Ng et al. (1982); 2 = Baes et al. (1984); 3 = NUREG/CR -5512.

6.4.7.5 Alternative B_{jv} Values

It is not likely that site-specific information can reduce the uncertainty in concentration factors. There are simply too many factors affecting B_{jv}, factors that vary non-linearly in time and across locations, even to determine which ones might be the most important to predicting B_{jv} (and thus, reducing uncertainty) at a particular site. It is known that the inclusion of environmental variables, such as soil texture and pH, reduces the variability in concentration factors only marginally (Sheppard and Evenden, 1990). Thus, there is no benefit in correlating B_{jv} to site-specific parameters such as precipitation or soil properties.

6.4.8 Interception Fraction for Vegetation, r_v (unitless)

6.4.8.1 Parameter Description

The interception fraction for vegetation, r_v, as defined for NUREG/CR-5512, Vol. 1, dose modeling, estimates the fraction of deposited contamination retained on various cultivars grown for food and animal feed after above-ground irrigation with contaminated water. The model accepts different values of r_v for plants grown both for direct human consumption: "leafy" vegetables, "other" vegetables, fruits, and grains and for indirect human consumption as animal feed: forage plants (e.g., grass and alfalfa), grain, and hay. Thus, this value should represent the average fraction of all contaminants retained on edible plant surfaces after irrigation.

6.4.8.2 Use of Parameter in Modeling

The interception fraction is important to modeling dose since the higher the value for r_v, the higher the CEDE value for ingestion via the agricultural pathway (i.e., irrigation water-plant-human and irrigation water-plant-animal-human).

The interception fraction is used to calculate the constant, average rate of accommodation of a contaminant on plants by retention from irrigation. The mathematical relation between deposition and retention is given in NUREG/CR-5512, Vol. 1 (Equation 5.22, p. 5.27), by:

$$R_{wvjg} = IR\ r_v\ T_v/Y_v[C_{wj}/C_{wi}], \qquad (6.81)$$

where:

R_{wvjg} = average accommodation rate of radionuclide j on edible parts of plant v from application of irrigation water per unit average concentration of parent radionuclide i in water (pCi/d kg^{-1} wet weight plant per pCi/L water),

IR = average annual application rate of irrigation water ($L/m^2 d^{-1}$),

r_v = fraction of initial application (in water) retained on plant v (pCi retained per pCi applied),

T_v = translocation factor for transfer of radionuclides from plant surfaces to edible parts of plant v (pCi in edible plant part per pCi retained),

Y_v = yield of plant v (kg wet weight/m^2),

C_{wj} = average annual concentration of parent radionuclide i in irrigation water over the current annual period (pCi/L water), and

C_{wi} = average annual concentration of radionuclide j in irrigation water over the current annual period (pCi/L water).

Because r_v represents the fraction of a contaminant in irrigation water that is retained on the surface of a plant, r_v must be between zero and one.

Hoffman et al. (1992) demonstrate that contaminants that have dried on plant surfaces after an irrigation event are not lost with subsequent washing. The model of continuous irrigation-rate-dependent accommodation, represented by Equation 6.81, is evidently appropriate. r_v was measured over a broad range of irrigation conditions, assumed here to be broad enough to encompass the expected range of variability in irrigation intensity and amount from one site to another.

Dose calculations require an estimate of the average, annual amount of a contaminant retained on a plant. In the irrigation water-plant-human pathway dose calculations, this is expressed as the amount of concentration received throughout the growing period and retained on the plant at the time of harvest (Equation 5.23, Vol. 1, p. 5.28):

$$C_{wvjh} = R_e\left[R_{wvjg}, t_{gv}\right], \qquad (6.82)$$

where:

C_{wvjh} = concentration factor for radionuclide j in plant v at harvest from retention on surfaces for an average unit concentration of parent radionuclide i in water (pCi/kg wet weight plant per pCi/L water),

t_{gv} = growing period for plant v (d), and

R_e = retention, accumulation operator used to develop the concentration factor of radionuclide j in plant v at harvest from application onto plant surfaces of an average unit concentration of parent radionuclide in water (pCi/kg wet weight plant per pCi/L water).

6.4.8.3 Information Reviewed to Define Distributions for r_v

The common value of 0.25 is proposed in Volume 1 for all plant types. This value, based on recommendations by Baker et al. (1976); is also adopted as a default value in Regulatory Guide 1.109. Baker et al. (1976) provide no explanation or justification of this value. As such, the only way to evaluate the appropriateness of this value is by comparison to existing experimental data.

Experimental results from an interception study using contaminated, simulated rain (Hoffman et al., 1992) indicate that biomass density is more important than vegetation type in affecting retention; when the data are normalized for biomass, differences in vegetation type, while statistically significant, are never major controlling variables for retention. Hoffman et al. (1992) also report similar results for a variety of herbaceous and woody plant types. Dose calculations using r_v include on inverse dependence on biomass yield (Y_v). A separate retention factor for different plant types is not included and the retention factors are assumed to apply equally to all plant types in the Volume 1 model.

The same experiment by Hoffman et al. (1992) provides information about the effects of ionic charge and solubility on retention. The study found that anions are essentially removed with the water once the vegetation surface becomes saturated, that cations are readily adsorbed to the plant surface, and that insoluble particles readily settle out on the plant surface. For cations, insoluble particles, and anions at irrigation rates comparable to those being considered (Section 6.2.7), the adsorption and settling rates are comparable, resulting in similar values of retention. Therefore, it is unnecessary to separate r_v into categories based on solubility or ionic charge. This approach is also impractical because the default scenario model does not represent detailed groundwater geochemistry. Because it is unknown what chemical forms contaminants might take, the effect of chemical form on the r_v parameter cannot be included in the generic model.

The adsorption (retention) of cations and insoluble particles on vegetation is similar, though the underlying processes differ. For cations, retention appears to be controlled by chemical adsorption to cation exchange sites in the leaf cuticle, while for insoluble materials, retention is controlled by the rapid settling out of particles from rain droplets and their consequent adsorption on the plant surface.

6.4.8.4 r_v Probability Distribution

Interception fractions for cations and insoluble particles as reported by Hoffman et al. (1992) generally range from 0.1 to 0.6 with geometric means ranging from 0.15 to 0.37. The mean of the geometric means is 0.28. Given this, the default value of 0.25 recommended in NUREG/CR-5512 seems appropriate as an average value for the retention of contaminants on plants for this particular group of contaminants. The data provide practical limits for r_v, suggesting that the mean value of r_v can be increased or decreased by a factor of two and still remain within experimentally-derived limits of r_v.

The interception fraction for anions, as measured with ^{131}I by Hoffman et al. (1992) is dependent on the amount of irrigation applied. "Low" irrigation amounts from Hoffman et al. (1992) are approximately 1-15 mm d^{-1} and are the only rates applicable here, as the average irrigation rate being proposed is approximately 0.7 mm d^{-1} (Section 6.2.7).

At low irrigation levels the average r_v for anions is approximately 0.3; as with cations and insoluble particles, the value of 0.25 recommended in NUREG/CR-5512 is slightly lower than that average. The data provide practical limits for r_v, with a range of 0.15 to 0.6, suggesting that the mean value of r_v can be increased or decreased by a factor of two and still remain within experimentally-derived limits. Thus, the range given for cations and insoluble particles (0.1 to 0.6) also applies to anions.

Values for r_v from NUREG/CR-5512, Vol. 1, and the updated range of values for r_v are provided in Table 6.76. The probability distribution function of r_v given three values (minimum, maximum, and mean) is modeled with a uniform distribution (Figure 6.60).

6.4.8.5 Uncertainty in r_v

For all contaminant categories, retention is positively correlated with the total amount of biomass. This is explicitly accounted for in the model, since the modeling of dose using r_v (i.e., Equation 5.22) increases with increasing amounts of biomass (Y_v).

6.4.8.6 Alternative r_v Values

The limits of r_v are not likely to change with site-specific data because r_v is not strongly dependent on vegetation type. The stronger effect of the amount of vegetation at a site is included via yield (as discussed above).

Table 6.76 NUREG/CR-5512, Vol. 1, values and PDFs for r_v

Vegetation type	NUREG/CR-5512 value	PDF of r_v (uniform distribution)		
		Minimum	Maximum	Mean
leafy vegetable	0.25	0.10	0.60	0.35
other vegetable	0.25	0.10	0.60	0.35
fruit	0.25	0.10	0.60	0.35
grain consumed by humans	0.25	0.10	0.60	0.35
forage consumed by beef cattle	0.25	0.10	0.60	0.35
forage consumed by poultry	0.25	0.10	0.60	0.35
forage consumed by milk cows	0.25	0.10	0.60	0.35
forage consumed by layer hens	0.25	0.10	0.60	0.35
stored grain consumed by beef cattle	0.25	0.10	0.60	0.35
stored grain consumed by poultry	0.25	0.10	0.60	0.35
stored grain consumed by milk cows	0.25	0.10	0.60	0.35
stored grain consumed by layer hens	0.25	0.10	0.60	0.35
stored hay consumed by beef cattle	0.25	0.10	0.60	0.35
stored hay consumed by poultry	0.25	0.10	0.60	0.35
stored hay consumed by milk cows	0.25	0.10	0.60	0.35
stored hay consumed by layer hens	0.25	0.10	0.60	0.35

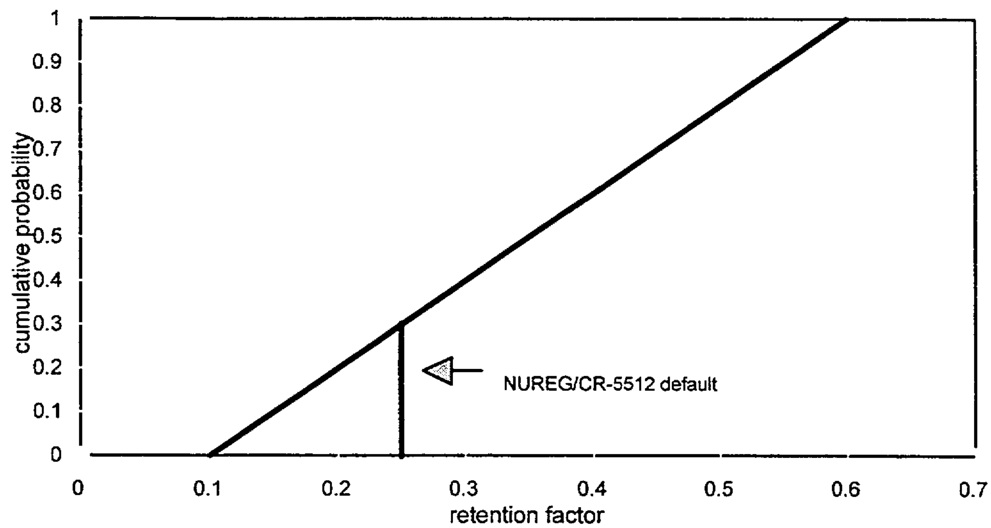

Figure 6.60 Retention factor cumulative probability distribution function

6.4.9 Wet-to-Dry-Weight Conversion Factors for Vegetables, Fruits, and Grains Consumed by Humans, W_v, and Forage, W_f, Stored Grain, W_g, and Stored Hay, W_h, Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens (kg dry-weight/kg wet-weight)

6.4.9.1 Parameter Description

The wet-to-dry-weight conversion factors for garden produce and animal feed, as defined for the NUREG /CR-5512, Vol. 1, dose model, describe the dry weight of edible plants grown for human and animal consumption and represent the average concentration of dry matter in plants.

The conversion factors are needed to correct for the moisture content in edible parts of plants since both dry-weight and wet-weight factors are used in the default dose model. For example, the soil-to-plant concentration factors for individual radionuclides are defined in terms of the dry weight of plants, while the crop yields are expressed as the wet weight of plants per area.

6.4.9.2 Wet-to-Dry-Weight Conversion Factors for Vegetables, Fruits, and Grains, W_v

The four wet-to-dry-weight conversion factors for leafy vegetables, non-leafy vegetables, fruit, and grain represent the fractions of dry matter in garden produce.

6.4.9.2.1 Use of Parameter in Modeling

The wet-to-dry-weight conversion factors convert the weight of the garden produce at harvest to the corresponding or equivalent dry weight. These factors are required in two pathways: 1) soil-plant-human pathway to calculate the concentration factor for radionuclide j in plant v at harvest from an initial unit concentration of parent radionuclide i in soil, C_{svjh}, and 2) irrigation water-soil-plant-human pathway to calculate the concentration factor for radionuclide j in plant v at time of harvest resulting from resuspension and root uptake for an average unit concentration of parent radionuclide i in water, C_{rvjh}. C_{svjh} is calculated from the following equation (Equation 5.5, p. 5.12 of NUREG/ CR-5512, Vol. 1):

$$C_{svjh} = 1000\left(ML_v + B_{jv}\right)W_v \; A\{C_{sj}, t_{gv}\}/C_{si}(0) \qquad (6.83)$$

where ML_v is the plant soil mass-loading factor for resuspension of soil to plant type v; B_{jv} is the concentration factor for uptake of radionuclide j from the soil in plant v; W_v is the wet-to-dry-weight conversion factor for plant v; $A\{C_{sj}, t_{gv}\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing period; t_{gv} is the growing period for food crop v; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil.

C_{rvjh}, is calculated from the following equation (Equation 5.31, p. 5.31 of NUREG/CR-5512, Vol. 1):

$$C_{rvjh} = \left(ML_v + B_{jv}\right)W_v \; C_{wvjh(soil)} \qquad (6.84)$$

where $C_{wvjh(soil)}$ is the concentration factor for radionuclide j in soil at harvest time for plant v for an average unit concentration of parent radionuclide i in water.

6.4.9.2.2 Information Used to Define the Distributions for W_v

Table 6.77 lists the plant types and the corresponding conversion factors used in NUREG/CR-5512, Vol.1. The conversion factors were taken from Till and Meyer (1983).

Table 6.77 Values for wet-to-dry-weight conversion factors for vegetables, fruits, and grains from NUREG/CR-5512, Vol. 1

Plant type	Conversion factor (kg dry-weight/kg wet-weight)
Vegetables, leafy	0.2
Vegetables, other	0.25
Fruit	0.18
Grain	0.91

The Human Nutrition and Information Service of the USDA compiled information on the nutritive value of over 900 foods, food products, and beverages (Gebhardt and Matthews, 1985). The data included water contents of vegetables, fruits, and grains, which are summarized in Table 6.78. The wet-to-dry-weight conversion factor is calculated from the following equation:

$$W_v = (100 - \%\ \text{water})/100 \qquad (6.85)$$

6.4.9.2.3 Distributions for Wet-to-Dry-Weight Conversion Factors for Vegetables, Fruit, and Grain

The moisture content varies from 77 to 96% in vegetables and fruits and from 11 to 12% in grains. Because of the similarity in the moisture content in vegetables and fruits, W_v for vegetables and fruits were assumed to have the same distribution. The frequency distribution and fitted PDF (Figure 6.61) for W_v (vegetables & fruits) were determined from data in Table 6.78. The PDF is defined by a gamma function with a mean of 0.1088 and lower and upper limits of 0.04 and 0.23. The calculated parameters for the gamma distribution are shown in Table 6.79. Figure 6.62 shows the cumulative distribution function for W_v for fruit and vegetables. Since W_v (grains) varies only slightly, a fixed value of 0.88 was used.

Table 6.78 Moisture content of farm and garden produce (Gebhardt and Matthews, 1985)

Garden produce	Water (% by wt.)
Vegetables, leafy	
Lettuce	96
Broccoli	91
Cauliflower	92
Celery	95
Parsley	88
Spinach	92
Cabbage	92
Vegetables, other	
Carrots	88
Radishes	95
Potatoes	77
Tomatoes	94
Peppers	93
Fruit	
Apples	84
Apricots	86
Blueberries	85
Cherries	90
Grapefruit	91
Grapes	81
Cantaloupe	90
Oranges	87
Peaches	88
Pears	84
Plums	85
Strawberries	92
Watermelon	92
Grain	
Wheat	12
Corn	12
Barley	11
Rice	12

Table 6.79 Distribution parameters for wet-to-dry-weight conversion factor for vegetables and fruits

Parameter	Value
κ	2.68
λ	35.1
ϵ	0.0324

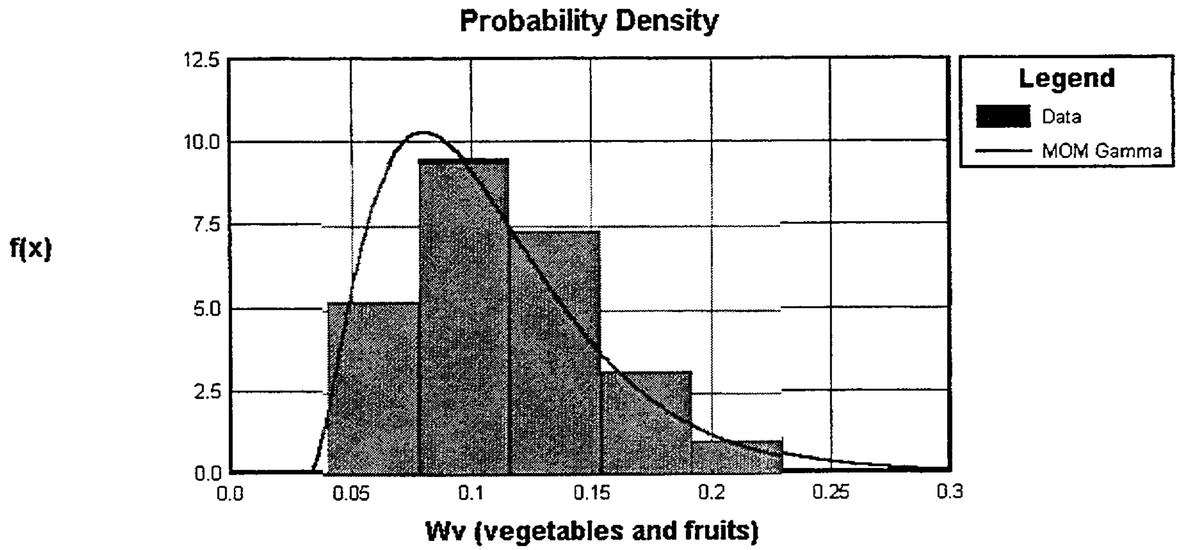

Figure 6.61 Frequency distribution and PDF for the wet-to-dry weight conversion factor for fruits and vegetables

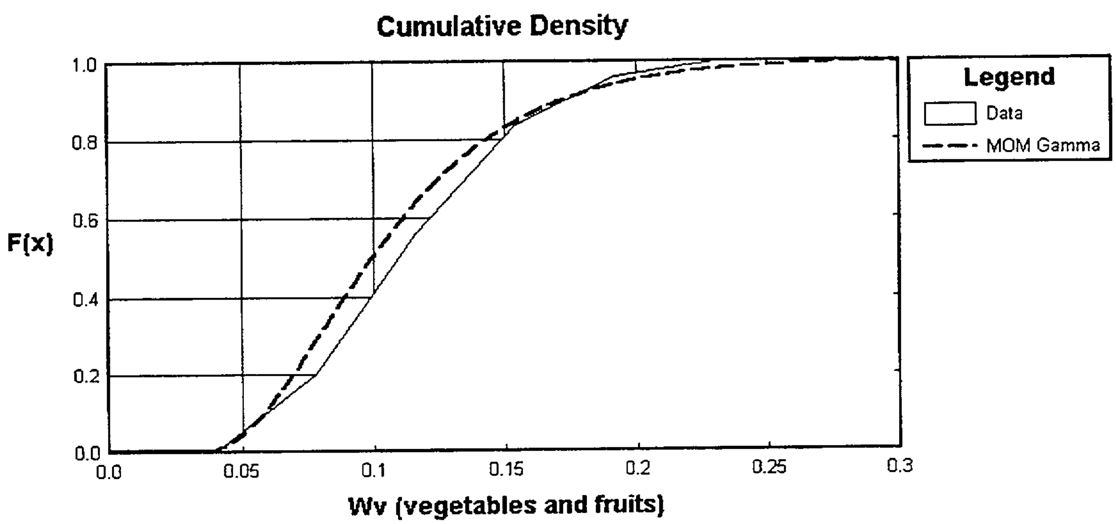

Figure 6.62 Cumulative distribution for the wet-to-dry-weight conversion factor for fruits and vegetables

6.4.9.3 Wet-to-Dry-Weight Conversion Factors for Forage Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens, W_f

The wet-to-dry-weight conversion factors for forage, W_f, as defined for the NUREG/CR-5512, Vol. 1, dose model, describe the fraction of dry matter in forage consumed by beef cattle, poultry, milk cows, and layer hens. The model uses a single, constant value for W_f for all contaminants. Thus, this value represents the average concentration of dry matter in all forage crops consumed by livestock in the residential scenario.

6.4.9.3.1 Use of W_f in Modeling

The wet to dry-weight conversion factor converts the weight of forage to the corresponding weight of dry matter. This factor is required in the soil-forage feed-animal-human pathway for calculating 1) the concentration factor for radionuclide j in fresh forage crop f at the time, t, from in initial unit concentration of parent radionuclide i in soil, C_{sfjt} (Equation 5.13, p. 5.19 of NUREG/CR-5512, Vol. 1), 2) the average concentration factor for radionuclide j in fresh forage crop f over the feeding period at the time of animal consumption of forage from an initial unit concentration of parent radionuclide i in soil, C_{sfjc} (Equation 5.15, p. 5.21 of NUREG/CR-5512, Vol. 1) and 3) the average concentration factor for animal product a over the fresh forage feeding period for soil ingestion by animals for radionuclide j for initial unit concentration of parent radionuclide in soil, C_{sajd} (Equation 5.19, p. 5.22 of NUREG/CR-5512, Vol. 1) according to the following equations:

$$C_{sfjt} = 1000\ (ML_f + B_{jf})\, W_f\, A\{C_{sj}, t\}/C_{si}(0) \qquad (6.86)$$

where ML_f is the plant soil mass-loading factor for resuspension of soil onto forage plant f, B_{jf} is the concentration factor for uptake of radionuclide j from the soil in fresh forage crop f, W_f is the dry to wet-weight conversion factor for fresh forage, $A\{C_{sj},t\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at time t during the feeding period for fresh forage crop f, and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period;

$$C_{sfjc} = 1000\ (ML_f + B_{jf})\ W_f\ S\{C_{sj}, t_{ff}\}/[t_{ff} C_{si}(0)] \qquad (6.87)$$

where $S\{C_{sj},t_{ff}\}$ is a concentration time-integral factor for radionuclide j in soil over the feeding period for crop forage, t_{ff}; and

$$C_{sajd} = 1000\ F_{aj}\ Q_d\ W_f\ Q_f\ x_f\ S\{C_{sj}, t_{ff}\}/[t_{ff} C_{si}(0)] \qquad (6.88)$$

where Q_d is the soil intake as a fraction of forage intake for the animal.

6.4.9.3.2 Information Used to Define the Distribution for W_f

A value of 0.22 for W_f was adopted in NUREG/CR-5512, Vol. 1, based on recommendations by Till and Meyer (1983).

The National Research Council published detailed information on nutrients in forage, hay and grain crops for livestock. Since livestock feed intake is based on dry-matter intake, and the corresponding nutrient content in dry matter, the National Research Council data included moisture content. Table 6.80 lists common types of grasses and the fraction of dry matter (National Research Council, 1996).

6.4.9.3.3 Distributions for Wet-to-Dry-Weight Conversion Factors for Forage

A distribution for W_f was defined from the average dry matter content over the twelve hay crops in Table 6.80.

Table 6.80 Moisture content in forage crops (National Research Council, 1996)

Hay crop	Dry matter (kg dry-weight/kg wet-weight
Alfalfa	0.234
Bermuda grass	0.303
Bluegrass	0.308
Broome grass	0.261
Canary grass	0.228
Clover, ladino	0.193
Clover, red	0.262
Fescue	0.313
Orchard grass	0.235
Rye grass	0.226
Trefoil	0.193
Timothy	0.267

Since the type of forage crop consumed by livestock is uncertain, each of the crops was considered equally likely. The distribution for the wet-to-dry weight conversion factor was determined by fitting a beta function to the reported conversion factors in Table 6.80. The parameters for the beta distribution are shown in Table 6.81. The frequency distribution and fitted PDF are shown in Figure 6.63. The PDF has a mean of 0.2519 and lower and upper limits of 0.183 and 0.323. The cumulative distribution for W_f is shown in Figure 6.64.

Table 6.81 Distribution parameters for wet-to-dry-weight conversion factor for forage

Parameter	Value
a_1	1.15
a_2	1.18
δ_1	0.183
δ_2	0.323

6.4.9.4 Wet-to-Dry-Weight Conversion Factors for Stored Grain Consumed by Beef Cattle, poultry, Milk Cows, and Layer Hens, W_g

The wet-to-dry-weight conversion factor, W_g, is the fraction of dry matter in stored grains. The quantity of moisture in grain varies with the type of grain and physical conditions under which the grain is stored (e.g., dew point).

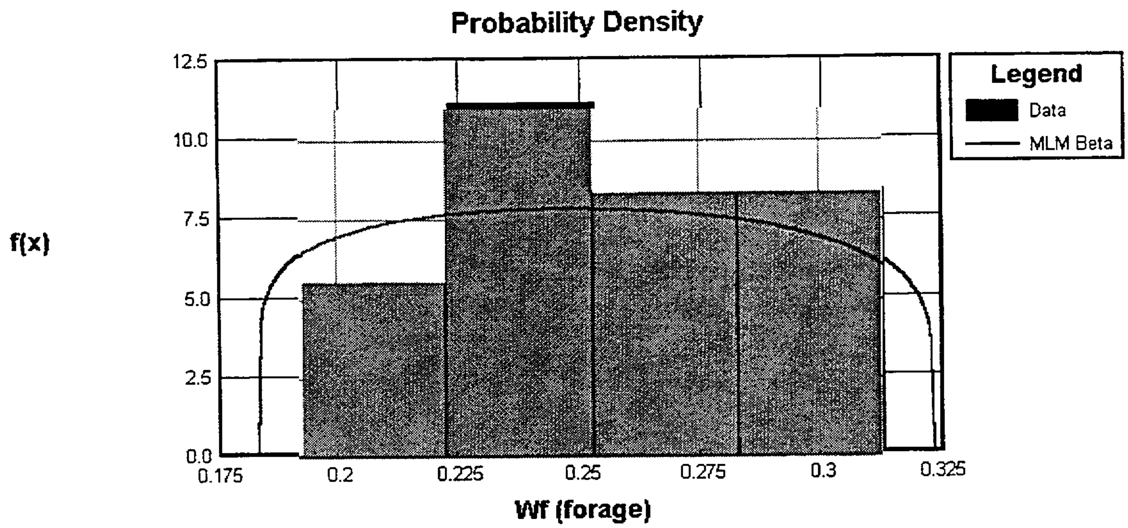

Figure 6.63 Frequency distribution and PDF for wet-to-dry-weight conversion factor for forage consumed by livestock

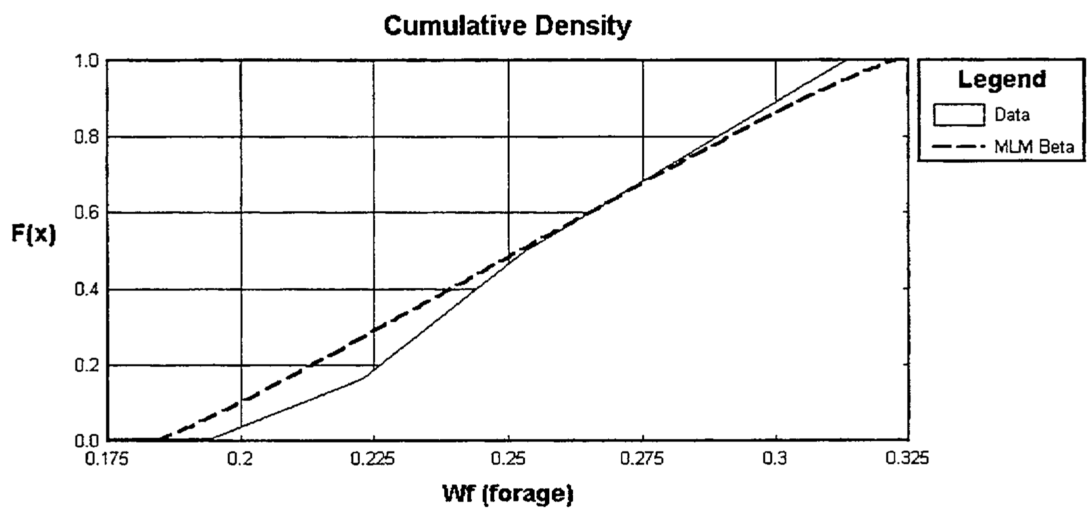

Figure 6.64 Cumulative distribution for wet-to-dry-weight conversion factor for forage consumed by livestock

6.4.9.4.1 Use of W_g in Modeling

The wet to dry-weight conversion factor converts the weight of the as-stored grain to a corresponding weight of dry matter. This factor is required in the soil-stored grain-animal-human pathway to determine the quantity of contaminated grain consumed by livestock and is used in the calculation of the concentration factor for radionuclide j in stored grain crop g at the time of initial feeding to animals from an initial unit concentration of parent radionuclide i in soil, C_{sgjc}, as shown in the following equation (Equation 5.12, p. 5.18 of NUREG/CR-5512, Vol. 1):

$$C_{sgjc} = 1000\left(ML_g + B_{jg}\right) \; W_g A\left\{C_{sj}, t_{ff}\right\} / C_{si}(0) \qquad (6.89)$$

where ML_g is the plant soil mass-loading factor for resuspension of soil onto grain plant g; B_{jg} is the concentration factor for uptake of radionuclide j from the soil into stored grain crop g; W_g is the wet to dry-weight conversion factor for stored grain crop g; $A\{C_{sj},t_{ff}\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing season; t_{gg} is the growing period for stored grain crop g; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period.

6.4.9.4.2 Information Used to Define the Distribution for W_g

The value for this parameter defined in NUREG/CR-5512, Vol. 1, is 0.91 (Till and Myer, 1983).

Grain crops provide the major dietary needs for poultry and layer hens and supplement of diets of ruminant animals in agricultural operations. The dry matter content of common grain crops for livestock consumption were taken from data compiled by the NRC (NRC, 1996) and are shown in Table 6.82.

6.4.9.4.3 Distribution for Wet-to-Dry-Weight Conversion Factors for Stored Grain

The distribution for the wet-to-dry weight conversion factor was determined by fitting a log normal function to the values reported in Table 6.82. The distribution parameters for the log normal distribution are shown in Table 6.83. The frequency distribution and fitted PDF are shown in Figure 6.65. The PDF has a mean of 0.8995 and lower and upper limits of 0.881 and 0.922. The cumulative distribution for W_g is shown in Figure 6.66.

Table 6.82 Moisture content in stored grain (National Research Council, 1996)

Grain crop	Dry matter (kg dry-weight/kg wet-weight)
Barley	0.881
Canola	0.922
Corn	0.900
Oats	0.892
Sorghum	0.900
Wheat	0.902

Table 6.83 Distribution parameters for wet-to-dry-weight conversion factor for stored grain

Parameter	Value
μ	0.0224
σ	0.500
ϵ	0.874

6.4.9.5 Wet-to-Dry-Weight Conversion Factors for Stored Hay Consumed by Beef Cattle, Poultry, Milk Cows, and Layer Hens, W_h

The wet-to-dry-weight conversion factor for stored hay consumed by beef cattle, poultry, milk cows, and layer hens converts the weight of the as-cut plant to a corresponding dry weight. The factor is a measure of the dry matter content in hay crops. The model uses a single, constant value for all stored hay crops.

6.4.9.5.1 Use of W_h in Modeling

The wet to dry-weight conversion factor converts the weight of the as-cut hay to a corresponding weight of dry matter. This factor is required in the soil-stored hay-animal-human pathway to determine the quantity of contaminated hay consumed by livestock. W_h is applied in the calculation of the concentration factor for radionuclide j in stored hay h at the time of initial feeding to animals from an initial unit concentration of parent radionuclide i in soil, C_{shjc}, according to the following equation (Equation 5.11, p. 5.18 of NUREG/CR-5512, Vol. 1):

$$C_{shjc} = 1000\left(ML_h + B_{jh}\right)\, W_h\, A\{C_{sj}, t_{gh}\} / C_{si}(0) \qquad (6.90)$$

where ML_h is the plant soil mass-loading factor for resuspension of soil onto hay plant h; B_{jh} is the concentration factor for uptake of radionuclide j from the soil into stored hay crop h; W_h is the wet to dry-weight conversion factor for stored hay crop h; $A\{C_{sj},t_{gh}\}$ is the decay operator notation used to develop the concentration of radionuclide j in soil at the end of the crop-growing season; t_{gh} is the growing period for stored hay crop h; and $C_{si}(0)$ is the initial concentration of parent radionuclide i in soil at the start of the growing period.

6.4.9.5.2 Review of Additional Information to Define the Distribution for W_h

The value of 0.22 for W_h was proposed in NUREG/CR-5512, Vol. 1, based on studies by Till and Meyer (1983).

Hay crops provide the major dietary needs for ruminant animals in agricultural operations. These hay crops are identical to the forage crops listed in Table 6.80 except in the manner in which the crops are harvested, stored, and subsequently fed to livestock. Since the wet-to-dry-weight conversion factor is equal to the dry matter content of the hay crop, W_h and W_f are equal.

6.4.9.6 Uncertainty in W_h

The distributions for wet-to-dry-weight conversion factors are established based on the average moisture content in a wide range of garden produce and forage, grain, and grain crops. Among the factors that affect the moisture content are the type of crop and environmental conditions under which the crops are grown (e.g., temperature, humidity, length of growing season).

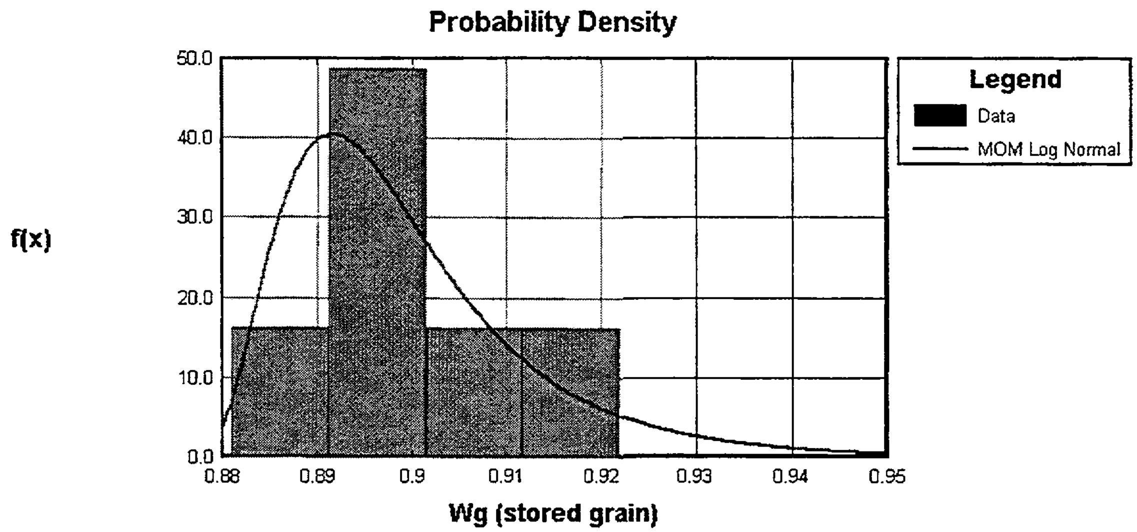

Figure 6.65 Frequency distribution and PDF for wet-to-dry-weight conversion factor for stored grain

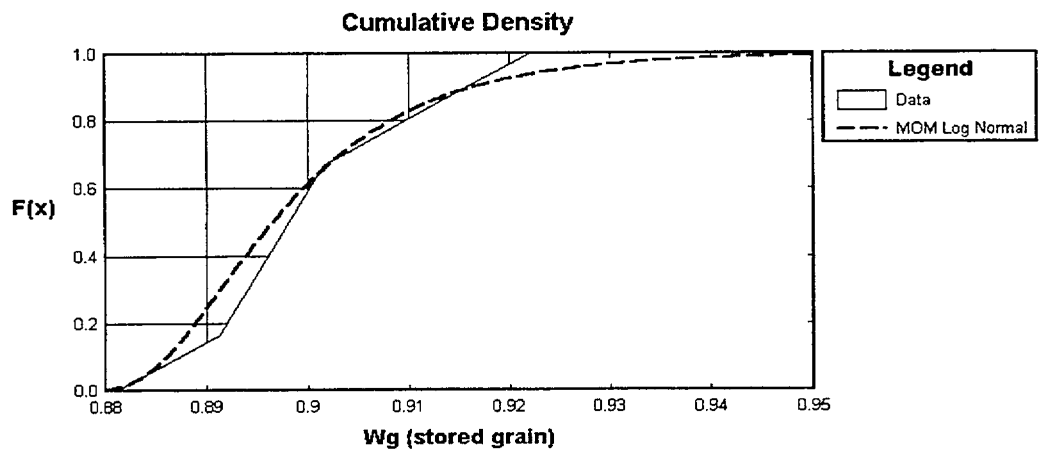

Figure 6.66 Cumulative distribution for wet-to-dry-weight conversion factor for stored grain

6.4.9.7 Alternative Values for W_h

This parameter will likely vary from site to site depending on the local growing conditions (i.e., some crops may not be suitable for growing because of soil and weather). Prevailing agricultural practice might be used to develop alternative values or distributions for these parameters.

6.4.10 Radionuclide Partition Coefficients, $Kd_{1,2i}$

6.4.10.1 Description of K_d

The radionuclide partition coefficients define the ratio between radionuclide solid concentrations (radionuclide quantity adsorbed on the soil/rock particles) and radionuclide liquid concentrations (radionuclide quantity dissolved in the soil/rock pore water) under equilibrium conditions and are expressed in volume per mass units (DandD units are mL/g).

6.4.10.2 Use of K_d in Modeling

Partition coefficients for the ith radionuclide are used to calculate radionuclide retardation in the soil layer (Rt_{1i}) and unsaturated zone (Rt_{2i}) as follows (Vol. 1, p. 49, Equations 4.9 and 4.12):

$$Rt_{1i} = 1 + Kd_{1i}\ \rho_1 / n_1 \qquad (6.91)$$

$$Rt_{2i} = 1 + Kd_{2i}\ \rho_2 / n_2 \qquad (6.92)$$

In Volume 1 it is assumed that partition coefficients for the i[th] radionuclide in the unsaturated layer (Kd_{2i}) are the same as partition coefficients of the soil layer (Kd_{1i}); bulk density of the soil layer (ρ_1) is the same as the bulk density of the unsaturated layer (ρ_2) ; and total porosity of the soil layer (n_1) is the same as total porosity of the unsaturated layer (n_2). These assumptions lead to an assumption that radionuclide retardation in the soil layer is the same as in the unsaturated layer ($Rt_{1i} = Rt_{2i}$).

The retardation coefficients define the radionuclide transport velocities within the soil layer (v_{1i}) and within the unsaturated layer (v_{2i}) as follows:

$$v_{1i} = I/\left(R_{1i}^{*}\ \theta_1\right) \tag{6.93}$$

$$v_{2i} = I/\left(R_{2i}^{*}\ \theta_2\right) \tag{6.94}$$

where I is infiltration rate and θ_1 and θ_2 are volumetric water contents of the soil layer and unsaturated zone respectively.

The differences in the transport velocities of the different elements is due solely to the differences in partition coefficients. The transport velocities determine the radionuclide leaching rates from the soil layer (L_{12i}) and from the unsaturated layer (L_{23i}) which, in turn, are the parameters of the system of ordinary differential equations that describes the time-dependent distribution of mass among the soil layer, unsaturated layer, and aquifer layer.

Partition coefficients can noticeably affect doses because they may significantly influence the mass transfer rates between the soil, unsaturated zone, and the aquifer and, consequently, the radionuclide concentrations in soil, drinking water consumed by the humans, water consumed by animals, water used for irrigation, and water in the surface pond. This affects the time-dependent distribution of the contaminant mass among all the contaminant pathways included in the residential scenario (partial pathway transfer factors, PPTFs, in Volume 1 terminology) and, as a result, the pathway doses and the TEDE. The influence of the partition coefficient on the total dose should be greater in the case when the leaching rates L_{12i} and L_{23i} are comparable to or greater than the radioactive decay constant.

6.4.10.3 Data Reviewed to Develop PDFs for Partition Coefficients

The partition coefficient values defined in Volume 1 are listed in Table 6.84. Of the total (73 elements) four elements in this table (H, Kr, Xe, and Rn) have partition coefficients equal to zero, since they only are transported in gaseous phase. The partition coefficient values for the remaining 69 elements represent either the minimum values (the most mobile conditions) of the experimentally derived values provided in Sheppard and Thibault (1990) and Sheppard, Sheppard, and Amiro (1991) (25 partition coefficients), or values estimated from soil-to-plant concentration ratios (43 partition coefficients) using the following formula:

$$\ln\left(Kd_{ki}\right) = 2.11 - 0.56 \ln\left(B_{iv}/4\right) \tag{6.95}$$

where B_{iv} is concentration ratio for vegetative parts of the plant v (dry-weight basis) for the ith radionuclide, 4 is a dry-weight to wet-weight conversion factor, and 2.11 and 0.56 are empirical coefficients proposed by Thibault, Sheppard, and Smith (1990) for sandy soil. These coefficients were used to calculate lower values for the estimated partition coefficients. The B_{iv} values were based on concentration ratios for leafy vegetables from the IUR (IUR, 1989); Baes et al. (1984); and Strenge, Bander, and Soldat (1987). The concentration ratio based estimates of the partition coefficient were used in the absence of experimental data.

Additional data to support the development of PDFs describing the variability in partition coefficient values were selected for this analysis based on the following:

- Individual measurements of partition coefficients obtained from experiments are preferable to mean or best-estimate values.
- Variability based on experimental measurements (Thibault et al., 1990; Sheppard and Thibault, 1990) represents small-scale spatial variability and may not sufficiently describe the variability in effective Kd values over a large soil volume. Given the potential scale-dependant variability, best estimates of small-scale Kd values derived from Thibault et al. (1990) should be compared to the best estimates of the large-scale Kd values. Estimates of large-scale Kd values are available from McKinkley and Scholtis (1991). McKinkley and Scholtis (1991) presented a summary of Kd databases used in repository performance assessment. These data do not provide information on ranges, number of samples, or other statistics, and cannot be used for developing empirical distributions. However, they provide best estimate values that can be evaluated against smaller-scale best estimates to gauge the scale effects.

Table 6.84 Default values of the radionuclide partition coefficients in mL/g from NUREG/CR-5512, Vol. 1, (Table 6.7 in Volume 1, p. 6.18)

Element	Partition coefficient	Basis*	Element	Partition coefficient	Basis*
H	0.0E+0	M	Sb	4.5E+1	E
Be	2.4E+2	R	Te	1.4E+2	R
C	6.7E+0	C	I	1.0E+0	E
F	8.7E+1	R	Xe	0.0E+0	M
Na	7.6E+1	R	Cs	2.7E+2	E
P	8.9E+0	R	Ba	5.2E+1	R
S	1.4E+1	R	La	1.2E+3	R
Cl	1.7E+0	R	Ce	5.0E+2	E
K	1.8E+1	R	Pr	2.4E+2	R
Ca	8.9E+0	R	Nd	2.4E+2	R
Sc	3.1E+2	R	Pm	2.4E+2	R
Cr	3.0E+1	E	Sm	2.4E+2	R
Mn	5.0E+1	E	Eu	2.4E+2	R
Fe	1.6E+2	E	Gd	2.4E+2	R
Co	6.0E+1	E	Tb	2.4E+2	R
Ni	4.0E+2	E	Ho	2.4E+2	R
Cu	3.0E+1	R	W	1.0E+2	R
Zn	2.0E+2	E	Re	1.4E+1	R
As	1.1E+2	R	Os	1.9E+2	R
Se	1.4E+2	R	Ir	9.1E+1	R
Br	1.4E+1	R	Au	3.0E+1	R
Kr	0.0E+0	M	Hg	1.9E+1	R
Rb	5.2E+1	R	Tl	3.9E+2	R
Sr	1.5E+1	E	Pb	2.7E+2	E
Y	1.9E+2	R	Bi	1.2E+2	R
Zr	5.8E+2	R	Po	1.5E+2	E
Nb	1.6E+2	R	Rn	0.0E+0	M
Mo	1.0E+1	E	Ra	5.0E+2	E
Tc	1.0E-1	E	Ac	4.2E+2	R
Ru	5.5E+1	E	Th	3.2E+3	E
Rh	5.2E+1	R	Pa	5.1E+2	R
Pd	5.2E+1	R	U	1.5E+1	E
Ag	9.0E+1	E	Np	5.0E+0	E
Cd	4.0E+1	E	Pu	5.5E+2	E
In	3.9E+2	R	Am	1.9E+3	E
Sn	1.3E+2	R	Cm	4.0E+3	E
Cf	5.1E+2	R			

* Values for partition coefficients are based on: M - Assumed to be mobile; R - Calculated from concentration ratios; C - Experimental data from Sheppard, Sheppard, and Amiro (1991); or E - Experimental data from Sheppard and Thibault (1990).

- The Nuclear Energy Agency (NEA) data base (NEA, 1989) is a significant source of information on partition coefficient values.

A large number of experimental data on partition coefficients is available from the NEA sorption database (SDB) (NEA, 1989). The SDB incorporates the information previously contained in the International Sorption Information Retrieval System (ISIRS) and additional data compiled by the NEA. The data base contains approximately 11,000 values of partition coefficients for different elements. Most of the data are from static batch sorption experiments, some are from column (dynamic) experiments, and a few data are from retardation (dynamic) studies. When available, the data base provides information on the reference source, method used, solution phase, initial contaminant concentration, type of solid material used, reducing/ oxidizing conditions, experiment duration, and other details.

The SDB was searched to extract data for the 69 elements of interest from experiments using unconsolidated and consolidated deposits. The unconsolidated deposits are described in the SDB in general terms such as: clay, fine sand, sand, soil, and loam. This differs from the classification used in Sheppard and Thibault (1990), where four different types of soils are specified based on the particle size distribution and organic material quantity. Additional data are provided for consolidated deposits, including dolomite, gypsum, sandstone, shale, limestone, rock of unspecified mineral composition and sediment.

Data from the SDB for unconsolidated and consolidated deposits were obtained for the following 19 radionuclides: C, Mn, Co, Ni, Zn, Sr, Y, Tc, Pd, Ag, I, Cs, Ce, Eu, Ra, U, Np, Pu, and Am. Experimental data for Pd and Y are not available from Thibault et al. (1990) or Sheppard and Thibault (1990). Data in the SDB were combined with data from Thibault et al. (1990) for this analysis.

The primary goals of the K_d data analysis were:

- to determine if there is a strong correlation between the composition of the unconsolidated deposits and their ability to sorb different radionuclides;
- to develop radionuclide partition coefficient probability distributions that provide the best fitting to all experimental data available for unconsolidated deposits; and,
- to develop radionuclide partition coefficient probability distributions for elements that do not have individual measurement data.

6.4.10.3.1 Correlation between Partition Coefficient Values and Composition of the Unconsolidated Deposits

Thibault et al. (1990) provide data on partition coefficient values along with information on the composition of the unconsolidated sediments used in each experiment. The data on sediment composition are expressed as percentage of clay particles, silt particles, sand particles, and organic material of the sample. These data were used to generate scatter plots of Kd versus composition (expressed in percent composition), and the degree of correlation was analyzed, quantitatively and qualitatively. When available, the partition coefficients were plotted against the percent of clay, silt, sand, and organic material. Table 6.85 describes the qualitative correlation observed between partition coefficient and composition for 21 elements.

As can be seen from Table 6.85, most of the elements analyzed show an absence of correlation with the percentage of the particles of different sizes: 16 of 19 elements show no correlation to percentage of clay; 14 of 16 elements show no correlation to percentage of silt; 11 of 16 elements show no correlation to percentage of sand; and 15 of 19 elements show no correlation to percentage of organic material. Some of the partition coefficient values show weak correlation; however, it is not sufficient to justify any functional relationship.

The data from NEA (1989) combined with the data from Thibault et al. (1990) were used to analyze correlation between the elements partition coefficient values and composition of deposits. The partition coefficient values for a few elements were plotted for the different unconsolidated deposit types (clay, sand, and loam) and for the different consolidated deposit types (gypsum, dolomite, sandstone, limestone, and shale). There was no discernible correlation or trends for the partition coefficient values across different types of unconsolidated deposits for Pu , Am, and Se. Pu and Am exhibited similar partition coefficients between unconsolidated and consolidated deposits. The partition coefficients typical of unconsolidated deposits for Se were significantly lower than the partition coefficients in consolidated deposits.

Based on this analysis, we concluded that no reliable correlations could be developed for the elements of

Table 6.85 Correlation between partition coefficient values and composition of the unconsolidated deposits

Element	Description of correlation			
	% Clay	% Silt	% Sand	% Organic
I	indistinguishable	indistinguishable	weak	insignificant
Pb	indistinguishable	NA	NA	indistinguishable
Ru	NA	NA	NA	weak
Ni	weak	indistinguishable	weak	indistinguishable
Fe	indistinguishable	weak	weak	weak
Po	indistinguishable	indistinguishable	indistinguishable	indistinguishable
U	indistinguishable	indistinguishable	indistinguishable	NA
Tc	indistinguishable	indistinguishable	indistinguishable	weak
Co	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Sr	indistinguishable	indistinguishable	weak	indistinguishable
Cd	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Cs	indistinguishable	weak	weak	indistinguishable
Ra	indistinguishable	indistinguishable	indistinguishable	weak
Mn	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Np	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Se	weak	NA	NA	indistinguishable
Th	indistinguishable	NA	NA	NA
Zn	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Cm	indistinguishable	indistinguishable	indistinguishable	indistinguishable
Cr	NA	NA	NA	indistinguishable
Ce	weak	indistinguishable	indistinguishable	indistinguishable

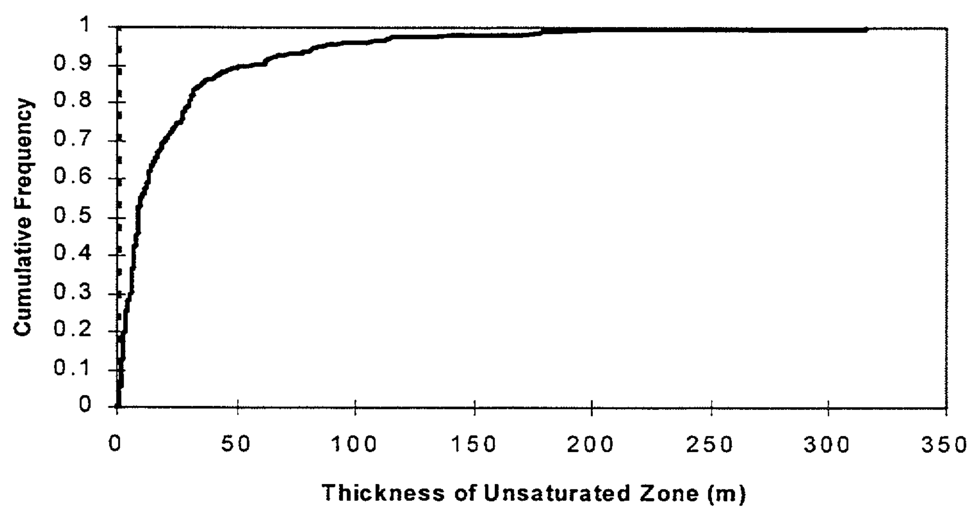

Figure 6.67 Cumulative frequency of sampled H2 values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

interest. The absence of a distinguishable correlation between the composition of the unconsolidated deposits and partition coefficients supports a single probability distribution function for each element based on all data available, rather than separate probability distributions for each element and soil type.

6.4.10.4 Probability Distributions for Partition Coefficients

6.4.10.4.1 Partition Coefficient Probability Distributions Based on Experimental Data for Unconsolidated Deposits

Experimental data on partition coefficients for unconsolidated deposits are available for 34 of the 69 elements of interest. The experimental data from Thibault et al. (1990) were used to develop probability distributions for 15 elements. The experimental data from the NEA SDB (1989) were used for two radionuclides. The experimental data from Thibault et al. were combined with the experimental data from the NEA SDB to develop probability distributions for the 17 remaining elements. Information on data sources and number of samples available for each element is provided in Table 6.86.

The computer code C-FIT (Center for Engineering Research Inc., 1996) was used to develop radionuclide probability distribution functions based on the experimental data. C-FIT provides three different optimization techniques (method of moments, maximum likelihood method, and least squares method) to fit experimental data into16 different possible probability distribution functions. The decision on which distribution provides the best fit can be made either visually based on the comparison of the experimental data histogram and different probability distribution functions and/or based on the results of the goodness-of-fit tests. Two test are available with the software: chi-square test and Kolmogorov-Smirnov test. Both tests calculate significance levels corresponding to the hypothesis that experimental data are sampled from a specified distribution. The higher the significance level, the higher the probability that the experimental data are from this distribution.

The analysis of data for each of 34 elements consisted of plotting the histograms of partition coefficients and logarithms of partition coefficients, and comparing them with the different theoretical distributions. In most of the cases developing distributions for partition coefficients using C-FIT was not successful in that the significance levels from both statistical tests were very low. This is due in part to the variability in the partition coefficient values over many orders of magnitude. To reduce the spread, distributions were fit to the log-transformed partition coefficient data. Using log-transformed data allowed development of histograms with smaller ranges and distributions with higher significance levels.

All three optimization methods were used to search for the best fit. Both statistical goodness-of-fit tests were performed for each run. However, it was found that chi-square test produced a low significance level even in the cases where the experimental data appeared to be in good agreement with the theoretical distribution. Conversely, the Kolmogorov-Smirnov test results were in good agreement with visual analysis of the results. The results of the Kolmogorov-Smirnov test were used to evaluate the goodness of fit.

The summary of the analysis is also included in Table 6.86. This table provides information on type of distribution obtained, parameters that characterize the distribution, the fitting method that provided the highest significance level, and the significance level from the Kolmogorov-Smirnov test. In addition to this information, Table 6.86 provides the corresponding values from NUREG/CR-5512, Vol. 1, and the best estimates of the partition coefficients (logarithmically converted) from the repository performance assessment studies compiled in McKinkley and Scholtis (1991), obtained for soil and surface deposits.

Seven of the 34 elements analyzed (Y, Ba, Eu, Cu, Ca, As, and Sb) did not have enough data (15 or fewer samples) to develop distributions fit to the data. The uncertainty in the log of these Kd values was represented by normal distributions with mean values based on the mean of the experimental data and a standard deviation based on the larger of the standard deviation in the data for that element or the standard deviation in the data for all elements.

For 21 of the 34 elements, the logarithms of the partition coefficients fit a normal distribution. The mean values of these distributions vary from 0.66 (Kd = 4.6 mL/g) for I to 3.83 (Kd = 6761 mL/g) for Cm with an average value of 2.37 (Kd = 234.4 mL/g).

Over the 34 elements, the average standard deviation of the fitted normal distributions is 1.09. However, some distributions have much lower standard deviations (e.g., 0.25 for Se) and some distributions have much higher standard deviations (e.g., 1.93 for Zn). The mean values for Pd, Tc, and Se lay outside of the range of the best estimated values provided in McKinkley and Scholtis (1991). In the cases of Pd and Se this may be related to the small size of the populations considered (nine

Table 6.86 Radionuclide partition coefficient distributions, logarithmic values in mL/g

Element	Data source (*)	Number of samples	Distribution type	Fitting method	Significance level (**)	Distribution parameters				Volume 1 default	PA study range (***)
						mean	std. dev.	other	variance		
Sr	1, 2	539	normal	LS	0.10	1.50	0.92		0.85	1.18	1.0 to 2.0
I	1, 2	109	normal	LS	0.37	0.66	0.95		0.90	0.00	-∞ to 2.0
Cs	1, 2	564	normal	MLM	0.06	2.65	1.01		1.02	2.43	2.0 to 4.0
Tc	1, 2	206	normal	LS	0.65	0.87	1.33		1.77	-1.0	-∞ to 0.7
Ra	1, 2	53	normal	MLM	0.52	3.55	0.74		0.55	2.70	
U	1, 2	60	normal	MLM	0.64	2.10	1.36		1.85	1.18	1.3 to 3.2
Ni	1, 2	52	normal	LS	0.23	1.57	1.48		2.19	2.60	1.0 to 3.0
Po	1	50	normal	LS	0.97	2.26	0.73		0.53	2.18	
Pb	1	18	normal	MOM	0.96	3.38	1.20		1.44	2.43	
Ru	1	47	normal	LS	0.30	3.20	1.36		1.85	1.74	
Cd	1	87	normal	LS	0.22	1.53	1.30		1.69	1.60	
Am	1, 2	219	normal	LS	0.53	3.16	1.37		1.88	3.28	2.0 to 5.0
Pu	1, 2	205	normal	MLM	0.75	2.98	0.82		0.67	2.74	2.5 to 5.0
Pd	2	9	normal	LS	0.92	2.27	1.37		1.88	1.72	0.6 to 2.0
Ce	1, 2	29	normal	LS	0.55	1.93	0.43		0.18	2.70	
Mo	1	24	normal	LS	1.00	1.42	0.75		0.56	1.00	
Th	1	26	normal	MLM	1.00	3.77	1.57		2.46	3.51	2.9 to 4.8
Cr	1	22	normal	LS	0.94	2.01	1.20		1.44	1.48	
Cm	1	23	normal	LS	0.90	3.83	0.79		0.62	3.60	
Zn	1, 2	98	normal	MLM	0.18	3.03	1.93		3.72	2.30	
Se	1	22	normal	MOM	1.00	2.06	0.25		0.06	2.15	0.0 to 1.7
Y	2	15	normal			2.90	1.4			2.28	
Mn	1, 2	127	log-normal	MLM	0.50	1.15	0.70			1.70	
Ag	1, 2	27	log-normal	MOM	0.75	2.04	0.52			1.95	
Eu	1, 2	14	normal			2.98	1.74			2.38	
Ba	1	9	normal			1.65	3.53			1.72	
C	1, 2	66	log-normal	MLM	0.02	1.32	0.79			0.83	-∞ to 2.0
Co	1, 2	292	Gumbel Min	MOM	0.59	3.00		1.18		1.78	
Fe	1	44	Gumbel Min	MLM	0.97	2.95		1.65		2.21	
Np	1, 2	262	Gumbel Max	MLM	0.29	0.85		1.28		0.70	1.0 to 3.0
Cu	1	4	normal			2.25	1.40			1.48	
Ca	1	4	normal			3.17	1.40			0.95	
As	1	4	normal			2.06	1.40			2.04	
Sb	1	4	normal			2.24	1.40			1.65	
Be	3					2.97	1.40			2.38	
F						0.70	1.40			1.94	
P	3					1.41	1.40			0.95	
S						2.00	1.40			1.15	
Cl						0.70	1.40			0.23	-∞ to 2.0
Sc						2.20	1.40			2.49	-∞ to 1.23
Br	3					1.75	1.40			1.15	
Te	3					2.74	1.40			2.15	-∞ to 1.2
La						0.70	1.40			3.08	
Pr						2.20	1.40			2.38	
Nd						2.20	1.40			2.38	
Pm	3					3.70	1.40			2.38	3 to 4
Sm	3					2.97	1.40			2.38	0 to 3.7
Gd						0.70	1.40			2.38	-1.5 to 3.0
Tb						2.20	1.40			2.38	0.8 to 2.9
Ho	3					2.97	1.40			2.38	2.4 to 3.4
W						2.20	1.40			2.00	

Table 6.86 Radionuclide partition coefficient distributions, logarithmic values in mL/g (continued)

Element	Data source (*)	Number of samples	Distribution type	Fitting method	Significance level (**)	Distribution parameters: mean	std. dev.	other	variance	Volume 1 default	PA study range (***)
Re	3					1.64	1.40			1.15	
Os						2.20	1.40			2.28	
Ir						2.20	1.40			1.96	
Au						2.20	1.40			1.48	
Rb	3					2.31	1.40			1.72	-1 to 2.2
Zr	3					3.38	1.40			2.76	1.0 to 3.9
Nb	3					2.80	1.40			2.20	0 to 3.7
Rh						2.20	1.40			1.72	
In						2.20	1.40			2.59	
Sn	3					2.70	1.40			2.11	1.7 to 2.9
Hg						2.20	1.40			1.28	
Tl						2.20	1.40			2.59	
Bi	3					2.65	1.40			2.08	1.2 to 2.2
Ac	3					3.24	1.40			2.62	1.0 to 3.7
Pa	3					3.31	1.40			2.71	
Cf						2.20	1.40			2.71	
Na						0.70	1.40			1.88	
K						0.70	1.40			0.10	

(*) - 1 = Thibault *et al.* (1990); 2 = Sorption Data Base(SDB), NEA(1989); 3 = Sheppard and Thibault (1990)
(**) - significance level from Kolmogorov-Smirnov goodness of fitness test
(***) - best estimate value range from the repository performance assessment study, McKinkley and Schottis (1991)

samples for Pd and 22 samples for Se) or the experiment scale since the McKinkley and Scholtis (1991) data are from large scale observations as opposed to the Thibault et al. (1990) data, which are from small scale experiments. In the case of Tc, the size of the population appears to be representative (206 samples) and the observed difference may be related to the experiment scale or the experiment scale since the mean the K_d values for I, Sr, Cs, U, Ni, Am, Pu, and Th are within the range reported by McKinkley and Scholtis (1991).

For three of the 34 elements (Mn, Ag and C), the logarithmic values of the partition coefficients demonstrated the best fit with a log-normal distribution. The log-normal distribution better describes the shift of the logarithms of the experimental data to the lower values. The mean values vary from 0.14 to 2.04. The standard deviation varies from 0.52 to 1.17. The data from McKinkley and Scholtis (1991) are available only for C. The mean value obtained for C is within the best estimate range.

For three other elements (Co, Fe, and Np), the logarithmic values of the partition coefficients demonstrated the best fit with the Gumbel distribution (Gumbel minimum for Co and Fe and Gumbel maximum for Np). The Gumbel distribution better describes the shift of the logarithms of the experimental data to the higher values. In all cases the population sizes (292 samples for Co, 44 samples for Fe, and 262 samples for Np) appear to be large enough to justify these distributions. The standard deviation varies from 0.52 to 1.17.

6.4.10.4.2 Partition Coefficient Probability Distributions for Elements without Data

The remaining 35 of the 69 elements of interest have no data on partition coefficient. In Volume 1, partition coefficients for these and other elements were defined based on plant-to-soil concentration ratio model [Equation (6.95)]. A different approach was taken in this analysis because of the potential for inconsistencies in describing uncertainty in partition coefficient values using concentration ratio data. These difficulties arise in estimating the partition coefficient based on plant uptake, because the concentration in plants is modeled as a function of the concentration ratio and the total soil concentration (which is a function of the partition coefficient).

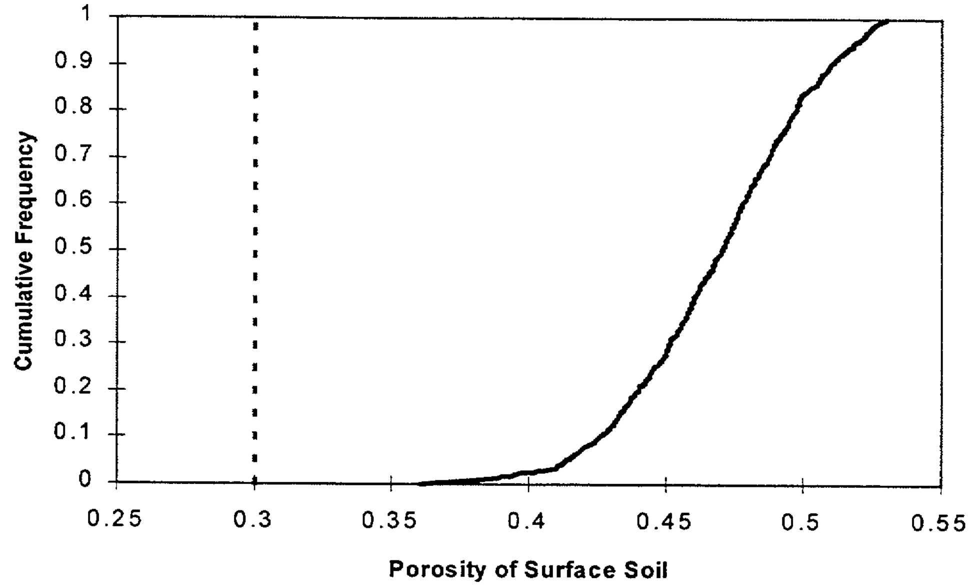

Figure 6.68 Cumulative frequency of sampled N1 values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

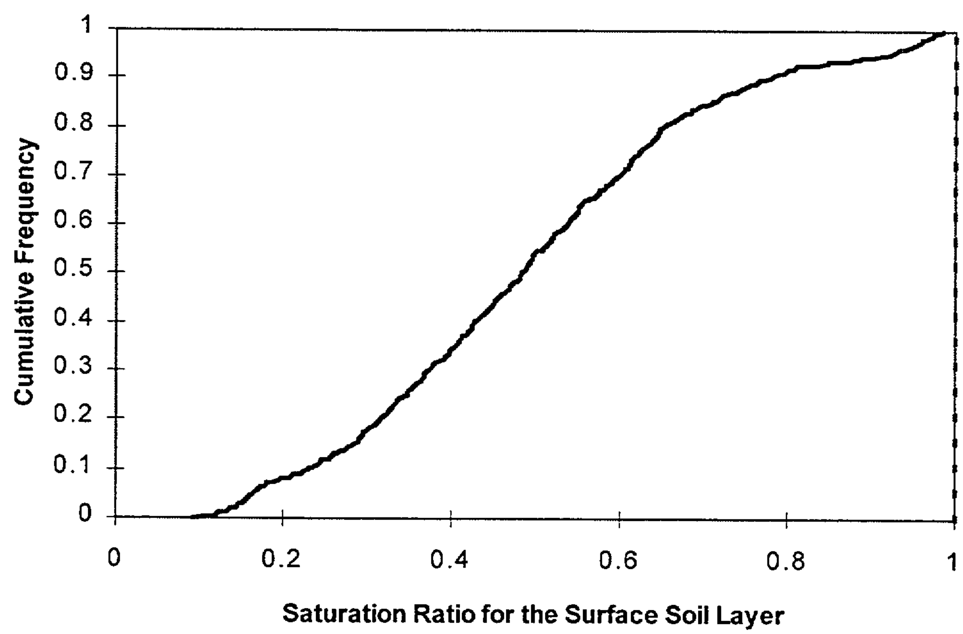

Figure 6.69 Cumulative frequency of sampled f1 values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

We have assumed that the variability in the logarithms of the partition coefficients for elements without experimental data is normally distributed. This assumption is based on the observation that the majority of the distributions fit to experimental data are normally distributed (see Table 6.86). In addition, we have assumed that the standard deviation of these normal distributions will be the same as the standard deviation derived from a distribution of *all* the experimental observations in Table 6.86. To obtain the pooled standard deviation, all the experimental data available for all the radionuclides were combined and analyzed. The resulting distribution is normal with the mean equal to 2.2 and the standard deviation equal to 1.4.

Mean values were based on review of additional literature. Additional information was found in Thibault et al. (1990) for Be, P, Br, Te, Sm, Ho, Re, Rb, Zr, Nb, Sn, Bi, Ac, and Pa. In Thibault et al. (1990), the mean values of the experimental data are presented for each of these 14 radionuclides for each of four types of soil (sand, clay, silt, and organic). Based on these data, the average value over all soil types was used to define the mean of the corresponding normal distributions having standard deviation of 1.4 (Table 6.86).

Eight elements were assumed to behave similarly to iodine: K, Na, F, S, Cl, La, Gd, and Tb (McKinley and Scholtis, 1991). These elements are known to have low sorption capabilities, similar to I, and were therefore assumed to have partition coefficients similar to iodine. The distribution of the log-transformed partition coefficients for these elements was assumed to have the same mean as I (0.7), but a higher standard deviation of 1.4 to account for potential differences (Table 6.86).

No additional information was found for the partition coefficients of the remaining 13 elements: Pm, Sc, Pr, Nd, W, Os, Ir, Au, Rh, In, Hg, Tl, and Cf. The partition coefficient probability distributions for these elements were based on the mean (2.2) and standard deviation (1.4) of all experimental data (Table 6.86).

6.5 Results of the Residential Scenario Parameter Analysis

The procedure described in Section 3.5 was applied to define default values for the residential scenario parameters. This section describes the parameter values produced by this procedure, as well as key intermediate results. Section 6.5.1 summarizes the parameter distributions used in the analysis. Section 6.5.2 describes the way the dose distributions for the individual source nuclides were calculated from these parameter distributions. Section 6.5.3 describes the way potential deterministic default values for the physical parameters were identified. Section 6.5.4 describes the way these potential default values were evaluated to select a particular solution as the set of default values.

6.5.1 Summary of Parameter Type, Variability, Means and Input PDFs

Table 6.87 summarizes the residential scenario model input parameters, including:

- The symbol, description, and units of each parameter;
- The parameter classification as either behavioral (B), physical (P), or metabolic (M);
- Whether the parameter is treated as a constant (C), is sampled from a distribution (S), or is a function of other parameters (F); and
- The mean value of the parameter.

The behavioral parameter values for the AMSG are defined by the mean values of the respective parameter distributions. For the residential scenario, the screening group is defined as adult male resident farmers. Distributions for the behavioral parameters for this group are described in Section 6.2. For these parameters, the average values in Table 6.87 define the default values used in the subsequent dose calculations.

6.5.2 Calculation of Dose Distributions

The dose distributions, which are used to define the default screening analysis, represent the possible site-specific dose values that might result from unit concentrations of each of the 106 potential source radionuclides having half-lives greater than 65 days (see Table 6.88 for a list of these radionuclides). As described in Section 3.5.2, dose distributions were estimated using a stratified Monte-Carlo sampling of the distributions for the physical parameters.

The residential scenario model has 435 physical parameters for which distributions were defined. The distribution functions for each sampled parameter are summarized in Table 6.87. This table contains the distribution definitions as specified to the LHS sampling program, and includes: the parameter description, the parameter symbol, the distribution type, and the values required to define the distribution (for example the mean and standard deviation for the NORMAL distribution type).

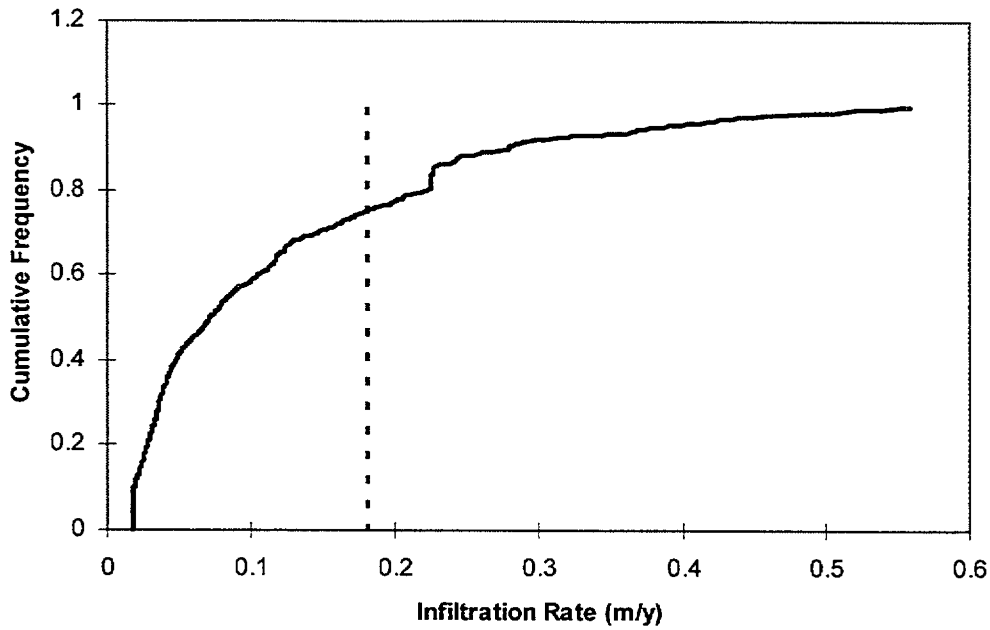

Figure 6.70 Cumulative frequency of sampled IR values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$

Part 1 - Element-independent parameters

Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
TI	Exposure period: indoors	d/y	B	S	2.37E+02	1.75E+02	2.98E+02	240
TX	Exposure period: outdoors	d/y	B	S	4.24E+01	1.69E+01	8.43E+01	40.2
TG	Exposure period:gardening	d/y	B	S	2.97E+00	3.92E-02	1.65E+01	2.92
TTR	Total time in the 1-year exposure period	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
SFI	Indoor shielding factor	-	B	S	5.85E-01	4.79E-01	8.57E-01	0.552
SFO	Outdoor Shielding Factor	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
PD	Floor dust-loading	g/m^2	P	S	1.60E-01	2.03E-02	3.00E-01	0.15986
RFR	Resuspension factor for indoor dust	1/m	P	S	1.20E-05	1.00E-07	7.95E-05	2.82E-06
CDI	Air dust-loading indoors	g/m^3	P	F	6.44E-06	2.84E-08	5.67E-05	1.41E-06
CDO	Air dust-loading outdoors	g/m^3	P	S	1.45E-05	1.01E-07	9.91E-05	3.14E-06
CDG	Air dust-loading gardening	g/m^3	P	S	4.00E-04	1.01E-04	7.00E-04	4.00E-04
VR	Breathing rate: indoors	m^3/h	M	C	9.00E-01	9.00E-01	9.00E-01	0.9
VX	Breathing rate: outdoors	m^3/h	M	C	1.40E+00	1.40E+00	1.40E+00	1.4
VG	Breathing rate: gardening	m^3/h	M	C	1.70E+00	1.70E+00	1.70E+00	1.7
GR	Soil ingestion transfer rate	g/d	B	S	5.00E-02	2.55E-03	9.80E-02	5.00E-02
UW	Drinking water ingestion rate	L/d	B	S	1.31E+00	2.31E-01	5.03E+00	1.31
H1	Thickness of surface-soil layer	m	P	C	1.50E-01	1.50E-01	1.50E-01	0.15
H2	Thickness of unsaturated zone	m	P	S	2.22E+01	3.05E-01	3.16E+02	1.22877
N1	Porosity of surface-soil	-	P	F	4.68E-01	3.61E-01	5.30E-01	0.459923

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Parameter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
N2	Porosity of unsaturated zone	-	P	F	4.68E-01	3.61E-01	5.30E-01	0.459923
F1	Saturation ratio for the surface-soil layer	-	P	F	4.94E-01	9.24E-02	9.84E-01	0.162572
F2	Saturation ratio for the unsaturated-soil layer	-	P	F	4.94E-01	9.24E-02	9.84E-01	0.162572
VDR	Volume of water for domestic uses	L	B	S	1.18E+05	5.49E+04	2.76E+05	118000
VSW	Volume of water in surface-water pond	L	P	C	1.30E+06	1.30E+06	1.30E+06	1.30E+06
I	Infiltration rate	m/y	P	F	1.19E-01	1.82E-02	5.59E-01	0.252555
AR	Area of land cultivated	m^2	B	F	2.40E+03	5.48E+02	8.64E+03	2400
IR	Irrigation rate	L/m^2-d	B	S	1.29E+00	3.72E-01	9.29E+00	1.29
PS	Soil areal density of surface plow layer	kg/m^2	P	F	2.12E+02	1.87E+02	2.54E+02	214.681
DIET	Fraction of annual diet derived from home-grown foods	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
UV(1)	Human diet of leafy vegetables	kg/y	B	S	2.14E+01	3.58E-02	2.13E+02	21.4
UV(2)	Human diet of other vegetables	kg/y	B	S	4.46E+01	3.41E-01	3.79E+02	44.6
UV(3)	Human diet of fruits	kg/y	B	S	5.28E+01	1.24E-01	6.53E+02	52.8
UV(4)	Human diet of grain	kg/y	B	S	1.44E+01	1.62E-01	9.70E+01	14.4
UA(1)	Human diet of beef	kg/y	B	S	3.98E+01	1.20E-01	2.22E+02	39.8
UA(2)	Human diet of poultry	kg/y	B	S	2.53E+01	5.77E-01	7.29E+01	25.3
UA(3)	Human diet of milk	L/y	B	S	2.33E+02	9.51E-01	1.21E+03	233
UA(4)	Human diet of eggs	kg/y	B	S	1.91E+01	2.62E-01	1.21E+02	19.1
UF	Human diet of fish	kg/y	B	S	2.06E+01	2.12E-01	8.28E+02	20.6
TCV(1)	Food consumption period for leafy vegetables	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCV(2)	Food consumption period for other vegetables	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCV(3)	Food consumption period for fruits	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCV(4)	Food consumption period for grain	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(1)	Food consumption period for beef	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(2)	Food consumption period for poultry	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(3)	Food consumption period for milk	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TCA(4)	Food consumption period for eggs	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
THV(1)	Holdup period for leafy vegetables	d	B	C	1.00E+00	1.00E+00	1.00E+00	1
THV(2)	Holdup period for other vegetables	d	B	C	1.40E+01	1.40E+01	1.40E+01	14
THV(3)	Holdup period for fruits	d	B	C	1.40E+01	1.40E+01	1.40E+01	14
THV(4)	Holdup period for grains	d	B	C	1.40E+01	1.40E+01	1.40E+01	14
THA(1)	Holdup period for beef	d	B	C	2.00E+01	2.00E+01	2.00E+01	20
THA(2)	Holdup period for poultry	d	B	C	1.00E+00	1.00E+00	1.00E+00	1
THA(3)	Holdup period for milk	d	B	C	1.00E+00	1.00E+00	1.00E+00	1
THA(4)	Holdup period for eggs	d	P	C	1.00E+00	1.00E+00	1.00E+00	1

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
TGV(1)	Minimum growing period for leafy vegetables	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGV(2)	Minimum growing period for other vegetables	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGV(3)	Minimum growing period for fruits	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGV(4)	Minimum growing period for grains	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGF(1)	Minimum growing period for forage consumed by beef cattle	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGF(2)	Minimum growing period for forage consumed by poultry	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGF(3)	Minimum growing period for forage consumed by milk cows	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGF(4)	Minimum growing period for forage consumed by layer hens	d	P	C	3.00E+01	3.00E+01	3.00E+01	30
TGG(1)	Minimum growing period for stored grain consumed by beef cattle	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGG(2)	Minimum growing period for stored grain consumed by poultry	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGG(3)	Minimum growing period for stored grain consumed by milk cows	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGG(4)	Minimum growing period for stored grain consumed by layer hens	d	P	C	9.00E+01	9.00E+01	9.00E+01	90
TGH(1)	Minimum growing period for stored hay consumed by beef cattle	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGH(2)	Minimum growing period for stored hay consumed by poultry	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGH(3)	Minimum growing period for stored hay consumed by milk cows	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
TGH(4)	Minimum growing period for stored hay consumed by layer hens	d	P	C	4.50E+01	4.50E+01	4.50E+01	45
RV(1)	Interception fraction for leafy vegetables	-	P	S	3.50E-01	1.00E-01	6.00E-01	0.349508
RV(2)	Interception fraction for other vegetables	-	P	S	3.50E-01	1.00E-01	5.99E-01	0.349765
RV(3)	Interception fraction for fruits	-	P	S	3.50E-01	1.01E-01	5.99E-01	0.349655
RV(4)	Interception fraction for grains	-	P	S	3.50E-01	1.00E-01	6.00E-01	0.349935
RF(1)	Interception fraction for beef cattle forage	-	P	S	3.50E-01	1.01E-01	6.00E-01	0.349497
RF(2)	Interception fraction for poultry forage	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RF(3)	Interception fraction for milk cow forage	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RF(4)	Interception fraction for layer hen forage	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RG(1)	Interception fraction for beef cattle grain	-	P	S	3.50E-01	1.00E-01	6.00E-01	0.34968
RG(2)	Interception fraction for poultry grain	-	P	F	3.50E-01	1.00E-01	6.00E-01	0.34968

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Parameter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
RG(3)	Interception fraction for milk cow grain	-	P	F	3.50E-01	1.00E-01	6.00E-01	0.34968
RG(4)	Interception fraction for layer hen grain	-	P	F	3.50E-01	1.00E-01	6.00E-01	0.34968
RH(1)	Interception fraction for beef cattle hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RH(2)	Interception fraction for poultry hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RH(3)	Interception fraction for milk cow hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
RH(4)	Interception fraction for layer hen hay	-	P	F	3.50E-01	1.01E-01	6.00E-01	0.349497
TV(1)	Translocation factor for leafy vegetables	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TV(2)	Translocation factor for other vegetables	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TV(3)	Translocation factor for fruits	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TV(4)	Translocation factor for grains	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TF(1)	Translocation factor for beef cattle forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TF(2)	Translocation factor for poultry forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TF(3)	Translocation factor for milk cow forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TF(4)	Translocation factor for layer hen forage	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TG(1)	Translocation factor for beef cattle grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TG(2)	Translocation factor for poultry grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TG(3)	Translocation factor for milk cow grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TG(4)	Translocation factor for layer hen grain	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TH(1)	Translocation factor for beef cattle hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TH(2)	Translocation factor for poultry hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TH(3)	Translocation factor for milk cow hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
TH(4)	Translocation factor for layer hen hay	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
XF(1)	Fraction of contaminated beef cattle forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XF(2)	Fraction of contaminated poultry forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XF(3)	Fraction of contaminated milk cow forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XF(4)	Fraction of contaminated layer hen forage	-	B	C	1.00E+00	1.00E+00	1.00E+00	1

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
XG(1)	Fraction of contaminated beef cattle grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XG(2)	Fraction of contaminated poultry grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XG(3)	Fraction of contaminated milk cow grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XG(4)	Fraction of contaminated layer hen grain	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(1)	Fraction of contaminated beef cattle hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(2)	Fraction of contaminated poultry hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(3)	Fraction of contaminated milk cow hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XH(4)	Fraction of contaminated layer hen hay	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(1)	Fraction of contaminated beef cattle water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(2)	Fraction of contaminated poultry water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(3)	Fraction of contaminated milk cow water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
XW(4)	Fraction of contaminated layer hen water	-	B	C	1.00E+00	1.00E+00	1.00E+00	1
YV(1)	Crop yield for leafy vegetables	kg/m^2	P	S	2.89E+00	2.70E+00	3.09E+00	2.88921
YV(2)	Crop yield for other vegetables	kg/m^2	P	S	2.40E+00	2.30E+00	2.52E+00	2.40002
YV(3)	Crop yield for fruits	kg/m^2	P	S	2.37E+00	2.18E+00	2.55E+00	2.36732
YV(4)	Crop yield for grains	kg/m^2	P	S	3.91E-01	2.86E-01	4.93E-01	0.390429
YF(1)	Crop yield for beef cattle forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YF(2)	Crop yield for poultry forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YF(3)	Crop yield for milk cow forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YF(4)	Crop yield for layer hen forage	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YG(1)	Crop yield for beef cattle grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YG(2)	Crop yield for poultry grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YG(3)	Crop yield for milk cow grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YG(4)	Crop yield for layer hen grain	kg/m^2	P	F	6.57E-01	3.97E-01	9.18E-01	0.656769
YH(1)	Crop yield for beef cattle hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YH(2)	Crop yield for poultry hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YH(3)	Crop yield for milk cow hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
YH(4)	Crop yield for layer hen hay	kg/m^2	P	F	1.91E+00	1.19E+00	2.77E+00	1.8868
WV(1)	Wet/dry conversion factor for leafy vegetables	-	P	S	1.09E-01	3.32E-02	3.24E-01	0.133577
WV(2)	Wet/dry conversion factor for other vegetables	-	P	S	1.09E-01	3.58E-02	3.13E-01	0.162031
WV(3)	Wet/dry conversion factor for fruits	-	P	S	1.09E-01	3.66E-02	3.25E-01	0.284903
WV(4)	Wet/dry conversion factor for grains	-	P	C	8.80E-01	8.80E-01	8.80E-01	0.88

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
WF(1)	Wet/dry conversion factor for beef cattle forage	-	P	S	2.52E-01	1.83E-01	3.23E-01	0.251767
WF(2)	Wet/dry conversion factor for poultry forage	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WF(3)	Wet/dry conversion factor for milk cow forage	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WF(4)	Wet/dry conversion factor for layer hen forage	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WG(1)	Wet/dry conversion factor for beef cattle grain	-	P	C	8.80E-01	8.80E-01	8.80E-01	0.88
WG(2)	Wet/dry conversion factor for poultry grain	-	P	F	8.80E-01	8.80E-01	8.80E-01	0.88
WG(3)	Wet/dry conversion factor for milk cow grain	-	P	F	8.80E-01	8.80E-01	8.80E-01	0.88
WG(4)	Wet/dry conversion factor for layer hen grain	-	P	F	8.80E-01	8.80E-01	8.80E-01	0.88
WH(1)	Wet/dry conversion factor for beef cattle hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WH(2)	Wet/dry conversion factor for poultry hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WH(3)	Wet/dry conversion factor for milk cow hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
WH(4)	Wet/dry conversion factor for layer hen hay	-	P	F	2.52E-01	1.83E-01	3.23E-01	0.251767
QF(1)	Ingestion rate for beef cattle forage	kg/d	P	F	8.53E+00	5.88E+00	1.23E+01	8.133
QF(2)	Ingestion rate for poultry forage	kg/d	P	F	6.60E-02	1.46E-02	1.48E-01	5.62E-02
QF(3)	Ingestion rate for milk cow forage	kg/d	P	F	3.52E+01	2.18E+01	7.68E+01	35.1654
QF(4)	Ingestion rate for layer hen forage	kg/d	P	F	7.52E-02	3.76E-02	1.17E-01	7.55E-02
QG(1)	Ingestion rate for beef cattle grain	kg/d	P	F	2.39E+00	1.94E+00	2.60E+00	2.41877
QG(2)	Ingestion rate for poultry grain	kg/d	P	F	5.53E-02	1.23E-02	9.59E-02	6.30E-02
QG(3)	Ingestion rate for milk cow grain	kg/d	P	F	1.95E+00	1.07E+00	2.99E+00	1.94662
QG(4)	Ingestion rate for layer hen grain	kg/d	P	F	6.33E-02	4.07E-02	7.58E-02	6.10E-02
QH(1)	Ingestion rate for beef cattle hay	kg/d	P	F	1.71E+01	1.09E+01	2.47E+01	16.2535
QH(2)	Ingestion rate for poultry hay	kg/d	P	C	0.00E+00	0.00E+00	0.00E+00	0
QH(3)	Ingestion rate for milk cow hay	kg/d	P	F	2.80E+01	1.69E+01	5.53E+01	26.1089
QH(4)	Ingestion rate for layer hen hay	kg/d	P	C	0.00E+00	0.00E+00	0.00E+00	0
QW(1)	Water ingestion rate for beef cattle	L/d	P	C	5.00E+01	5.00E+01	5.00E+01	50
QW(2)	Water ingestion rate for poultry	L/d	P	C	3.00E-01	3.00E-01	3.00E-01	0.3
QW(3)	Water ingestion rate for milk cows	L/d	P	C	6.00E+01	6.00E+01	6.00E+01	60
QW(4)	Water ingestion rate for layer hens	L/d	P	C	3.00E-01	3.00E-01	3.00E-01	0.3
QD(1)	Soil intake fraction for beef cattle	-	P	C	2.00E-02	2.00E-02	2.00E-02	2.00E-02
QD(2)	Soil intake fraction for poultry	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
QD(3)	Soil intake fraction for milk cows	-	P	C	2.00E-02	2.00E-02	2.00E-02	2.00E-02
QD(4)	Soil intake fraction for layer hens	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
MLV(1)	Mass-loading factor for leafy vegetables	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLV(2)	Mass-loading factor for other vegetables	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLV(3)	Mass-loading factor for fruits	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLV(4)	Mass-loading factor for grains	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
LAMBDW	Weathering rate for activity removal from plants	1/d	P	C	4.95E-02	4.95E-02	4.95E-02	4.95E-02
RHO1	Surface Soil Density	g/mL	P	F	1.41E+00	1.25E+00	1.69E+00	1.4312
RHO2	Unsaturated Zone Soil Density	g/mL	P	F	1.41E+00	1.25E+00	1.69E+00	1.4312
TTG	Total time in gardening period	d	B	C	9.00E+01	9.00E+01	9.00E+01	90
TF	Fish consumption period	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
TD	Drinking-water consumption period	d	B	C	3.65E+02	3.65E+02	3.65E+02	365.25
MLF(1)	Mass-loading factor for beef cattle forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLF(2)	Mass-loading factor for poultry forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLF(3)	Mass-loading factor for milk cow forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLF(4)	Mass-loading factor for layer hen forage	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(1)	Mass-loading factor for beef cattle grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(2)	Mass-loading factor for poultry grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(3)	Mass-loading factor for milk cow grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLG(4)	Mass-loading factor for layer hen grain	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(1)	Mass-loading factor for beef cattle hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(2)	Mass-loading factor for poultry hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(3)	Mass-loading factor for milk cow hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
MLH(4)	Mass-loading factor for layer hen hay	g/g	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
TFF(1)	Feeding period for beef cattle forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFF(2)	Feeding period for poultry forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFF(3)	Feeding period for milk cow forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFF(4)	Feeding period for layer hen forage	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(1)	Feeding period for beef cattle grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(2)	Feeding period for poultry grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(3)	Feeding period for milk cow grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFG(4)	Feeding period for layer hen grain	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFH(1)	Feeding period for beef cattle hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFH(2)	Feeding period for poultry hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
TFH(3)	Feeding period for milk cow hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFH(4)	Feeding period for layer hen hay	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(1)	Water ingestion period for beef cattle	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(2)	Water ingestion period for poultry	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(3)	Water ingestion period for milk cows	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
TFW(4)	Water ingestion period for layer hens	d	P	C	3.65E+02	3.65E+02	3.65E+02	365.25
fca(1)	Carbon fraction for beef cattle	-	P	C	3.60E-01	3.60E-01	3.60E-01	0.36
fca(2)	Carbon fraction for poultry	-	P	C	1.80E-01	1.80E-01	1.80E-01	0.18
fca(3)	Carbon fraction for milk cows	-	P	C	6.00E-02	6.00E-02	6.00E-02	6.00E-02
fca(4)	Carbon fraction for layer hens	-	P	C	1.60E-01	1.60E-01	1.60E-01	0.16
fcf(1)	Carbon fraction for beef cattle forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fcf(2)	Carbon fraction for poultry forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fcf(3)	Carbon fraction for milk cow forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fcf(4)	Carbon fraction for layer hen forage	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fch(a)	Carbon fraction for beef cattle hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fch(a)	Carbon fraction for poultry hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fch(a)	Carbon fraction for milk cow hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fch(a)	Carbon fraction for layer hen hay	-	P	C	7.00E-02	7.00E-02	7.00E-02	7.00E-02
fcg(a)	Carbon fraction for beef cattle grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcg(a)	Carbon fraction for poultry grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcg(a)	Carbon fraction for milk cow grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcg(a)	Carbon fraction for layer hen grain	-	P	C	4.00E-01	4.00E-01	4.00E-01	0.4
fcd05	Fraction of carbon in soil	-	P	C	3.00E-02	3.00E-02	3.00E-02	3.00E-02
satac	Specific activity equivalence for livestock	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
fha(1)	Hydrogen fraction for beef cattle	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fha(2)	Hydrogen fraction for poultry	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fha(3)	Hydrogen fraction for milk cows	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fha(4)	Hydrogen fraction for layer hens	-	P	C	1.10E-01	1.10E-01	1.10E-01	0.11
fhv(1)	Hydrogen fraction for leafy vegetables	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhv(2)	Hydrogen fraction for other vegetables	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhv(3)	Hydrogen fraction for fruits	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhv(4)	Hydrogen fraction for grains	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhf(1)	Hydrogen fraction for beef cattle forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhf(2)	Hydrogen fraction for poultry forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhf(3)	Hydrogen fraction for milk cow forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01

Table 6.87 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Part 1 - Element-independent parameters								
Para-meter	Description	Units	Physical/ behavioral/ metabolic	Sampled/ function/ constant	Statistics for sampled values			Solution
					Average	Min	Max	
fhf(4)	Hydrogen fraction for layer hen forage	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(1)	Hydrogen fraction for beef cattle hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(2)	Hydrogen fraction for poultry hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(3)	Hydrogen fraction for milk cow hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhh(4)	Hydrogen fraction for layer hen hay	-	P	C	1.00E-01	1.00E-01	1.00E-01	1.00E-01
fhg(1)	Hydrogen fraction for beef cattle grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhg(2)	Hydrogen fraction for poultry grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhg(3)	Hydrogen fraction for milk cow grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhg(4)	Hydrogen fraction for layer hen grain	-	P	C	6.80E-02	6.80E-02	6.80E-02	6.80E-02
fhd016	Fraction of hydrogen in soil	-	P	F	1.82E-02	3.49E-03	3.65E-02	5.80E-03
sasvh	Tritium equivalence: plant/soil	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
sawvh	Tritium equivalence: plant/water	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
satah	Tritium equivalence: animal product/intake	-	P	C	1.00E+00	1.00E+00	1.00E+00	1
sh	Moisture content of soil	L/m^3	P	F	1.64E-01	3.14E-02	3.29E-01	5.22E-02

6.5.2.1 Parameter Sample Distributions

Five hundred and eighty samples from these distributions were generated using stratified Monte-Carlo (LHS) sampling. The results of the parameter sampling are illustrated in Figures 6.67 through 6.95. These figures show the cumulative frequency of the physical parameter values based on the LHS sampling. Default parameter values from NUREG/CR-5512, Vol. 1, are indicated for reference. Two of the parameters, partition coefficient and vegetation concentration factor, have a separate distribution for each of 69 chemical elements. Each of these distributions is summarized in Table 6.87. Because of the large number of element-specific parameters, four representative distributions are shown for the partition coefficients and concentration factors. Figures 6.85 through 6.88 show example distributions of concentration factors; Figures 6.92 through 6.95 show example partition coefficient distributions.

6.5.2.2 Dose Modeling Results

For each set of sampled parameter values, dose to the AMSG was calculated for unit concentrations of each of the 106 potential source radionuclides having half-lives greater than 65 days (see Table 6.88). For each source, the distribution describing possible doses to the AMSG was then constructed from these calculated doses. From the resulting dose distributions, the dose quantiles d_{Ci} can be estimated for various values of P_{crit} (see Equation 3.7). These quantiles represent screening dose values for unit concentrations of individual radionuclides, and also define the lower limits on the doses calculated using default parameter values (Equation 3.8). This section describes the calculations used to estimate the dose distributions, and presents the resulting dose quantiles for three selected values of P_{crit}.

6.5.2.2.1 Evaluation of the Mixing Cell Model

Due to the large number of calculations required by this analysis, the mixing cell model described in NUREG/CR-5512, Vol. 1, was used to represent the groundwater pathway. This model results in faster execution time than the more accurate numerical transport model, but introduces some amount of numerical dispersion.

Selected calculations were done with both the mixing cell model and the numerical model of the unsaturated zone to assess the effect of numerical dispersion. Using the mean values for all model parameters, the TEDE for all 106 isotopes was calculated using both the mixing

Table 6.88 Source nuclides used in the parameter analysis

Source ID	Source	Source ID	Source	Source ID	Source
1	3H	87	126Sn+C	180	232Th
2	10Be	89	125Sb	181	232Th+C
3	14C	93	123mTe	183	231Pa
5	22Na	95	127mTe	184	231Pa+C
9	35S	106	129I	187	232U
10	36Cl	114	134Cs	188	232U+C
11	40K	115	135Cs	189	233U
12	41Ca	117	137Cs	190	233U+C
13	45Ca	128	144Ce	191	234U
14	46Sc	132	147Pm	192	235U
16	54Mn	137	147Sm	193	235U+C
18	55Fe	138	151Sm	194	236U
20	57Co	140	152Eu	196	238U
21	58Co	141	154Eu	197	238U+C
22	60Co	142	155Eu	199	237Np
23	59Ni	144	153Gd	200	237Np+C
24	63Ni	145	160Tb	203	236Pu
27	65Zn	146	166mHo	205	238Pu
31	75Se	147	181W	206	239Pu
32	79Se	148	185W	207	240Pu
41	90Sr	150	187Re	208	241Pu
48	93Zr	151	185Os	209	242Pu
49	93Zr+C	153	192Ir	211	244Pu
52	93mNb	156	210Pb	212	241Am
53	94Nb	160	210Po	213	242mAm
58	93Mo	165	226Ra	215	243Am
61	99Tc	166	226Ra+C	216	242Cm
65	106Ru	167	228Ra	217	243Cm
69	107Pd	169	227Ac	218	244Cm
71	110mAg	170	227Ac+C	219	245Cm
73	109Cd	173	228Th	220	246Cm
74	113mCd	174	228Th+C	221	247Cm
81	119mSn	175	229Th	222	248Cm
82	121mSn	176	229Th+C	223	252Cf
84	123Sn	177	230Th		
86	126Sn	178	230Th+C		

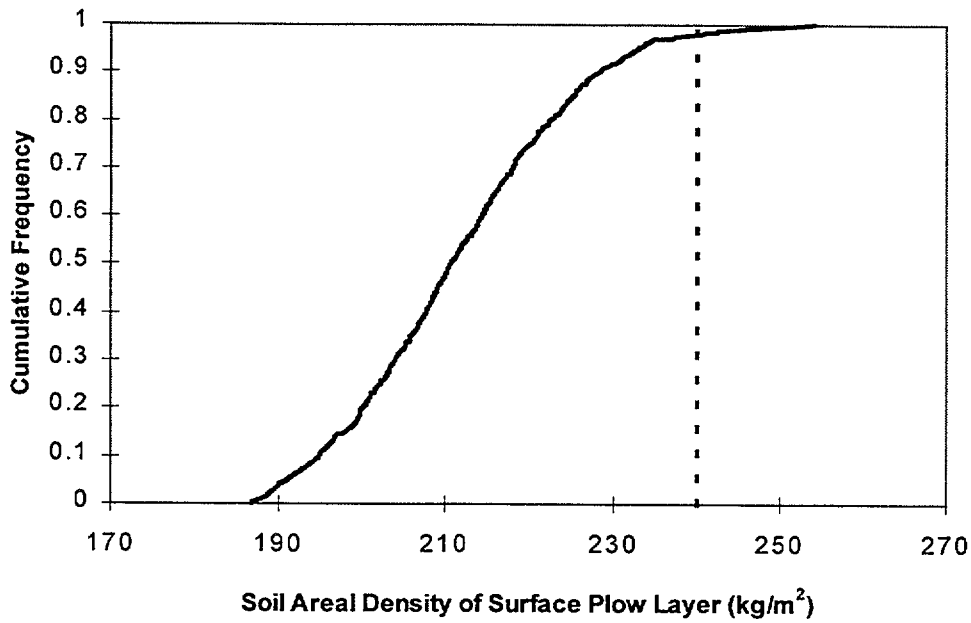

Figure 6.71 Cumulative frequency of sampled Ps values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

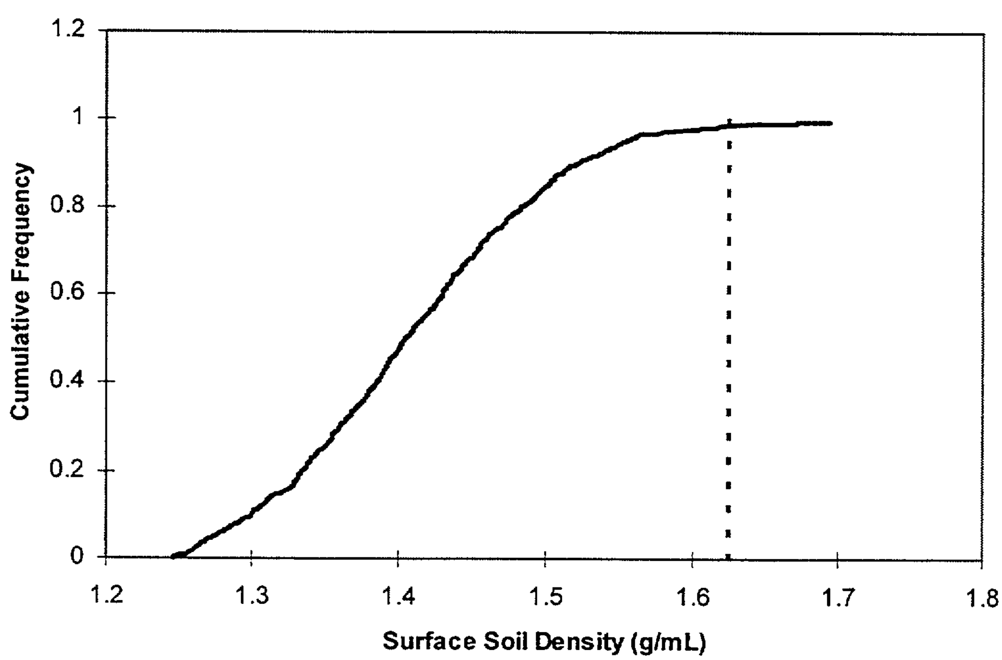

Figure 6.72 Cumulative frequency of sampled ρ values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

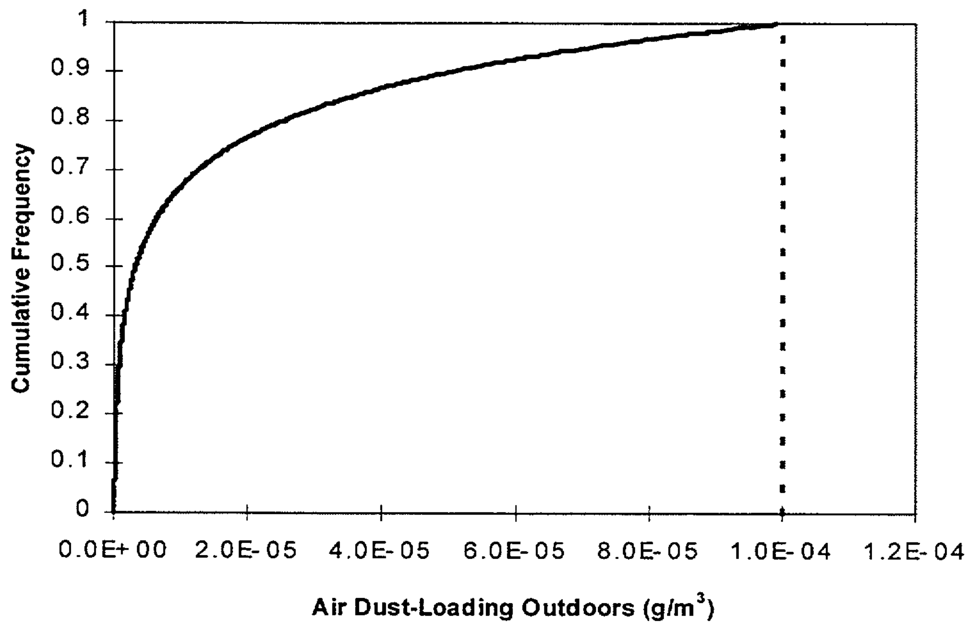

Figure 6.73 Cumulative frequency of sampled CDO values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

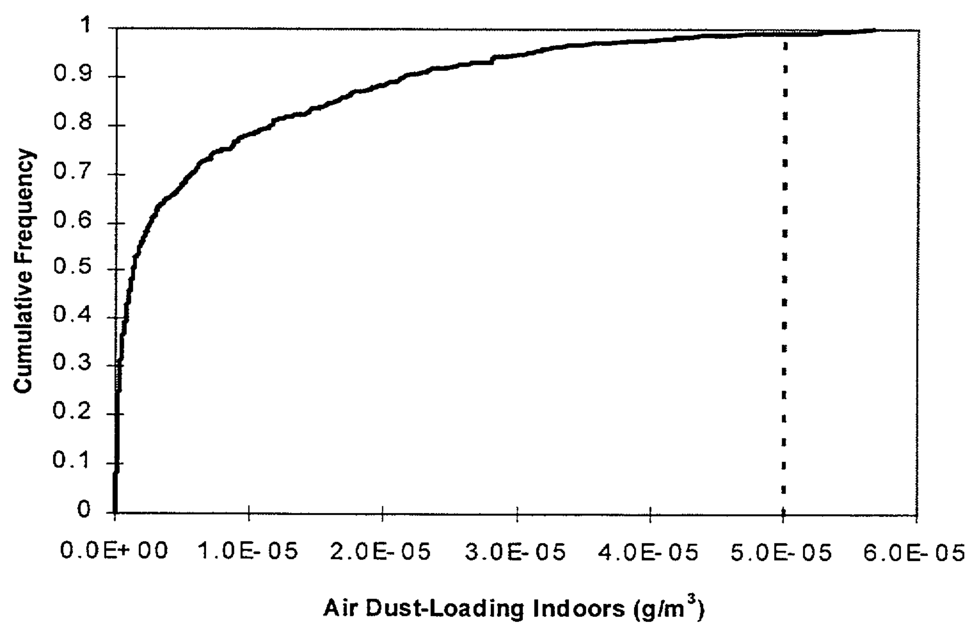

Figure 6.74 Cumulative frequency of CDI values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

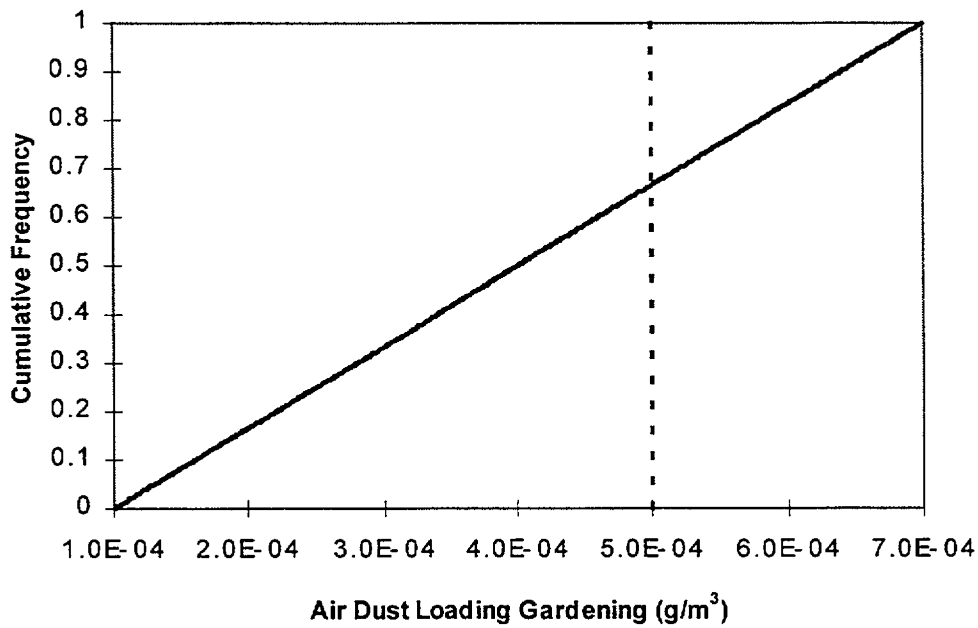

Figure 6.75 Cumulative frequency sampled CDG values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

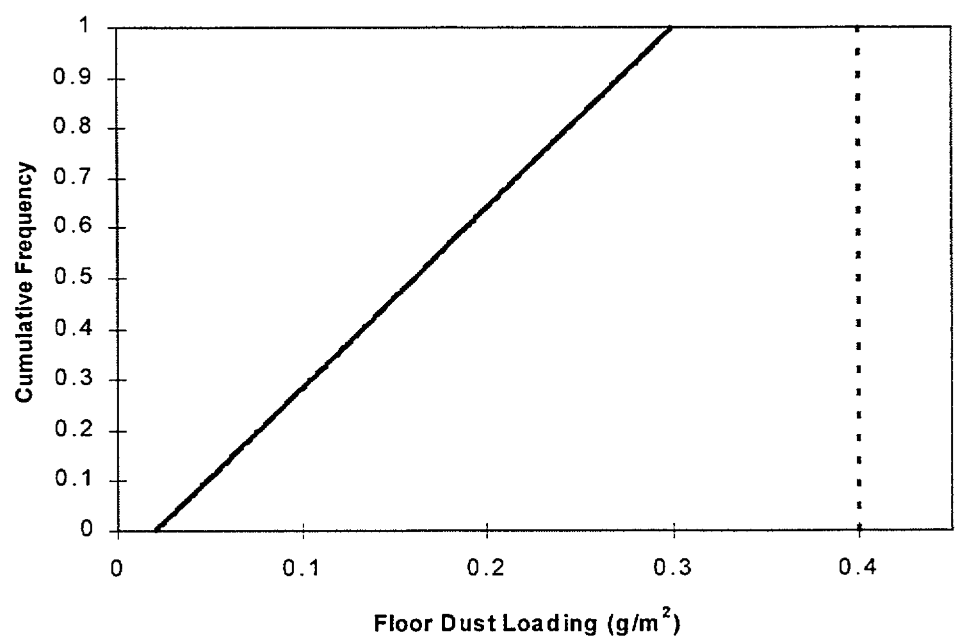

Figure 6.76 Cumulative frequency sampled Pd values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

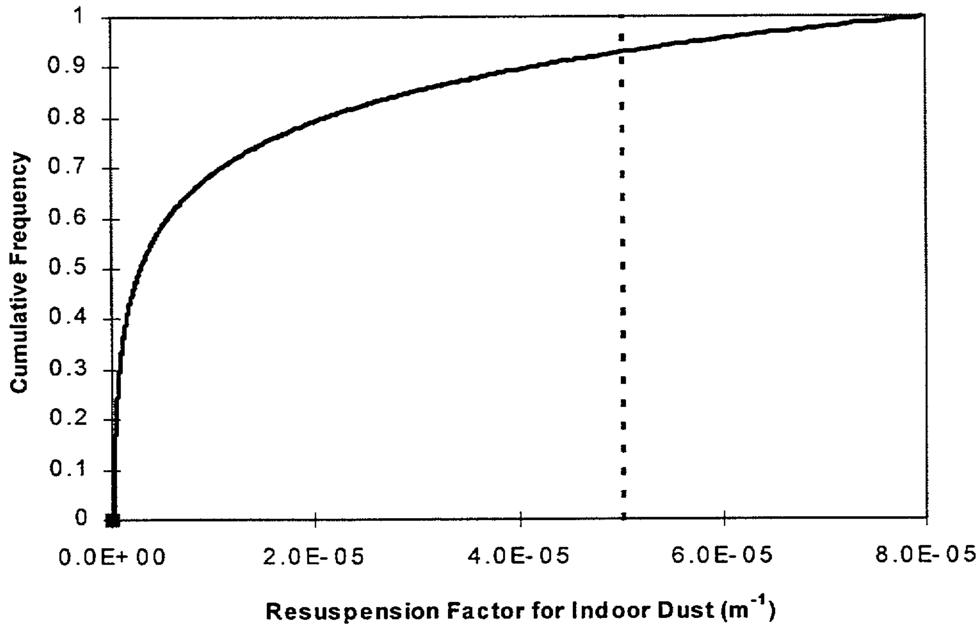

Figure 6.77 Cumulative frequency sampled RFr values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

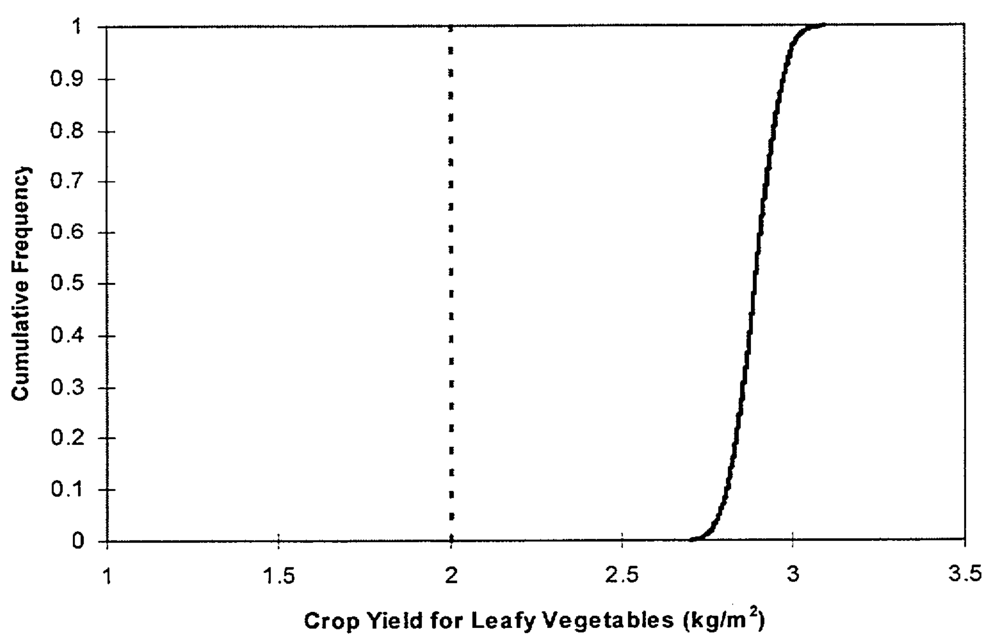

Figure 6.78 Cumulative frequency sampled Yv values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

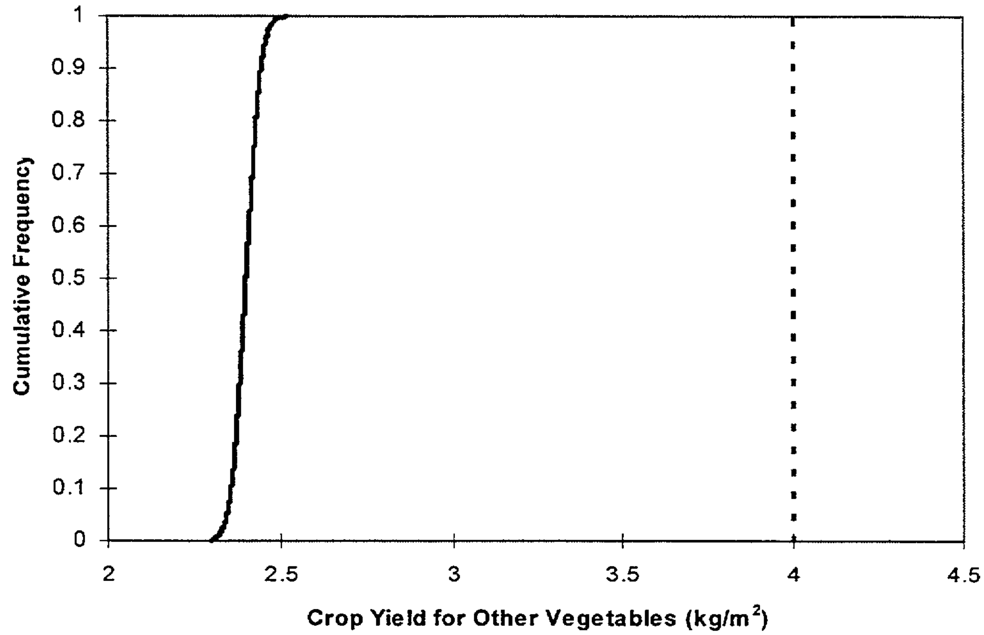

Figure 6.79 Cumulative frequency sampled Yv (other) values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

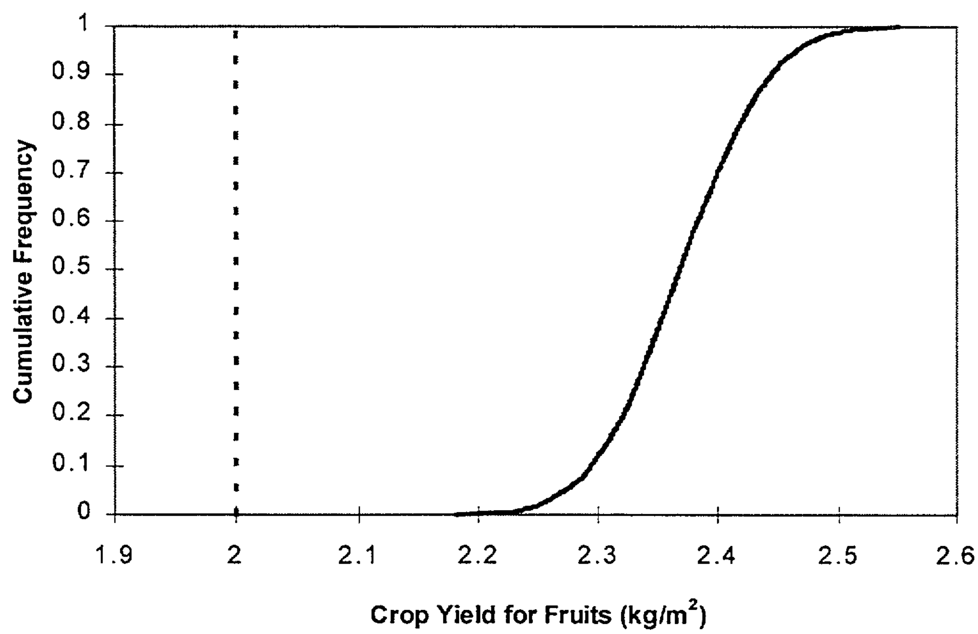

Figure 6.80 Cumulative frequency sampled Yv (fruit) values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

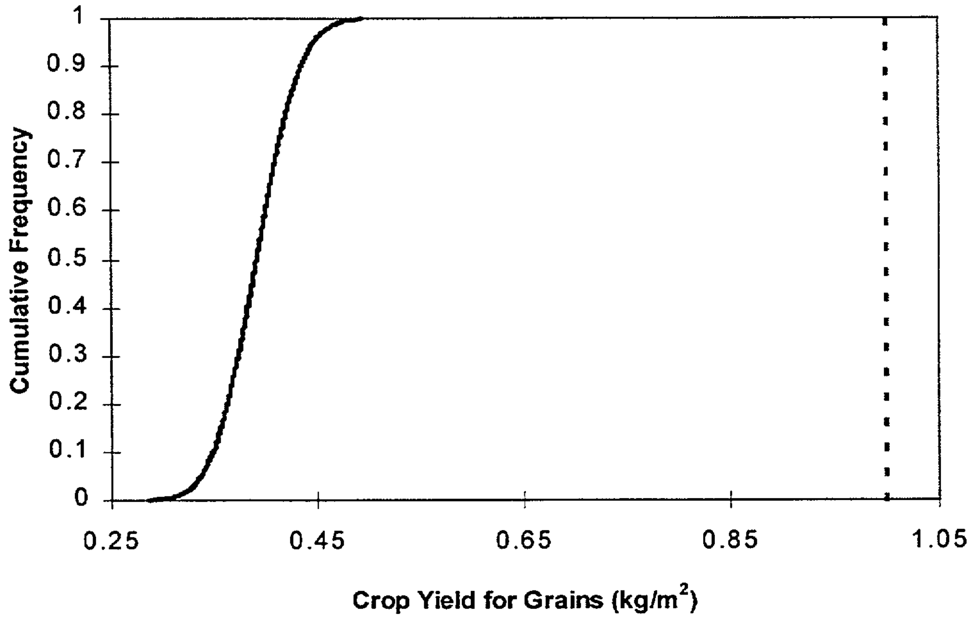

Figure 6.81 Cumulative frequency sampled Yg values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

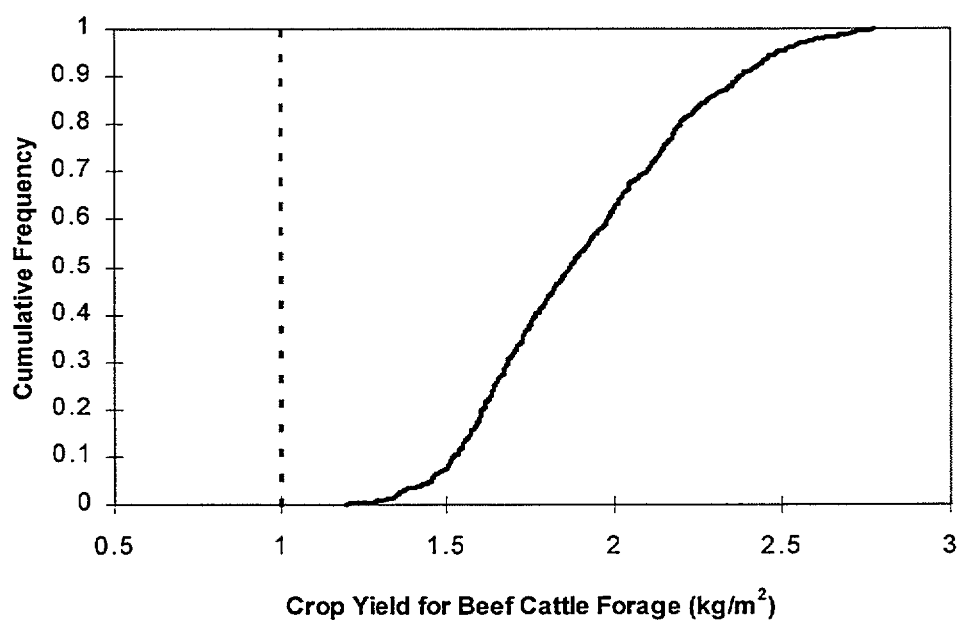

Figure 6.82 Cumulative frequency sampled Yf values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

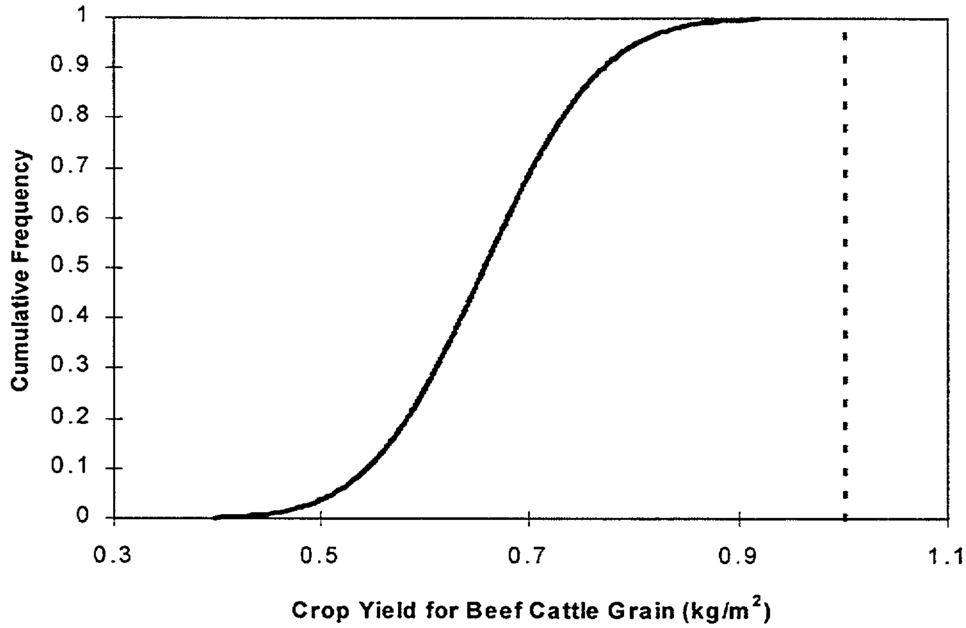

Figure 6.83 Cumulative frequency sampled Yg values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

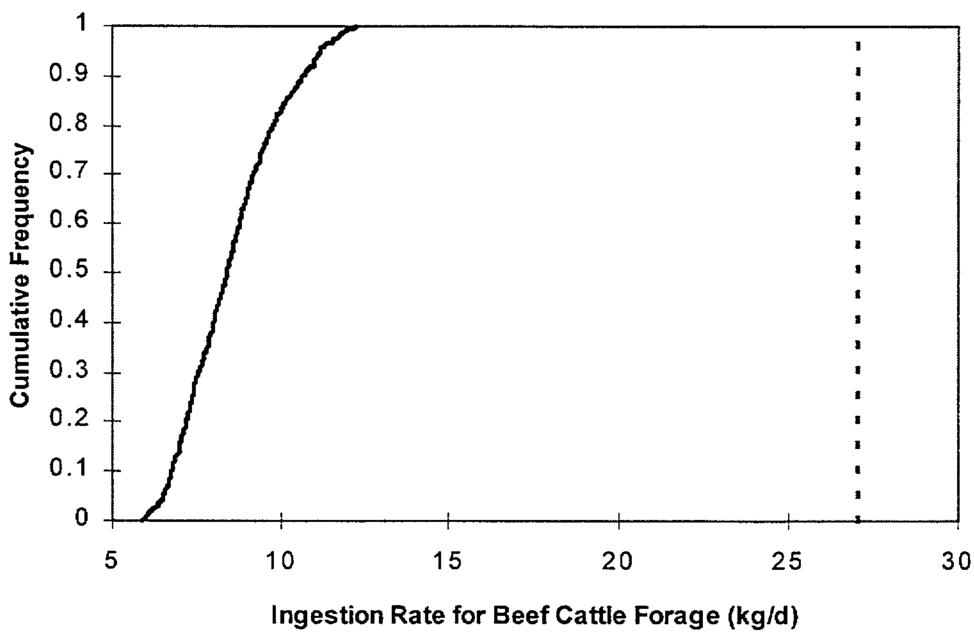

Figure 6.84 Cumulative frequency sampled Qf values (NUREG/CR-5512, Vol. 1, default shown as vertical dashed line)

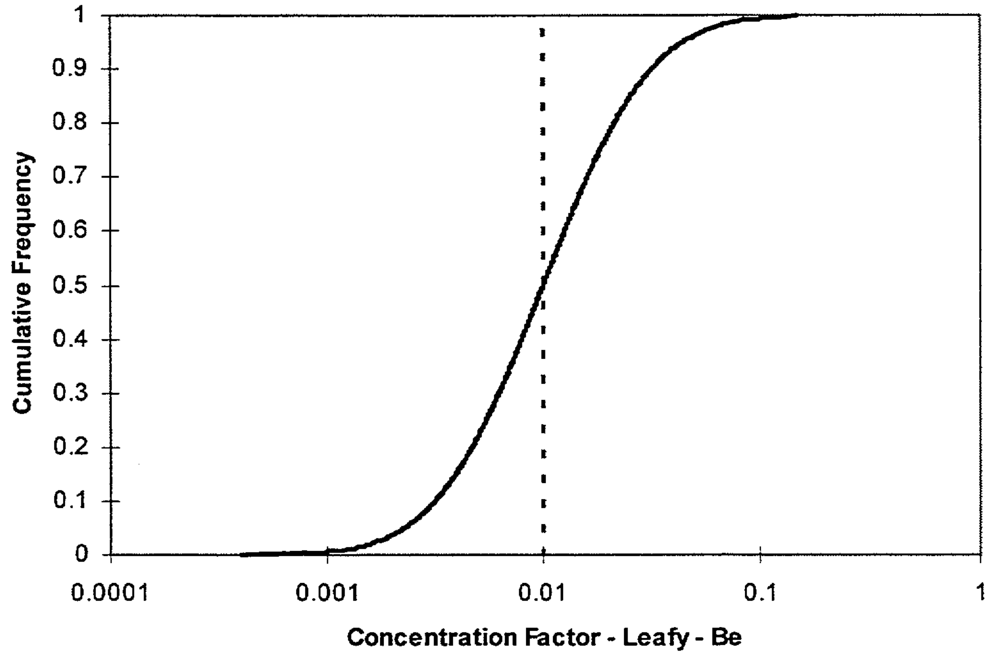

Figure 6.85 Cumulative frequency of sampled Bjv for Be in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

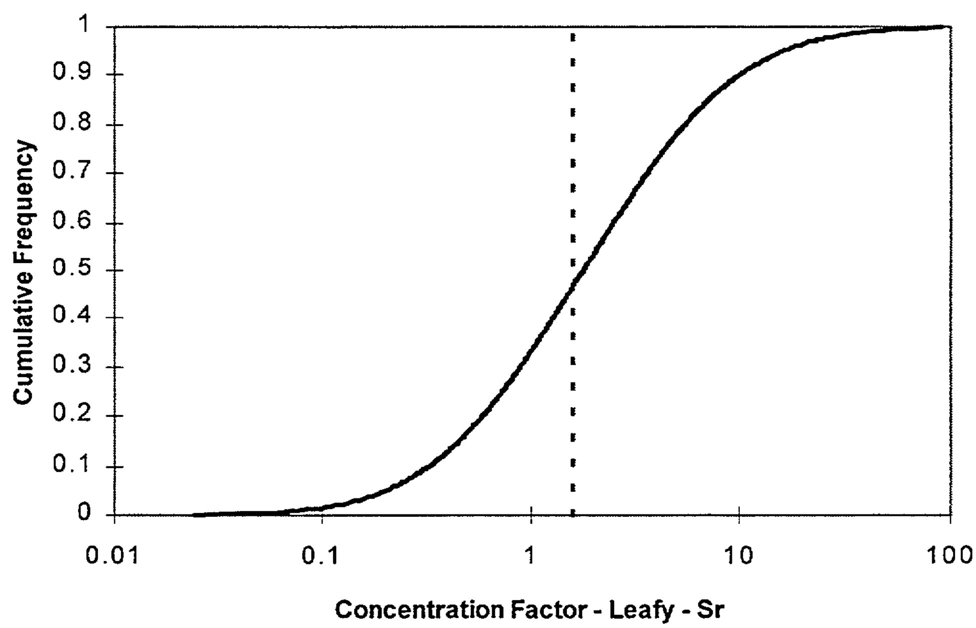

Figure 6.86 Cumulative frequency of sampled Bjv for Sr in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

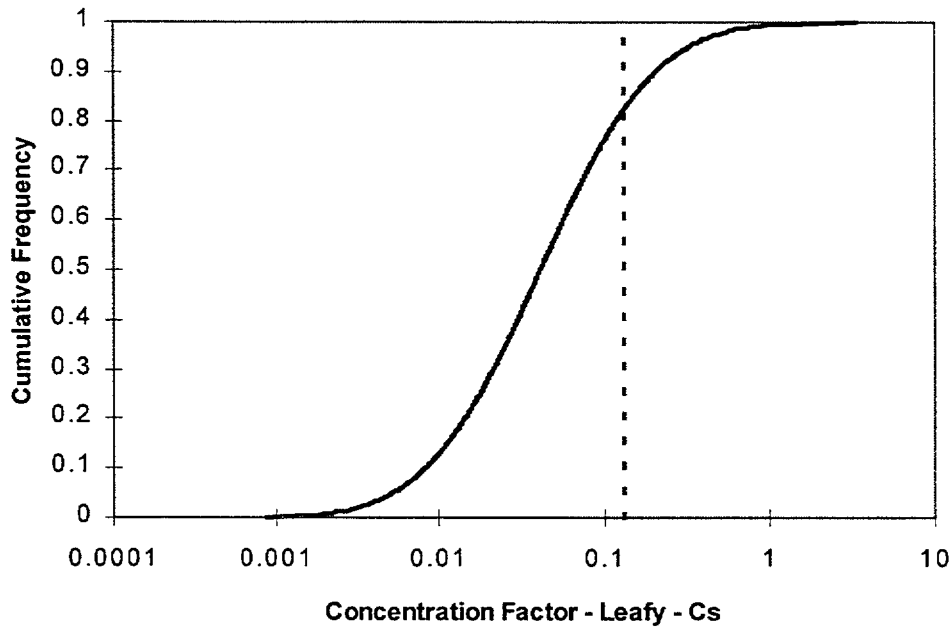

Figure 6.87 Cumulative frequency of sampled Bjv for Cs in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

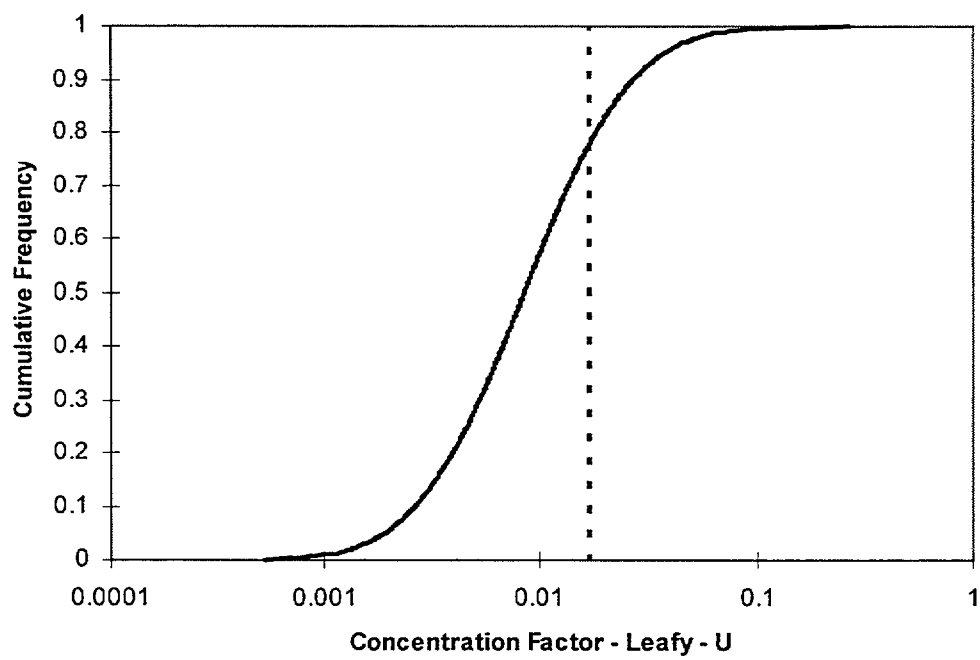

Figure 6.88 Cumulative frequency of sampled Bjv for U in leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

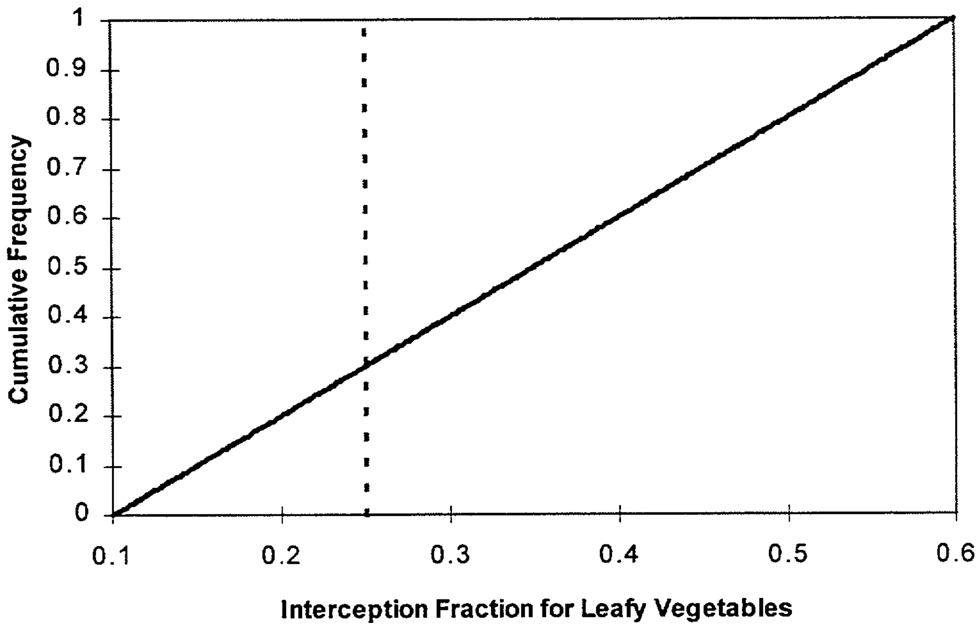

Figure 6.89 Cumulative frequency of sampled r_v for leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

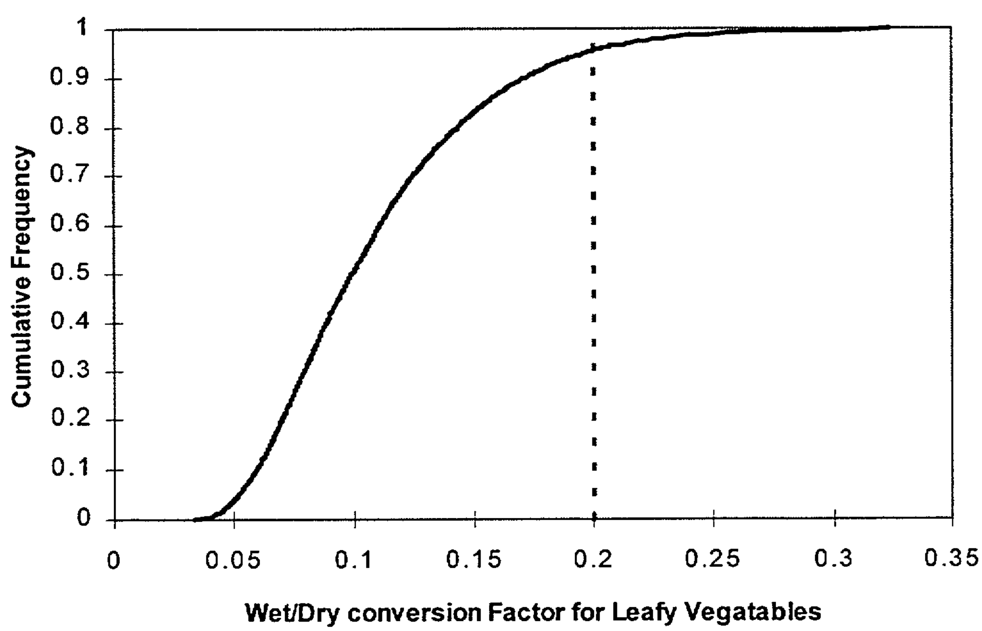

Figure 6.90 Cumulative frequency of sampled Wv for leafy vegetables (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

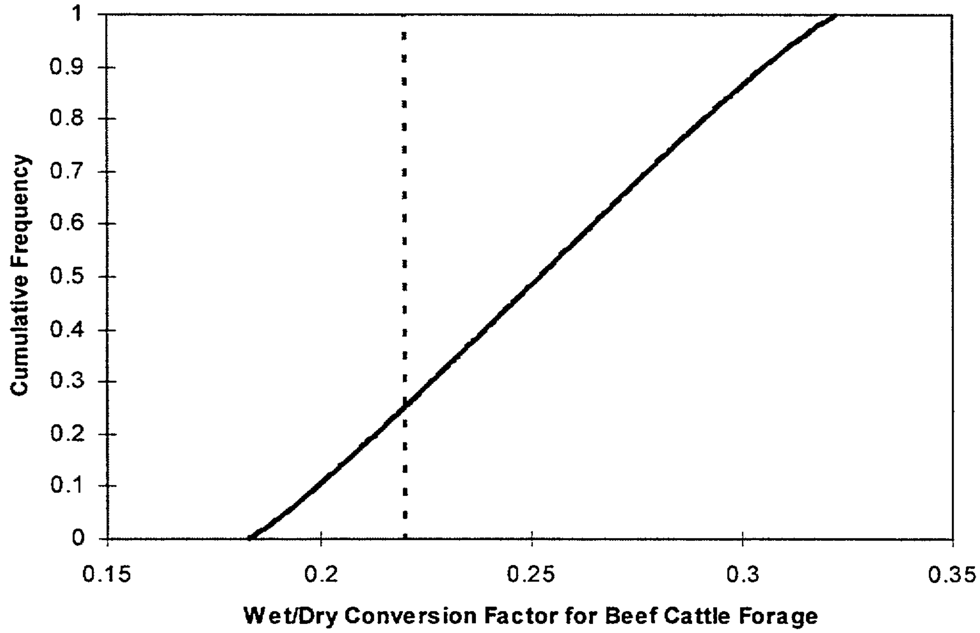

Figure 6.91 Cumulative frequency of sampled Wf for leafy vegetables (dashed vertical line = NUREG/CR 5512, Vol. 1, default)

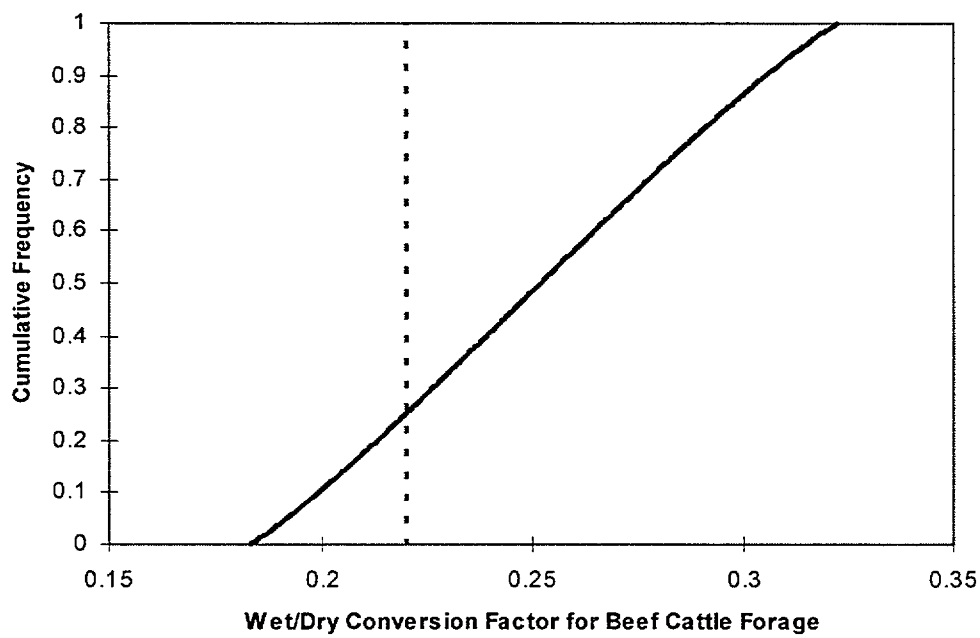

Figure 6.92 Cumulative frequency of sampled Kd for Cs (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

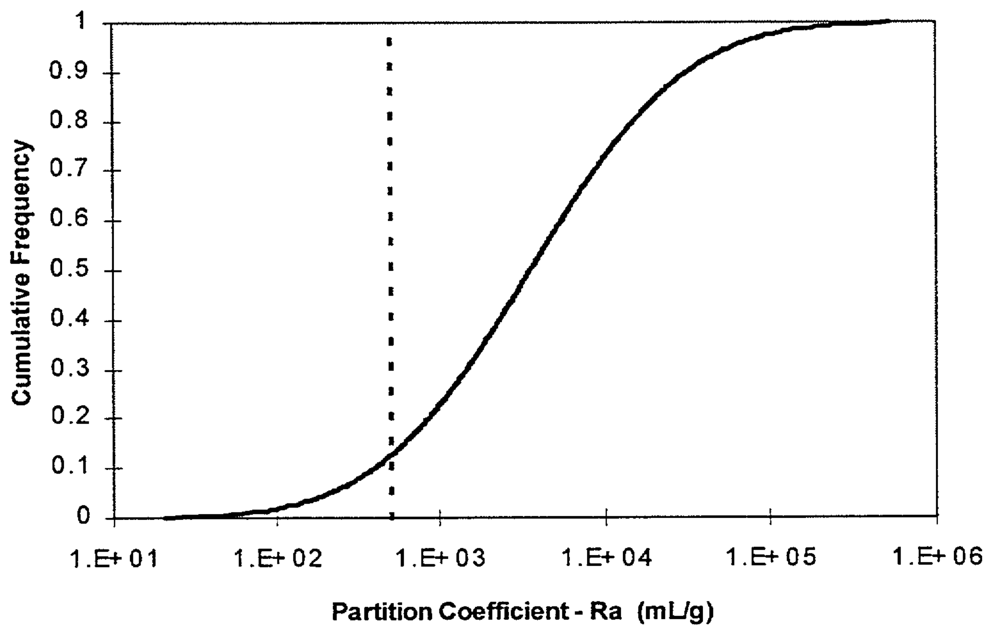

Figure 6.93 Cumulative frequency of sampled Kd for Ra (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

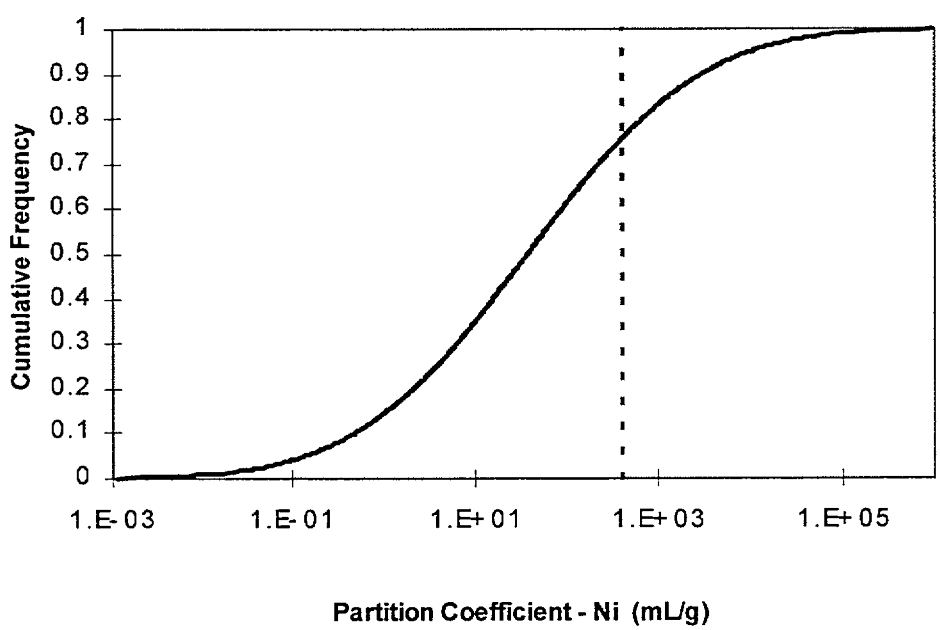

Figure 6.94 Cumulative frequency of sampled Kd for Ni (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

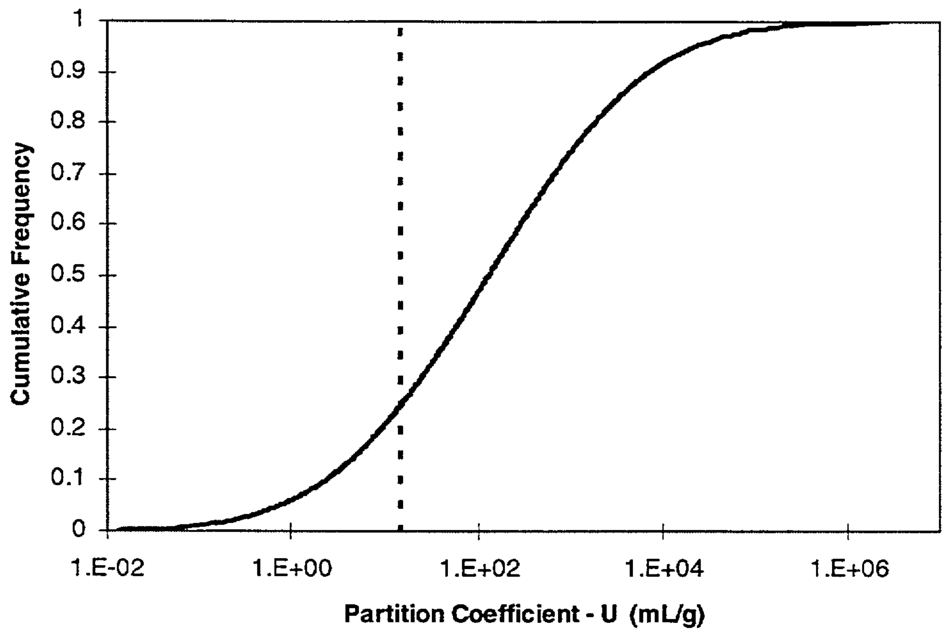

Figure 6.95 Cumulative frequency of sampled Kd for U (dashed vertical line = NUREG/CR-5512, Vol. 1, default)

Table 6.89 Unsaturated zone model error analysis

Radionuclide	H2 (meters)	Unsat'd zone model	TEDE	% Error
Co-60	100	Mixing Cell	6.79e+00	-9.75e-01
	100	Numerical	6.73e+00	
	200	Mixing Cell	6.76e+00	-4.88e-01
	200	Numerical	6.73e+00	
Mo-93	100	Mixing Cell	4.89e-02	-3.03e+00
	100	Numerical	4.75e-02	
	200	Mixing Cell	4.82e-02	-1.52e+00
	200	Numerical	4.75e-02	
Th-230	100	Mixing Cell	1.39e+01	6.35e+00
	100	Numerical	1.49e+01	
	200	Mixing Cell	8.91e+00	6.98e+00
	200	Numerical	9.58e+00	
H-3	100	Mixing Cell	1.61e-01	6.21e-04
	100	Numerical	1.61e-01	
	200	Mixing Cell	1.61e-01	-8.69e-03
	200	Numerical	1.61e-01	
I-129	100	Mixing Cell	6.47e+00	7.37e+00
	100	Numerical	6.98e+00	
	200	Mixing Cell	5.85e+00	-1.18e+01
	200	Numerical	5.24e+00	
U-235	100	Mixing Cell	1.67e+00	6.35e+00
	100	Numerical	1.79e+00	
	200	Mixing Cell	1.46e+00	-9.51e+00
	200	Numerical	1.33e+00	

cell and numerical models. The TEDE for every nuclide was the same to six significant figures except for ^3H, ^{75}Se, ^{93}Mo, ^{129}I, ^{226}Ra, ^{226}Ra+C, ^{230}Th, ^{230}Th+C, ^{233}U, ^{238}U+C, ^{245}Cm, and ^{247}Cm. For these radionuclides, the TEDE's from the mixing cell and numerical models were equivalent to three significant digits.

Analyzing these results indicated that the mean radionuclide partition coefficients, most of which are larger than the default values proposed in NUREG/CR-5512, Vol. 1,[3] cause radionuclides to be retained in the unsaturated zone, thereby decreasing the importance of the dose from the ground water pathways. This in turn decreases the sensitivity to the choice of the mixing cell or numerical model for unsaturated zone transport.

To bound the potential error associated with using the mixing cell model instead of the numerical model, calculations were conducted assuming no sorption and a relatively thick unsaturated zone. Results for selected radionuclides are shown in Table 6.89. For each of these radionuclides, the maximum relative error (numerical solution TEDE minus mixing cell solution TEDE divided by the numerical solution TEDE) is less than 12%. TEDE tends to be overestimated by the mixing cell model.

6.5.2.2.2 Dose Distributions

For each source, the distribution describing possible doses to the AMSG was estimated from the dose values calculated using the 580 sampled parameter values. For three alternative values of P_{crit}, and for each source nuclide, the value of d_{Ci} (the quantile of order 1 - P_{crit} from Equation 3.7) was determined from the calculated distribution. Table 6.90 lists the values of d_{Ci} for each of the source nuclides, and for the three selected values of P_{crit}. The increase in d_{Ci} for decreasing (more restrictive) values of P_{crit} indicates the spread of the underlying dose distribution. As a further measure of distribution spread, Table 6.90 also shows the ratio of dose at the 99th percentile to the median (50th percentile) dose.

Dose values at the selected quantiles can also be used to calculate the source concentration equivalent to a dose of 25 mrem. Table 6.91 summarizes these concentration values.

[3]The mean of the PDF for Kd for 50 of the 69 elements is greater than the Volume 1 default

6.5.3 Identification of Default Parameter Values

Using the dose quantile values d_{Ci} estimated from the dose distributions, vectors of parameter values $\mathbf{x}_d$ which satisfied Equation 3.8 were identified using the procedure outlined in Section 3.3. This section describes the application of that procedure, and summarizes the solutions obtained.

The initial LHS sample set was examined for solutions to Equation 3.8 at the P_{crit} values of 0.50, 0.25, and 0.10. None were found, and the basic genetic algorithm described in Appendix B was used to construct new sets of parameter vectors, using the solution count values to select parent vectors. After six iterations of the basic genetic algorithm, only two solutions were produced at the least restrictive P_{crit} value of 0.50, and no solution vectors had been produced for the P_{crit} value of 0.10. In addition, the increase in solution counts with successive generations was discouraging. Figure 6.96 shows the distributions of solution counts, for a P_{crit} value of 0.10, for the initial set of sample vectors and the first six iterations of the basic genetic algorithm.

Because of the very slow improvement in solution counts produced by the basic genetic algorithm, the "genetic engineering" algorithm described in Appendix C was applied beginning with the original set of LHS sample vectors. Figure 6.97 show the distribution of solution counts for the sets of sample vectors produced by three successive applications of this algorithm. The third set of vectors contained 63 solutions to Equation 3.8 for a P_{crit} value of 0.10.

6.5.4 Ranking of Solutions

For each of the 63 solution vectors found in the solution search, the joint parameter exceedance probability and the average inversion probability were calculated as described in Appendix B. Given that Equation 3.8 is satisfied, solutions having large values of these measures are preferred to solutions with small values.

Figure 6.98 is a scatter plot showing the values of these measures for the 63 solution vectors. The average inversion probability is confined to a fairly narrow range between 0.013 and 0.03. The maximum theoretical value for the average inversion probability is P_{crit}, which would only be obtained for a parameter vector that satisfied Equation 3.8 as a strict equality for all sources. Such a solution may not exist because of the large number of source term constraints that must be satisfied. The joint parameter exceedance probability, in contrast,

Table 6.90 Selected quantiles of unit-concentrationTEDE distributions for the residential scenario (mrem)

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Dose @ $P_{crit} = 0.01$/ Dose @ $P_{crit} = 0.50$
3H	1.41E-01	2.32E-01	3.10E-01	4.15
10Be	1.48E-02	1.65E-02	1.88E-02	13.17
14C	6.10E-01	2.15E+00	3.85E+00	33.61
22Na	5.49E+00	5.88E+00	6.85E+00	2.98
35S	6.46E-02	9.26E-02	1.20E-01	4.56
36Cl	4.46E+01	6.91E+01	8.54E+01	4.87
40K	2.74E+00	6.94E+00	1.48E+01	19.24
41Ca	2.28E-01	3.77E-01	4.86E-01	6.51
45Ca	2.69E-01	4.41E-01	5.84E-01	6.88
46Sc	1.70E+00	1.70E+00	1.70E+00	1.01
54Mn	1.60E+00	1.69E+00	1.79E+00	1.37
55Fe	2.21E-03	2.43E-03	2.67E-03	10.10
57Co	1.66E-01	1.69E-01	1.73E-01	1.25
58Co	7.17E-01	7.20E-01	7.24E-01	1.05
60Co	6.49E+00	6.60E+00	6.79E+00	1.24
59Ni	2.07E-03	4.51E-03	1.35E-02	39.83
63Ni	5.65E-03	1.19E-02	3.49E-02	39.30
65Zn	1.84E+00	2.32E+00	2.80E+00	3.38
75Se	4.24E-01	4.29E-01	4.32E-01	1.05
79Se	1.05E-01	1.21E-01	1.35E-01	1.92
90Sr	8.80E+00	1.46E+01	2.05E+01	8.42
93Zr	1.82E-02	2.32E-02	3.86E-02	13.38
93Zr+C	9.84E-03	1.33E-02	2.01E-02	12.60
93mNb	1.24E-02	1.38E-02	1.67E-02	7.68
94Nb	4.30E+00	4.32E+00	4.34E+00	1.03
93Mo	5.94E-02	1.17E-01	1.67E-01	11.03
99Tc	8.57E-01	1.34E+00	1.68E+00	5.63
106Ru	4.73E-01	4.94E-01	5.18E-01	1.29
107Pd	2.76E-03	3.89E-03	6.11E-03	12.35
110mAg	4.93E+00	5.08E+00	5.23E+00	1.20
109Cd	1.63E-01	2.35E-01	3.46E-01	10.77
113mCd	2.84E+00	5.05E+00	9.07E+00	19.52
119mSn	6.95E-03	8.10E-03	1.10E-02	14.69
121mSn	1.83E-02	4.39E-02	1.94E-01	61.15
123Sn	2.86E-02	3.24E-02	4.06E-02	5.76
126Sn	5.30E+00	5.32E+00	5.36E+00	2.13
126Sn+C	2.48E+00	2.49E+00	2.53E+00	2.13
125Sb	9.71E-01	9.76E-01	9.82E-01	1.16
123mTe	1.34E-01	1.35E-01	1.36E-01	1.22
127mTe	1.64E-02	1.75E-02	1.88E-02	3.54
129I	1.47E+01	4.65E+01	1.01E+02	49.83
134Cs	4.18E+00	4.40E+00	4.66E+00	1.92
135Cs	8.94E-02	1.36E-01	2.18E-01	29.74
137Cs	2.06E+00	2.27E+00	2.54E+00	5.67

Table 6.90 **Selected quantiles of unit-concentration TEDE distributions for the residential scenario (mrem) (continued)**

Source	$P_{crit} = 0.25$	$P_{crit} = 0.10$	$P_{crit} = 0.05$	Dose @ $P_{crit} = 0.01$/ Dose @ $P_{crit} = 0.50$
144Ce	1.29E-01	1.36E-01	1.44E-01	1.36
147Pm	2.75E-03	3.05E-03	3.24E-03	1.92
147Sm	6.07E-01	6.91E-01	8.66E-01	6.61
151Sm	1.24E-03	1.42E-03	1.67E-03	6.26
152Eu	2.88E+00	2.88E+00	2.89E+00	1.01
154Eu	3.12E+00	3.12E+00	3.12E+00	1.01
155Eu	8.75E-02	8.80E-02	8.86E-02	1.07
153Gd	7.66E-02	7.93E-02	8.83E-02	1.66
160Tb	8.29E-01	8.29E-01	8.29E-01	1.02
166mHo	4.49E+00	4.49E+00	4.50E+00	1.01
181W	1.64E-02	1.66E-02	1.77E-02	1.95
185W	1.87E-03	2.43E-03	5.51E-03	27.86
187Re	4.09E-04	5.95E-04	8.25E-04	7.15
185Os	6.48E-01	6.49E-01	6.50E-01	1.03
192Ir	6.04E-01	6.05E-01	6.05E-01	1.01
210Pb	2.63E+01	2.95E+01	3.17E+01	5.37
210Po	2.64E+00	2.82E+00	2.97E+00	1.69
226Ra	3.22E+01	3.60E+01	3.86E+01	5.60
226Ra+C	4.15E+00	4.58E+00	4.85E+00	5.24
228Ra	6.49E+00	6.84E+00	7.05E+00	1.24
227Ac	4.22E+01	4.70E+01	5.16E+01	8.85
227Ac+C	5.28E+00	5.88E+00	6.43E+00	8.83
228Th	5.12E+00	5.29E+00	5.43E+00	1.15
228Th+C	7.37E-01	7.62E-01	7.81E-01	1.15
229Th	1.22E+01	1.35E+01	1.46E+01	5.99
229Th+C	1.53E+00	1.69E+00	1.83E+00	5.98
230Th	1.19E+01	1.36E+01	1.51E+01	9.18
230Th+C	3.88E+00	4.33E+00	4.67E+00	6.32
232Th	2.05E+01	2.21E+01	2.32E+01	3.01
232Th+C	2.12E+00	2.27E+00	2.40E+00	3.15
231Pa	6.82E+01	7.66E+01	9.01E+01	7.49
231Pa+C	8.24E+00	9.38E+00	1.06E+01	7.36
232U	1.01E+01	1.28E+01	4.25E+01	17.79
232U+C	1.43E+00	1.72E+00	5.21E+00	15.34
233U	1.71E+00	2.74E+00	6.76E+00	21.20
233U+C	1.53E+00	1.79E+00	2.55E+00	6.90
234U	1.12E+00	1.89E+00	6.62E+00	22.71
235U	2.22E+00	3.11E+00	7.47E+00	20.57
235U+C	6.99E+00	7.91E+00	9.09E+00	7.19
236U	1.06E+00	1.79E+00	6.27E+00	22.81
238U	1.11E+00	1.80E+00	6.33E+00	21.80
238U+C	3.04E+00	3.51E+00	4.59E+00	7.03
237Np	1.41E+02	2.72E+02	4.30E+02	11.45
237Np+C	1.36E+01	2.55E+01	4.35E+01	10.12

Table 6.90 Selected quantiles of unit-concentration TEDE distributions for the residential scenario (mrem) (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Dose @ P_{crit} = 0.01/ Dose @ P_{crit} = 0.50
236Pu	2.74E+00	3.06E+00	3.35E+00	2.87
238Pu	8.88E+00	9.83E+00	1.05E+01	1.93
239Pu	9.88E+00	1.09E+01	1.17E+01	2.47
240Pu	9.88E+00	1.09E+01	1.17E+01	2.46
241Pu	3.02E-01	3.49E-01	5.81E-01	11.58
242Pu	9.38E+00	1.04E+01	1.11E+01	2.47
244Pu	1.03E+01	1.13E+01	1.21E+01	2.23
241Am	1.05E+01	1.20E+01	1.65E+01	10.28
242mAm				
243Am	1.09E+01	1.24E+01	1.68E+01	9.96
242Cm	1.38E-01	1.53E-01	1.61E-01	1.43
243Cm	7.15E+00	7.82E+00	8.26E+00	1.41
244Cm	5.46E+00	6.00E+00	6.34E+00	1.42
245Cm	1.53E+01	1.81E+01	2.12E+01	3.93
246Cm	1.03E+01	1.14E+01	1.20E+01	1.42
247Cm	1.07E+01	1.18E+01	1.24E+01	1.35
248Cm	3.80E+01	4.18E+01	4.41E+01	1.42
252Cf	3.12E+00	3.64E+00	4.42E+00	12.34

Table 6.91 Concentration (pCi/g) equivalent to 25 mrem/y for three values of P_{crit}

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05
3H	1.77E+02	1.08E+02	8.06E+01	166mHo	5.57E+00	5.56E+00	5.56E+00
10Be	1.69E+03	1.51E+03	1.33E+03	181W	1.52E+03	1.51E+03	1.41E+03
14C	4.10E+01	1.16E+01	6.50E+00	185W	1.34E+04	1.03E+04	4.54E+03
22Na	4.55E+00	4.25E+00	3.65E+00	187Re	6.12E+04	4.20E+04	3.03E+04
35S	3.87E+02	2.70E+02	2.08E+02	185Os	3.86E+01	3.85E+01	3.85E+01
36Cl	5.61E-01	3.62E-01	2.93E-01	192Ir	4.14E+01	4.13E+01	4.13E+01
40K	9.13E+00	3.60E+00	1.69E+00	210Pb	9.50E-01	8.46E-01	7.90E-01
41Ca	1.10E+02	6.63E+01	5.15E+01	210Po	9.46E+00	8.87E+00	8.41E+00
45Ca	9.29E+01	5.67E+01	4.28E+01	226Ra	7.77E-01	6.94E-01	6.48E-01
46Sc	1.47E+01	1.47E+01	1.47E+01	226Ra+C	6.03E+00	5.45E+00	5.16E+00
54Mn	1.57E+01	1.48E+01	1.39E+01	228Ra	3.85E+00	3.65E+00	3.54E+00
55Fe	1.13E+04	1.03E+04	9.35E+03	227Ac	5.92E-01	5.31E-01	4.85E-01
57Co	1.51E+02	1.48E+02	1.44E+02	227Ac+C	4.74E+00	4.25E+00	3.89E+00
58Co	3.49E+01	3.47E+01	3.45E+01	228Th	4.89E+00	4.73E+00	4.61E+00
60Co	3.85E+00	3.79E+00	3.68E+00	228Th+C	3.39E+01	3.28E+01	3.20E+01
59Ni	1.21E+04	5.54E+03	1.85E+03	229Th	2.04E+00	1.85E+00	1.71E+00
63Ni	4.43E+03	2.11E+03	7.17E+02	229Th+C	1.63E+01	1.48E+01	1.36E+01
65Zn	1.36E+01	1.08E+01	8.93E+00	230Th	2.10E+00	1.83E+00	1.65E+00
75Se	5.89E+01	5.83E+01	5.78E+01	230^{Th}+C	6.44E+00	5.78E+00	5.36E+00
79Se	2.39E+02	2.07E+02	1.85E+02	232Th	1.22E+00	1.13E+00	1.08E+00

Table 6.91 Concentration (pCi/g) equivalent to 25 mrem/y for three values of P_{crit} (continued)

Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05	Source	P_{crit} = 0.25	P_{crit} = 0.10	P_{crit} = 0.05
90Sr	2.84E+00	1.72E+00	1.22E+00	232Th+C	1.18E+01	1.10E+01	1.04E+01
93Zr	1.38E+03	1.08E+03	6.48E+02	231Pa	3.66E-01	3.27E-01	2.77E-01
93Zr+C	2.54E+03	1.88E+03	1.25E+03	231Pa+C	3.03E+00	2.67E+00	2.36E+00
93mNb	2.02E+03	1.81E+03	1.49E+03	232U	2.47E+00	1.96E+00	5.88E-01
94Nb	5.81E+00	5.79E+00	5.76E+00	232U+C	1.74E+01	1.46E+01	4.80E+00
93Mo	4.21E+02	2.13E+02	1.49E+02	233U	1.47E+01	9.11E+00	3.70E+00
99Tc	2.92E+01	1.87E+01	1.49E+01	233U+C	1.63E+01	1.40E+01	9.81E+00
106Ru	5.28E+01	5.06E+01	4.83E+01	234U	2.23E+01	1.32E+01	3.78E+00
107Pd	9.07E+03	6.43E+03	4.09E+03	235U	1.13E+01	8.04E+00	3.35E+00
110mAg	5.07E+00	4.92E+00	4.78E+00	235U+C	3.58E+00	3.16E+00	2.75E+00
109Cd	1.54E+02	1.06E+02	7.23E+01	236U	2.36E+01	1.40E+01	3.99E+00
113mCd	8.80E+00	4.95E+00	2.76E+00	238U	2.26E+01	1.39E+01	3.95E+00
119mSn	3.60E+03	3.09E+03	2.26E+03	238U+C	8.21E+00	7.13E+00	5.44E+00
121mSn	1.37E+03	5.70E+02	1.29E+02	237Np	1.77E-01	9.18E-02	5.81E-02
123Sn	8.74E+02	7.71E+02	6.16E+02	237Np+C	1.84E+00	9.81E-01	5.75E-01
126Sn	4.72E+00	4.70E+00	4.66E+00	236Pu	9.11E+00	8.17E+00	7.45E+00
126Sn+C	1.01E+01	1.00E+01	9.89E+00	238Pu	2.81E+00	2.54E+00	2.39E+00
125Sb	2.57E+01	2.56E+01	2.55E+01	239Pu	2.53E+00	2.28E+00	2.15E+00
123mTe	1.86E+02	1.85E+02	1.84E+02	240Pu	2.53E+00	2.28E+00	2.15E+00
127mTe	1.52E+03	1.43E+03	1.33E+03	241Pu	8.28E+01	7.16E+01	4.30E+01
129I	1.70E+00	5.38E-01	2.47E-01	242Pu	2.66E+00	2.41E+00	2.26E+00
134Cs	5.98E+00	5.68E+00	5.36E+00	244Pu	2.42E+00	2.22E+00	2.07E+00
135Cs	2.80E+02	1.83E+02	1.15E+02	241Am	2.39E+00	2.08E+00	1.52E+00
137Cs	1.22E+01	1.10E+01	9.83E+00	243Am	2.30E+00	2.01E+00	1.49E+00
144Ce	1.93E+02	1.84E+02	1.74E+02	243mAm			
147Pm	9.08E+03	8.20E+03	7.71E+03	242Cm	1.81E+02	1.64E+02	1.56E+02
147Sm	4.12E+01	3.62E+01	2.89E+01	243Cm	3.50E+00	3.20E+00	3.03E+00
151Sm	2.01E+04	1.76E+04	1.50E+04	244Cm	4.58E+00	4.17E+00	3.94E+00
152Eu	8.68E+00	8.67E+00	8.66E+00	245Cm	1.63E+00	1.38E+00	1.18E+00
154Eu	8.02E+00	8.01E+00	8.00E+00	246Cm	2.42E+00	2.20E+00	2.09E+00
155Eu	2.86E+02	2.84E+02	2.82E+02	247Cm	2.33E+00	2.12E+00	2.02E+00
153Gd	3.27E+02	3.15E+02	2.83E+02	248Cm	6.57E-01	5.98E-01	5.67E-01
160Tb	3.02E+01	3.02E+01	3.02E+01	252Cf	8.00E+00	6.86E+00	5.66E+00

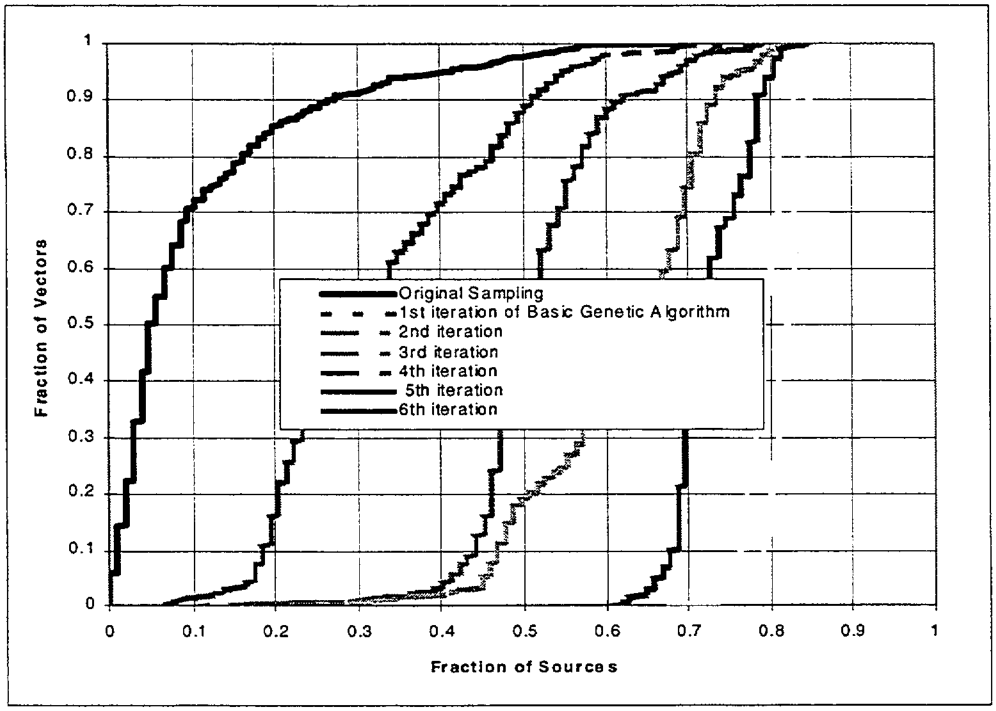

Figure 6.96 Solution count distributions for the original LHS sample set and the first 6 iterations of the basic genetic algorithm

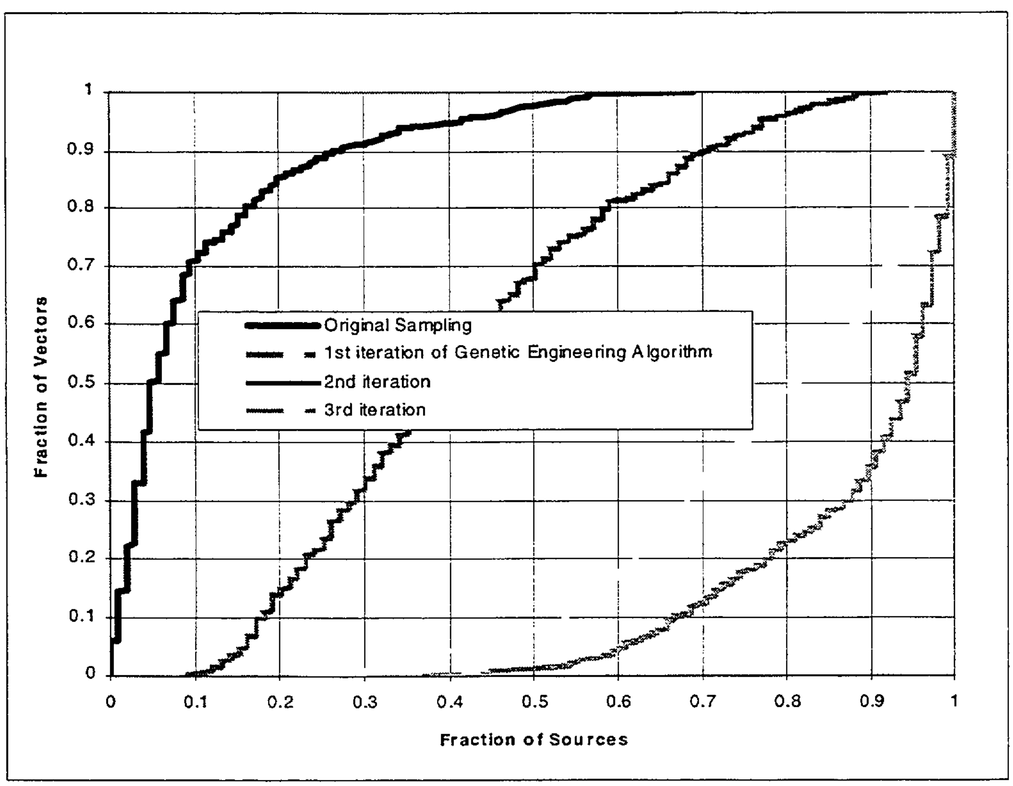

Figure 6.97 Solution count distributions for the original LHS sample set and the first 3 iterations of the genetic engineering algorithm

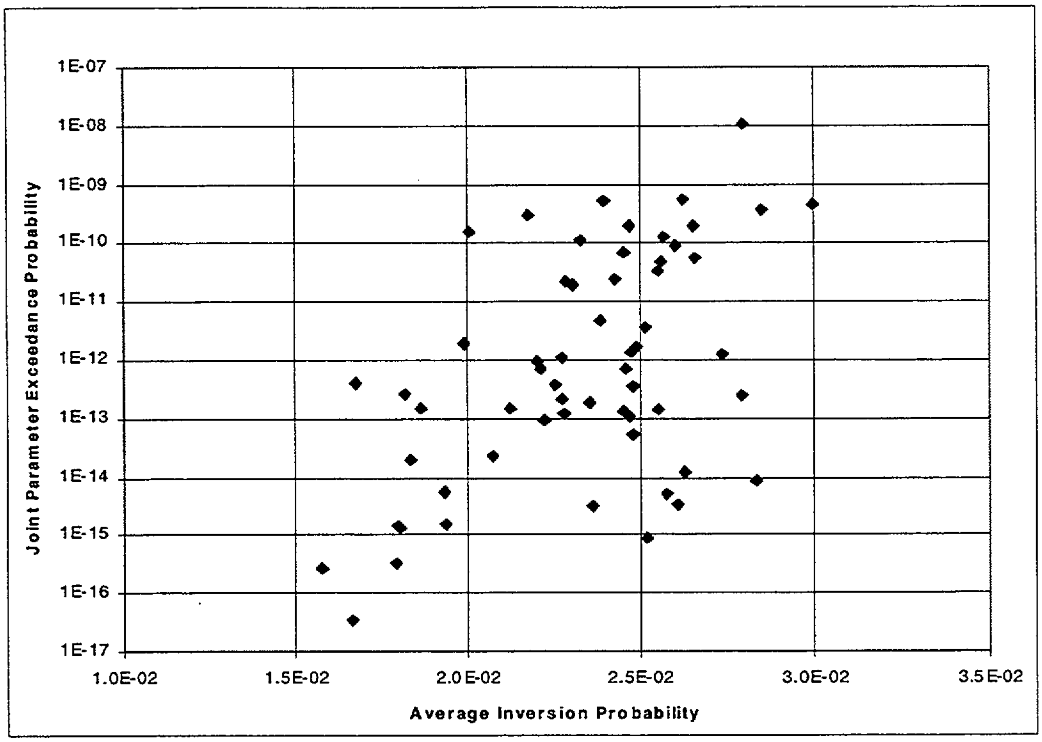

Figure 6.98 Scatterplot of joint parameter exceedance probabilities and average inversion probabilities for 63 solution vectors

varies over several orders of magnitude. The largest observed value is approximately 1×10^{-8}. Because this value is substantially greater than the next largest alternative, and because the average inversion probability for this vector is also relatively large, this solution was selected to define the default parameter values.

Tables 6.92 and 6.93 list the parameter values for this solution. Statistics of the values sampled from the parameter distribution are also included for comparison.

6.5.5 Sensitivity Analysis

The results of the Monte-Carlo dose calculations were processed to identify parameters controlling TEDE for each source. The dependence of TEDE on the model parameter values is potentially complex: total dose may depend non-monotonically on the parameter value, or may be sensitive to the parameter value only within certain limits, or only in conjunction with certain ranges of values for other parameters. Because of these complexities, a linear regression analysis was not used to identify sensitive parameters.

Instead, a robust test which does not rely on monotonicity was employed. For each source nuclide, sensitive parameters were identified by dividing the sample vectors into two groups with equal numbers of samples: vectors having doses above the median dose, and vectors with doses below the median dose. For each parameter, the Kolmogorov-Smirnov (K-S) test was used to assess the significance of the differences in the distributions of parameter values between these two groups. Parameters whose distributions differed at a significance level of 0.0001 were selected. A restrictive value of the significance level is appropriate in this analysis because of the large number of tests performed (580 vectors × 435 sampled parameters), and the correspondingly high prospect of producing low K-S statistic values by random chance.

For each parameter selected, the strength of the dependence of TEDE on the parameter value was calculated by segregating the sample vectors on the basis of the parameter value. This segregation defines two groups of sample vectors: vectors having values for the selected parameter less than a chosen quantile; and vectors having parameter values greater than the chosen quantile. Within each group, the TEDE distribution was estimated using only vectors in that group. The 95th percentile of this distribution was then compared to the 95th percentile of the original TEDE distribution using all sample vectors. The ratio of the 95th percentile TEDE value from the segregated sample to the 95th

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10

Part 2 - Partition coefficients in mL/g (kd)				
Element	**Statistics for sampled values**			**Solution**
	Average	**Min**	**Max**	**Vector 105**
H	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Be	9.98E+04	6.84E-02	2.10E+07	**9.29E+02**
C	4.83E+11	2.71E-01	2.80E+14	**4.34E+00**
F	4.50E+02	1.85E-04	7.42E+04	**4.97E+00**
Na	6.54E+02	1.08E-04	1.86E+05	**3.56E-02**
P	2.86E+03	1.85E-03	5.91E+05	**2.57E+01**
S	9.58E+03	4.73E-03	1.88E+06	**9.92E+01**
Cl	4.56E+02	2.87E-05	7.01E+04	**4.95E+00**
K	6.12E+02	1.07E-04	1.59E+05	**5.01E+00**
Ca	1.56E+05	2.97E-02	3.38E+07	**1.47E+03**
Sc	1.54E+04	3.43E-03	2.07E+06	**5.06E-01**
Cr	3.40E+03	1.68E-02	4.00E+05	**1.01E+02**
Mn	4.67E+07	7.60E+00	2.59E+10	**8.41E+01**
Fe	1.10E+03	7.70E-02	1.39E+04	**5.35E+02**
Co	1.91E+03	3.42E-03	4.43E+04	**1.51E+03**
Ni	5.54E+03	1.10E-03	9.47E+05	**3.70E+01**
Cu	1.66E+04	2.90E-03	2.88E+06	**1.76E+02**
Zn	2.09E+06	5.82E-04	5.19E+08	**1.06E+03**
As	1.21E+04	3.38E-03	2.69E+06	**1.14E+02**
Se	1.35E+02	2.13E+01	6.23E+02	**1.15E+02**
Br	6.67E+03	1.55E-03	1.69E+06	**5.62E+01**
Kr	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Rb	3.10E+04	3.49E-03	9.33E+06	**2.02E+02**
Sr	3.62E+02	5.46E-02	7.41E+04	**3.14E+01**
Y	1.09E+05	2.51E-02	3.01E+07	**7.89E+02**
Zr	4.33E+05	1.86E-02	1.59E+08	**4.66E+04**
Nb	2.02E+05	2.84E-02	9.26E+07	**8.26E-01**
Mo	1.30E+02	1.58E-01	1.56E+04	**2.61E+01**
Tc	4.96E+02	1.89E-04	8.34E+04	**7.37E+00**
Ru	1.95E+05	3.51E-03	6.11E+07	**1.58E+03**
Rh	1.85E+04	3.33E-03	4.79E+06	**1.57E+02**
Pd	1.51E+04	7.38E-03	2.88E+06	**1.85E+02**
Ag	8.41E+07	4.07E+00	4.78E+10	**1.91E+02**
Cd	2.19E+03	3.72E-03	4.86E+05	**3.36E+01**
In	1.45E+04	2.25E-03	2.48E+06	**1.58E+02**
Sn	5.86E+04	1.43E-02	1.30E+07	**2.52E+01**
Sb	1.73E+04	9.10E-03	3.36E+06	**6.83E+04**
Te	4.89E+04	1.90E-02	6.91E+06	**5.48E+02**
I	5.07E+01	4.71E-03	7.52E+03	**2.83E-01**
Xe	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Part 2 - Partition coefficients in mL/g (kd)				
Element	Statistics for sampled values			Solution
	Average	Min	Max	Vector 105
Cs	5.78E+03	3.43E-01	5.97E+05	**1.05E+01**
Ba	2.65E+09	1.62E-09	1.16E+12	**4.40E+01**
La	9.25E+02	3.89E-05	3.51E+05	**4.98E+00**
Ce	1.39E+02	4.66E+00	1.97E+03	**8.48E+01**
Pr	8.53E+04	1.21E-02	4.31E+07	**1.57E+02**
Nd	1.34E+04	7.03E-03	2.00E+06	**1.58E+02**
Pm	5.55E+05	1.47E-01	1.25E+08	**5.00E+03**
Sm	1.08E+05	6.02E-02	2.47E+07	**9.30E+02**
Eu	3.25E+06	5.01E-03	1.62E+09	**9.40E+02**
Gd	4.78E+02	2.94E-04	6.67E+04	**1.32E-02**
Tb	1.58E+04	9.63E-03	3.02E+06	**5.32E+01**
Ho	1.59E+05	5.53E-02	5.44E+07	**6.69E+00**
W	1.79E+04	9.09E-03	3.97E+06	**1.56E+02**
Re	5.27E+03	2.32E-03	1.37E+06	**4.35E+01**
Os	1.76E+04	1.26E-02	4.14E+06	**1.57E+02**
Ir	3.95E+04	1.56E-03	1.67E+07	**1.58E+02**
Au	1.85E+04	6.93E-03	3.75E+06	**1.57E+02**
Hg	1.41E+04	1.04E-02	2.08E+06	**1.57E+02**
Tl	1.64E+04	7.60E-03	3.28E+06	**1.58E+02**
Pb	1.61E+05	2.45E-01	5.54E+07	**2.38E+03**
Bi	4.02E+04	3.00E-02	6.36E+06	**4.43E+02**
Po	7.70E+02	3.26E-01	5.59E+04	**2.64E+01**
Rn	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Ra	1.42E+04	2.05E+01	5.18E+05	**3.53E+03**
Ac	3.07E+05	1.96E-02	1.13E+08	**1.73E+03**
Th	1.70E+06	7.02E-02	4.02E+08	**1.19E+02**
Pa	1.87E+05	1.19E-01	2.88E+07	**4.80E+00**
U	1.23E+04	1.30E-02	2.67E+06	**2.18E+00**
Np	7.52E+03	1.97E-01	3.68E+06	**1.36E+01**
Pu	6.16E+03	3.40E+00	7.70E+05	**1.36E+01**
Am	1.24E+05	1.27E-01	2.42E+07	**1.43E+03**
Cm	3.88E+04	5.68E+00	4.82E+06	**1.09E+05**
Cf	2.15E+04	6.65E-04	6.28E+06	**1.58E+02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for P_{crit} = 0.10 (continued)

Element	Leafy: Statistics for sampled values Average	Min	Max	Leafy Solution Vector 105	Root: Statistics for sampled values Average	Min	Max	Root Solution Vector 105
Part 3 - Plant concentration factors (B_{jv}) (leafy and root)								
H	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Be	1.50E-02	4.01E-04	1.47E-01	**1.00E-02**	2.25E-03	9.76E-05	2.52E-02	**1.50E-03**
C	1.05E+00	4.65E-02	1.15E+01	**3.20E-01**	1.05E+00	4.63E-02	1.12E+01	**7.00E-01**
N	4.50E+01	2.12E+00	4.54E+02	**3.00E+01**	4.49E+01	1.62E+00	4.45E+02	**3.00E+01**
F	8.99E-02	3.95E-03	9.51E-01	**6.00E-02**	9.04E-03	3.36E-04	1.24E-01	**6.00E-03**
Na	1.11E-01	2.30E-03	1.35E+00	**7.40E-02**	1.33E-01	2.50E-04	2.64E+00	**2.80E-02**
Mg	1.50E+00	6.16E-02	1.52E+01	**1.00E+00**	8.25E-01	2.70E-02	8.67E+00	**5.50E-01**
Si	5.25E-01	1.90E-02	5.88E+00	**3.50E-01**	1.05E-01	2.96E-03	1.40E+00	**7.00E-02**
P	5.25E+00	2.40E-01	5.57E+01	**3.50E+00**	5.27E+00	2.05E-01	6.56E+01	**3.50E+00**
S	2.25E+00	6.49E-02	2.54E+01	**2.30E+00**	2.25E+00	1.05E-01	2.47E+01	**1.50E+00**
Cl	1.06E+02	4.44E+00	1.59E+03	**1.60E+02**	1.05E+02	4.43E+00	1.32E+03	**7.00E+01**
Ar	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
K	1.51E+00	5.87E-02	2.14E+01	**8.40E+00**	8.25E-01	3.58E-02	8.22E+00	**5.50E-01**
Ca	5.30E+00	1.93E-01	8.22E+01	**1.40E+01**	5.27E-01	2.42E-02	6.58E+00	**3.50E-01**
Sc	9.03E-03	4.09E-04	1.23E-01	**6.00E-03**	1.50E-03	6.33E-05	1.90E-02	**1.00E-03**
Cr	3.03E-02	1.64E-03	4.17E-01	**2.20E-02**	1.81E-01	1.05E-02	2.18E+00	**8.00E-02**
Mn	4.04E+00	3.11E-04	1.10E+03	**3.30E-01**	4.58E+00	5.47E-03	2.08E+02	**1.10E+01**
Fe	1.35E-02	1.00E-04	3.92E-01	**5.60E-03**	1.00E-02	6.07E-05	2.74E-01	**2.60E-03**
Co	2.91E-01	5.54E-04	1.51E+01	**4.00E-02**	3.31E-01	3.00E-03	8.20E+00	**2.90E+00**
Ni	6.63E-02	6.05E-04	1.24E+00	**3.40E-02**	3.44E-01	1.12E-02	4.03E+00	**2.50E+00**
Cu	7.74E-01	2.47E-02	1.15E+01	**4.90E-01**	5.49E+00	2.60E-04	3.30E+02	**2.60E-01**
Zn	9.08E-01	3.53E-02	9.94E+00	**3.10E-01**	3.00E+00	2.02E-02	1.25E+02	**2.40E-01**
Ga	6.00E-03	2.20E-04	6.74E-02	**4.00E-03**	5.99E-04	2.33E-05	5.68E-03	**4.00E-04**
As	6.04E-02	2.38E-03	9.04E-01	**4.00E-02**	9.02E-03	3.70E-04	9.65E-02	**6.00E-03**
Se	3.75E-02	1.69E-03	4.03E-01	**4.90E-02**	3.79E-02	1.38E-03	6.65E-01	**2.50E-02**
Br	2.25E+00	9.95E-02	2.17E+01	**1.50E+00**	2.26E+00	5.98E-02	2.75E+01	**1.50E+00**
Kr	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Rb	1.82E+00	1.34E-02	3.69E+01	**8.10E-01**	1.05E-01	2.24E-03	1.03E+00	**7.00E-02**
Sr	4.31E+00	2.39E-02	9.02E+01	**6.40E+01**	2.00E+00	2.05E-02	6.27E+01	**4.60E-01**
Y	2.24E-02	8.30E-04	2.26E-01	**1.50E-02**	9.15E-03	2.75E-04	1.83E-01	**6.00E-03**
Zr	9.21E-02	6.04E-03	9.87E-01	**7.20E-02**	9.79E-02	1.04E-05	9.48E+00	**4.70E-03**
Nb	3.00E-02	1.24E-03	2.82E-01	**4.60E-02**	7.52E-03	3.36E-04	9.13E-02	**5.00E-03**
Mo	4.48E+00	4.52E-02	1.03E+02	**5.20E+01**	8.98E-02	3.48E-03	8.78E-01	**6.00E-02**
Tc	1.43E+01	6.38E-01	1.79E+02	**3.60E+01**	2.25E+00	8.65E-02	2.48E+01	**1.50E+00**
Ru	2.05E-01	6.25E-04	6.33E+00	**1.80E-02**	5.10E-02	7.41E-05	2.05E+00	**8.60E-03**
Rh	2.26E-01	6.16E-03	3.04E+00	**1.50E-01**	6.02E-02	2.79E-03	6.84E-01	**4.00E-02**
Pd	2.27E-01	5.62E-03	3.41E+00	**1.20E+00**	6.01E-02	2.16E-03	7.15E-01	**4.00E-02**
Ag	6.03E-01	1.88E-02	7.74E+00	**5.50E+00**	1.51E-01	4.90E-03	2.33E+00	**1.00E-01**
Cd	8.29E-01	2.24E-02	1.11E+01	**5.00E+00**	2.24E-01	1.03E-02	2.18E+00	**1.50E-01**
In	5.99E-03	2.05E-04	6.00E-02	**4.00E-03**	6.02E-04	1.17E-05	7.39E-03	**4.00E-04**
Sn	4.50E-02	1.80E-03	4.56E-01	**4.30E-02**	9.07E-03	2.70E-04	1.41E-01	**6.00E-03**
Sb	3.03E-01	1.27E-02	4.76E+00	**9.00E-01**	4.51E-02	1.83E-03	5.56E-01	**3.00E-02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Element	Leafy: Statistics for sampled values Average	Leafy: Min	Leafy: Max	Leafy: Solution Vector 105	Root: Statistics for sampled values Average	Root: Min	Root: Max	Root: Solution Vector 105
Part 3 - Plant concentration factors (B_{jv}) (leafy and root)								
Te	3.74E-02	1.67E-03	3.56E-01	**1.70E-02**	6.02E-03	2.61E-04	7.49E-02	**4.00E-03**
I	3.46E-01	2.78E-03	6.46E+00	**1.60E-01**	1.70E-01	3.54E-04	7.62E+00	**2.80E-02**
Xe	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Cs	9.18E-02	8.79E-04	3.43E+00	**1.80E-02**	1.70E-01	9.37E-04	1.76E+01	**3.10E-02**
Ba	7.04E-02	8.60E-04	2.23E+00	**3.90E-02**	2.68E-02	3.54E-04	5.74E-01	**8.00E-03**
La	1.50E-02	7.00E-04	1.46E-01	**1.00E-02**	5.99E-03	2.35E-04	6.12E-02	**4.00E-03**
Ce	5.96E-02	1.48E-04	1.84E+00	**6.40E-01**	4.13E-02	1.92E-05	2.58E+00	**4.50E-03**
Pr	1.50E-02	5.61E-04	1.77E-01	**1.00E-02**	5.99E-03	2.70E-04	5.87E-02	**4.00E-03**
Nd	1.52E-02	4.92E-04	2.85E-01	**1.00E-02**	5.99E-03	2.16E-04	5.83E-02	**4.00E-03**
Pm	1.50E-02	6.07E-04	1.58E-01	**1.00E-02**	6.11E-03	2.52E-04	1.23E-01	**4.00E-03**
Sm	1.50E-02	2.81E-04	1.81E-01	**1.00E-02**	6.00E-03	2.81E-04	6.57E-02	**4.00E-03**
Eu	1.50E-02	6.59E-04	1.69E-01	**1.00E-02**	6.00E-03	2.37E-04	6.15E-02	**4.00E-03**
Gd	1.50E-02	6.49E-04	1.46E-01	**1.00E-02**	6.07E-03	2.51E-04	1.04E-01	**4.00E-03**
Tb	1.51E-02	6.20E-04	2.21E-01	**1.00E-02**	6.00E-03	1.79E-04	6.74E-02	**4.00E-03**
Dy	1.50E-02	2.61E-04	1.56E-01	**1.00E-02**	6.06E-03	1.50E-04	9.13E-02	**4.00E-03**
Ho	1.50E-02	6.21E-04	1.49E-01	**1.00E-02**	6.00E-03	2.75E-04	6.59E-02	**4.00E-03**
Er	1.50E-02	6.94E-04	1.52E-01	**1.00E-02**	6.01E-03	2.67E-04	7.03E-02	**4.00E-03**
Hf	5.24E-03	2.14E-04	5.04E-02	**3.50E-03**	1.28E-03	4.91E-05	1.51E-02	**8.50E-04**
Ta	1.52E-02	5.83E-04	2.93E-01	**1.00E-02**	3.79E-03	1.35E-04	6.37E-02	**2.50E-03**
W	6.80E-02	1.67E-03	1.03E+00	**3.10E-01**	1.50E-02	2.13E-04	1.55E-01	**1.00E-02**
Re	2.25E+00	9.72E-02	2.30E+01	**7.50E+00**	5.27E-01	9.81E-03	6.61E+00	**3.50E-01**
Os	2.24E-02	8.99E-04	2.16E-01	**9.40E-02**	5.27E-03	2.38E-04	6.85E-02	**3.50E-03**
Ir	8.26E-02	3.66E-03	9.75E-01	**1.50E-01**	2.26E-02	8.84E-04	2.58E-01	**1.50E-02**
Au	5.99E-01	2.14E-02	5.85E+00	**4.00E-01**	1.50E-01	3.96E-03	1.47E+00	**1.00E-01**
Hg	1.36E+00	5.93E-02	2.01E+01	**9.00E-01**	2.99E-01	1.18E-02	2.83E+00	**2.00E-01**
Tl	6.01E-03	1.89E-04	6.85E-02	**4.00E-03**	6.00E-04	1.71E-05	6.74E-03	**4.00E-04**
Pb	6.78E-02	2.61E-03	8.19E-01	**4.50E-02**	1.35E-02	5.74E-04	1.74E-01	**9.00E-03**
Bi	5.25E-02	2.16E-03	5.67E-01	**3.50E-02**	7.52E-03	3.02E-04	9.05E-02	**5.00E-03**
Po	3.78E-03	1.19E-04	5.76E-02	**2.50E-03**	6.00E-04	2.29E-05	6.30E-03	**4.00E-04**
Rn	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Ra	2.25E-02	9.78E-04	2.64E-01	**1.50E-02**	2.25E-03	8.40E-05	2.15E-02	**1.50E-03**
Ac	5.39E-03	2.39E-04	1.33E-01	**3.50E-03**	5.24E-04	2.37E-05	5.36E-03	**3.50E-04**
Th	1.28E-03	5.98E-05	1.49E-02	**8.50E-04**	1.27E-04	4.98E-06	1.33E-03	**8.50E-05**
Pa	3.75E-03	1.72E-04	4.18E-02	**2.50E-03**	3.75E-04	1.68E-05	4.59E-03	**2.50E-04**
U	1.30E-02	5.31E-04	2.68E-01	**8.50E-03**	6.09E-03	2.57E-04	1.05E-01	**4.00E-03**
Np	4.04E+00	8.30E-03	2.77E+02	**1.90E+01**	1.19E+00	1.98E-02	3.05E+01	**1.90E-01**
Pu	6.75E-04	2.91E-05	7.17E-03	**4.50E-04**	6.92E-05	3.16E-06	1.78E-03	**4.50E-05**
Am	8.29E-03	3.12E-04	1.16E-01	**5.50E-03**	3.76E-04	1.48E-05	4.56E-03	**2.50E-04**
Cm	1.28E-03	5.46E-05	1.69E-02	**8.50E-04**	2.24E-05	9.06E-07	2.16E-04	**1.50E-05**
Cf	1.50E-02	5.60E-04	1.62E-01	**1.00E-02**	1.50E-02	7.03E-04	1.54E-01	**1.00E-02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Element	Fruit: Statistics for sampled values – Average	Fruit: Min	Fruit: Max	Fruit: Solution Vector 105	Grain: Statistics for sampled values – Average	Grain: Min	Grain: Max	Grain: Solution Vector 105
Part 3 - Plant concentration factors (B_{jv}) (fruit and grain)								
H	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Be	2.25E-03	8.25E-05	2.18E-02	**1.50E-03**	2.26E-03	3.42E-05	3.15E-02	**1.50E-03**
C	1.06E+00	4.52E-02	1.67E+01	**7.00E-01**	1.05E+00	3.88E-02	1.04E+01	**2.20E-01**
N	4.51E+01	1.42E+00	5.03E+02	**3.00E+01**	4.52E+01	1.24E+00	5.77E+02	3.00E+01
F	9.04E-03	3.01E-04	1.11E-01	**6.00E-03**	8.98E-03	2.80E-04	8.79E-02	**6.00E-03**
Na	1.33E-01	5.84E-04	4.04E+00	**1.60E-02**	1.38E-02	5.02E-05	3.59E-01	**5.20E-03**
Mg	8.25E-01	3.65E-02	7.97E+00	**5.50E-01**	8.36E-01	3.52E-02	1.62E+01	**5.50E-01**
Si	1.05E-01	3.88E-03	1.04E+00	**7.00E-02**	1.05E-01	3.34E-03	1.16E+00	**7.00E-02**
P	5.25E+00	2.35E-01	5.97E+01	**3.50E+00**	5.24E+00	2.12E-01	5.56E+01	**3.50E+00**
S	2.30E+00	8.80E-02	5.30E+01	**1.50E+00**	2.25E+00	4.48E-02	2.35E+01	**1.50E+01**
Cl	1.05E+02	4.13E+00	1.07E+03	**7.00E+01**	1.05E+02	3.96E+00	9.99E+02	**1.00E+03**
Ar	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
K	8.25E-01	3.00E-02	9.15E+00	**5.50E-01**	8.23E-01	2.78E-02	7.74E+00	**1.30E+00**
Ca	5.30E-01	2.36E-02	8.51E+00	**3.50E-01**	5.25E-01	2.41E-02	6.33E+00	**1.60E+00**
Sc	1.50E-03	4.23E-05	1.43E-02	**1.00E-03**	1.52E-03	6.87E-05	2.91E-02	**1.00E-03**
Cr	1.80E-01	1.07E-02	1.72E+00	**4.60E-02**	1.87E-02	1.56E-03	1.24E-01	**1.50E-02**
Mn	4.22E+00	5.25E-03	1.53E+02	**4.20E+00**	4.75E-01	1.30E-03	1.97E+01	**1.40E-01**
Fe	9.79E-03	1.17E-04	2.04E-01	**1.50E-03**	1.03E-03	1.14E-05	2.06E-02	**4.80E-04**
Co	3.35E-01	1.82E-03	1.05E+01	**2.20E-02**	3.45E-02	2.41E-04	6.56E-01	**1.10E-02**
Ni	3.44E-01	1.25E-02	3.15E+00	**3.40E-01**	3.61E-02	6.47E-04	3.75E-01	**3.80E-02**
Cu	5.92E+00	4.57E-04	5.80E+02	**1.50E-01**	5.70E-01	2.70E-05	4.23E+01	**4.90E-02**
Zn	2.95E+00	1.55E-02	7.58E+01	**1.10E+00**	3.13E-01	2.04E-03	9.40E+00	**5.50E+00**
Ga	6.01E-04	2.57E-05	6.98E-03	**4.00E-04**	6.01E-04	7.82E-06	6.38E-03	**4.00E-04**
As	8.97E-03	2.95E-04	8.67E-02	**6.00E-03**	8.97E-03	2.89E-04	8.59E-02	**6.00E-03**
Se	3.85E-02	1.35E-03	9.97E-01	**2.50E-02**	3.75E-02	1.53E-03	4.54E-01	**1.60E-01**
Br	2.25E+00	1.06E-01	2.51E+01	**1.50E+00**	2.25E+00	1.03E-01	2.50E+01	**1.50E+00**
Kr	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Rb	1.06E-01	4.97E-03	1.66E+00	**7.00E-02**	1.06E-01	4.71E-03	1.48E+00	**7.00E-02**
Sr	1.93E+00	8.70E-03	4.40E+01	**2.60E-01**	2.06E-01	1.30E-03	5.64E+00	**8.50E-02**
Y	9.10E-03	2.93E-04	1.52E-01	**6.00E-03**	9.03E-03	3.65E-04	1.13E-01	**6.00E-03**
Zr	8.80E-02	7.97E-06	8.47E+00	**2.70E-03**	9.75E-03	7.73E-07	9.41E-01	**8.70E-04**
Nb	7.50E-03	3.03E-04	8.62E-02	**5.00E-03**	7.53E-03	2.77E-04	1.00E-01	**4.30E-03**
Mo	9.14E-02	3.98E-03	1.85E+00	**6.00E-02**	9.00E-02	3.66E-03	8.71E-01	**6.00E-02**
Tc	2.25E+00	1.01E-01	2.30E+01	**1.50E+00**	2.25E+00	7.56E-02	2.57E+01	**7.30E-01**
Ru	5.99E-02	1.81E-04	7.27E+00	**3.00E-01**	5.46E-03	7.30E-06	1.88E-01	**1.60E-03**
Rh	6.01E-02	1.75E-03	6.95E-01	**4.00E-02**	6.01E-02	2.25E-03	6.48E-01	**4.00E-02**
Pd	6.04E-02	2.29E-03	9.35E-01	**4.00E-02**	6.04E-02	2.79E-03	8.67E-01	**1.80E-01**
Ag	1.50E-01	6.39E-03	1.78E+00	**1.00E-01**	1.51E-01	6.70E-03	1.88E+00	**1.00E-01**
Cd	2.26E-01	7.98E-03	2.92E+00	**6.70E-01**	2.25E-01	1.02E-02	2.47E+00	**2.20E-01**
In	6.01E-04	1.97E-05	7.02E-03	**4.00E-04**	6.03E-04	2.63E-05	8.20E-03	**4.00E-04**
Sn	9.03E-03	4.09E-04	1.06E-01	**6.00E-03**	9.08E-03	4.10E-04	1.35E-01	**1.00E-02**
Sb	4.50E-02	1.75E-03	4.68E-01	**3.00E-02**	4.52E-02	7.85E-04	6.42E-01	**3.00E-02**

Table 6.92 Default values for residential scenario parameters satisfying Equation 3.8 for $P_{crit} = 0.10$ (continued)

Element	Fruit: Statistics for sampled values Average	Min	Max	Fruit: Solution Vector 105	Grain: Statistics for sampled values Average	Min	Max	Grain: Solution Vector 105
Part 3 - Plant concentration factors (B_{jv}) (fruit and grain)								
Te	6.02E-03	1.37E-04	7.37E-02	**4.00E-03**	5.99E-03	2.74E-04	6.18E-02	**2.50E-03**
I	1.68E-01	2.26E-04	8.52E+00	**1.60E-02**	1.85E-02	3.60E-05	1.24E+00	**5.10E-03**
Xe	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Cs	1.46E-01	6.11E-04	5.37E+00	**1.40E-01**	1.60E-02	5.68E-05	9.62E-01	**6.60E-03**
Ba	2.61E-02	2.67E-04	5.59E-01	**4.60E-03**	2.84E-03	4.75E-05	8.41E-02	**1.50E-03**
La	6.05E-03	2.41E-04	8.51E-02	**4.00E-03**	5.99E-03	2.58E-04	5.68E-02	**4.00E-03**
Ce	5.02E-02	2.31E-05	7.03E+00	**2.00E-03**	4.08E-03	2.81E-06	1.78E-01	**8.20E-04**
Pr	5.99E-03	2.00E-04	5.97E-02	**4.00E-03**	5.99E-03	1.29E-04	6.54E-02	**4.00E-03**
Nd	6.09E-03	1.67E-04	1.20E-01	**4.00E-03**	6.00E-03	2.46E-04	6.02E-02	**4.00E-03**
Pm	6.02E-03	2.33E-04	7.58E-02	**4.00E-03**	5.98E-03	1.50E-04	5.69E-02	**4.00E-03**
Sm	6.02E-03	2.63E-04	7.10E-02	**4.00E-03**	6.00E-03	2.48E-04	5.85E-02	**4.00E-03**
Eu	6.13E-03	2.58E-04	1.38E-01	**4.00E-03**	6.00E-03	1.96E-04	6.77E-02	**4.00E-03**
Gd	6.00E-03	1.90E-04	6.00E-02	**4.00E-03**	5.99E-03	2.09E-04	6.18E-02	**4.00E-03**
Tb	6.08E-03	2.84E-04	1.12E-01	**4.00E-03**	5.99E-03	2.19E-04	5.92E-02	**4.00E-03**
Dy	6.17E-03	2.71E-04	1.60E-01	**4.00E-03**	6.00E-03	2.45E-04	5.96E-02	**4.00E-03**
Ho	6.00E-03	2.67E-04	6.89E-02	**4.00E-03**	6.03E-03	1.90E-04	7.66E-02	**4.00E-03**
Er	6.01E-03	2.24E-04	6.94E-02	**4.00E-03**	5.98E-03	1.85E-04	5.65E-02	**4.00E-03**
Hf	1.28E-03	5.08E-05	1.35E-02	**8.50E-04**	1.27E-03	5.36E-05	1.36E-02	**8.50E-04**
Ta	3.76E-03	1.05E-04	4.32E-02	**2.50E-03**	3.77E-03	1.31E-04	4.53E-02	**2.50E-03**
W	1.50E-02	6.98E-04	1.48E-01	**1.00E-02**	1.50E-02	4.68E-04	1.50E-01	**4.10E-02**
Re	5.25E-01	9.93E-03	5.42E+00	**3.50E-01**	5.28E-01	1.68E-02	8.07E+00	**9.50E-01**
Os	5.31E-03	2.17E-04	8.87E-02	**3.50E-03**	5.24E-03	1.62E-04	5.30E-02	**3.50E-03**
Ir	2.26E-02	9.48E-04	2.86E-01	**1.50E-02**	2.24E-02	9.43E-04	2.15E-01	**1.00E-02**
Au	1.50E-01	5.63E-03	1.52E+00	**1.00E-01**	1.50E-01	7.05E-03	1.49E+00	**1.00E-01**
Hg	3.00E-01	9.97E-03	2.86E+00	**2.00E-01**	3.00E-01	1.01E-02	2.96E+00	**2.00E-01**
Tl	5.99E-04	2.65E-05	5.98E-03	**4.00E-04**	6.00E-04	2.54E-05	6.11E-03	**4.00E-04**
Pb	1.35E-02	4.83E-04	1.31E-01	**9.00E-03**	1.35E-02	5.45E-04	1.48E-01	**9.00E-03**
Bi	7.50E-03	3.03E-04	7.89E-02	**5.00E-03**	7.48E-03	2.70E-04	7.62E-02	**5.00E-03**
Po	6.02E-04	1.64E-05	6.93E-03	**4.00E-04**	6.04E-04	2.45E-05	8.13E-03	**4.00E-04**
Rn	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Ra	2.25E-03	9.86E-05	2.22E-02	**1.50E-03**	2.26E-03	8.50E-05	3.03E-02	**1.50E-03**
Ac	5.24E-04	2.04E-05	5.23E-03	**3.50E-04**	5.34E-04	2.11E-05	1.12E-02	**3.50E-04**
Th	1.28E-04	3.97E-06	1.26E-03	**8.50E-05**	1.28E-04	3.85E-06	1.50E-03	**8.50E-05**
Pa	3.75E-04	1.62E-05	4.12E-03	**2.50E-04**	3.76E-04	1.58E-05	4.70E-03	**2.50E-04**
U	5.99E-03	8.33E-05	5.88E-02	**4.00E-03**	5.99E-03	1.69E-04	5.65E-02	**4.00E-03**
Np	1.18E+00	1.87E-02	4.29E+01	**1.30E-01**	1.24E-01	2.02E-03	2.11E+00	**6.80E-02**
Pu	6.72E-05	2.28E-06	7.05E-04	**4.50E-05**	6.88E-05	3.11E-06	1.43E-03	**4.50E-05**
Am	3.75E-04	1.57E-05	4.28E-03	**2.50E-04**	3.75E-04	1.63E-05	3.84E-03	**2.50E-04**
Cm	2.24E-05	9.50E-07	2.34E-04	**1.50E-05**	2.25E-05	7.49E-07	3.04E-04	**1.50E-05**
Cf	1.51E-02	6.35E-04	2.21E-01	**1.00E-02**	1.51E-02	5.09E-04	2.55E-01	**1.10E-02**

percentile TEDE value from the original sample measures the strength of the relationship between the TEDE and the parameter. This measure of the strength of dependence of dose on parameter value provides a direct indication of the potential for site-specific parameter information (expressed as a revised limit on the parameter value) to change the estimated dose.

Finally, those parameters with "significant" potential to modify the screening dose value were selected based on the calculated strength measure. A threshold value of 0.52 for "significant" reduction of the 95th percentile of the dose distribution was selected. Parameters having strength measures less than this threshold (i.e., with the potential to effect a greater reduction in the 95th percentile) were considered to be strongly and significantly correlated with dose. The threshold strength measure value of 0.52 was selected by noting the spurious associations between parameter values and TEDE that emerged. The indoor shielding factor SFI was identified as significant by the K-S test, and had an associated strength measure of 0.52. This parameter, however, was not used in the calculation, and the reported strength measure is an artifact of sampling error. Strength measure values less than this threshold were assumed to be significant.

Table 6.94 lists, for each source nuclide, the identifiers of the model input parameters identified as having a strong significant relationship to dose due to that nuclide. Some parameters listed in Table 6.94 are an artifact of the functional connection among soil properties and soil type. The fraction of hydrogen in soil, for example, is only used in the tritium model. It appears as a significant parameter for dose due to 129I, however, because of the functional connection between the hydrogen fraction and the soil saturation fraction, F1.

For many source nuclides, no significant controlling parameters were identified. The small range of the dose distribution for some nuclides may make the relationship between parameter values and dose difficult to distinguish from sampling error.

Table 6.93 Model parameters having significant strong correlations with TEDE

Source	Parameter symbol	Parameter description	Relative change in dose
3H	fhd016	Fraction of hydrogen in soil	0.22
	sh	Moisture content of soil	0.22
	F1	Saturation ratio for the surface-soil layer	0.27
	F2	Saturation ratio for the unsaturated layer	0.27
	I	Infiltration rate	0.29
	N1	Porosity of the surface-soil layer	0.40
	N2	Porosity of the unsaturated layer	0.40
	PS	Soil areal density of surface plow layer	0.40
	RHO1	Surface Soil Density	0.40
	RHO2	Unsaturated Zone Soil Density	0.40
14C	F1	Saturation ratio for the surface-soil layer	0.14
	F2	Saturation ratio for the unsaturated layer	0.14
	fhd016	Fraction of hydrogen in soil	0.15
	sh	Moisture content of soil	0.15
	KdC	C Partition Coefficient	0.18
	I	Infiltration rate	0.18
	H2	Thickness of unsaturated zone	0.19
36Cl	B4Cl	Concentration factor: grain Cl	0.48
40K	H2	Thickness of unsaturated zone	0.20
	KdK	K Partition Coefficient	0.22
41Ca	B1Ca	Concentration factor: leafy Ca	0.25
45Ca	B1Ca	Concentration factor: leafy Ca	0.21
59Ni	I	Infiltration rate	0.17

Table 6.93 Model parameters having significant strong correlations with TEDE (continued)

Source	Parameter symbol	Parameter description	Relative change in dose
	KdNi	Ni Partition Coefficient	0.19
63Ni	KdNi	Ni Partition Coefficient	0.20
93Mo	B1Mo	Concentration factor: leafy Mo	0.28
99Tc	B1Tc	Concentration factor: leafy Tc	0.33
107Pd	B1Pd	Concentration factor: leafy Pd	0.50
113mCd	KdCd	Cd Partition Coefficient	0.41
121mSn	KdSn	Sn Partition Coefficient	0.10
129I	F1	Saturation ratio for the surface-soil layer	0.10
	F2	Saturation ratio for the unsaturated layer	0.10
	fhd016	Fraction of hydrogen in soil	0.11
	sh	Moisture content of soil	0.11
	KdI	I Partition Coefficient	0.14
	H2	Thickness of unsaturated zone	0.15
	I	Infiltration rate	0.16
185W	KdW	W Partition Coefficient	0.39
	WV(2)	Wet/dry conversion: nonleafy	0.43
232U	H2	Thickness of unsaturated zone	0.25
	WV(2)	Wet/dry conversion: nonleafy	0.26
	KdU	U Partition Coefficient	0.27
232U+C	WV(2)	Wet/dry conversion: nonleafy	0.29
233U	H2	Thickness of unsaturated zone	0.26
	WV(2)	Wet/dry conversion: nonleafy	0.30
	U	U Partition Coefficient	0.33
234U	U	U Partition Coefficient	0.19
	WV(2)	Wet/dry conversion: nonleafy	0.25
235U	WV(2)	Wet/dry conversion: nonleafy	0.36
	U	U Partition Coefficient	0.37
236U	I	Infiltration rate	0.18
	U	U Partition Coefficient	0.19
	WV(2)	Wet/dry conversion: nonleafy	0.25
238U	U	U Partition Coefficient	0.20
	WV(2)	Wet/dry conversion: nonleafy	0.25

7.0 References

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Appendix A: Equations for Distribution Functions and LHS Calculations

C-Fit Program PDF Equations

The following equations and definitions were taken from the C-Fit™ software (C-Fit, 1996) that was used to fit functions probability for some residential scenario parameters based on supporting data. Among the many distribution types included in C-Fit, normal, log normal, beta, gamma, and Gumbel distributions were used. Distributions were selected based on either the Chi-square or Kolmogorov-Smirnov goodness of fitness tests.

The following equations describe the distribution types used in our analysis, using notation from the C-Fit User Guide.

Normal Distribution

$$f(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad (1)$$

where μ and σ are the mean and standard deviation of the variable and are defined as:

$$\text{Mean } \mu_x = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

and Standard Deviation is:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \mu_x\right)^2} \qquad (3)$$

Log Normal

$$f(x;\mu,\sigma,\varepsilon) = \frac{e^{-\frac{1}{2\sigma^2}\left[\log\left(\frac{x-\varepsilon}{\mu}\right)\right]^2}}{(x-\varepsilon)\sigma\sqrt{2\pi}} \qquad (4)$$

Gumbel (Extreme Value Type I Max.)

$$f(x;\mu,\alpha) = \alpha e^{\left(\alpha(\mu-x) - e^{\alpha(\mu-x)}\right)} \qquad (5)$$

Gamma

$$f(x;\kappa,\lambda,\varepsilon) = \frac{\lambda[\lambda(x-\varepsilon)]^{\kappa-1} e^{-[\lambda(x-\varepsilon)]}}{\Gamma(\kappa)} \qquad (6)$$

where:

$$\kappa = \frac{\mu^2}{\sigma^2} \quad \lambda = \frac{\kappa}{\mu} \qquad (7)$$

and the gamma function is defined by:

$$\Gamma(\kappa) = \int_0^\infty t^{\kappa-1} e^{-t} dt \qquad (8)$$

Beta

$$f(x;a_1,a_2,\delta_1,\delta_2) = \frac{\left(\frac{x-\delta_1}{\delta_2-\delta_1}\right)^{a_1-1}\left(1-\frac{x-\delta_1}{\delta_2-\delta_1}\right)^{a_2-}}{(\delta_2-\delta_1)B(a_1,a_2)} \qquad (9)$$

and the beta function is given by:

$$B(x,y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)} = \int_0^1 t^{x-1}(1-t)^{y-1} dt \qquad (10)$$

LHS Distribution Equations

The LHS program was used to generate samples of parameter values based on the distribution functions assigned to the parameters. The general mathematical forms for the distribution functions used in this analysis are described below, using the notation of the LHS input guide (Iman & Shortencarier, 1984?)

Unbounded Normal Distribution

There are two input parameters required when defining a normal distribution: the mean and the standard deviation. The mean may be any real value; however, the standard deviation must be strictly positive. The normal distribution is defined in terms of the mean μ and standard deviation or by the following density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad -\infty<x<\infty \tag{11}$$

The defining parameters are the same as those used by C-FIT [Equation (1)].

Unbounded Lognormal Distribution

A lognormal distribution is defined by the density function:

$$f(y) = \frac{1}{y\sigma\sqrt{2\pi}} e^{-\frac{(\ln y-\mu)^2}{2\sigma^2}} \quad y>0 \tag{12}$$

where the mean, variance and median are, respectively:

$$E(y) = e^{\left(\mu+\frac{\sigma^2}{2}\right)} \tag{13}$$

$$V(y) = e^{2\mu+\sigma^2}\left(e^{\sigma^2}-1\right) \tag{14}$$

$$\text{Median} = e^{\mu} \tag{15}$$

In the input to LHS, this distribution is described by the mean and an error factor parameter. The error factor is the ratio of the value at the 95% quantile to the median; it is also the ratio of the median to the 5% quantile. The program collects the input mean and error factor into the mean and standard deviation of the underlying normal distribution using the following relations:

$$\sigma = \frac{\ln(\text{error factor})}{1.645} \tag{16}$$

$$\mu = \ln(\text{input mean}) - \frac{1}{2}\sigma^2 \tag{17}$$

The C-FIT formulation for this distribution, Equation (4), includes a displacement parameter ε, and a different definition for the parameter μ.

Uniform Distribution - Uniform Intervals

This distribution samples values uniformly between two specified interval endpoints A and B. It is defined by the following density function:

$$f(x) = \frac{1}{B-A}, \quad A \le x \le B \tag{18}$$

The mean and variance are:

$$E(x) = \frac{A+B}{2} \quad \text{and} \quad V(x) = \frac{(B-A)^2}{12} \tag{19}$$

Loguniform Distribution - Uniform Intervals

The logarithm of a variable having a loguniform distribution is uniform between the log base 10 of the specified end points A and B, where A and B are both >0.

The following equations are stated in terms of natural logarithms to simplify the presentation. The density function for this distribution is:

$$f(x) = \frac{1}{x}(\ln A - \ln B), \quad A<x<B \tag{20}$$

The mean, variance, and median (respectively) are as follows:

$$E(x) = \frac{B-A}{\ln B - \ln A} \tag{21}$$

$$V(x) = (B-A)\frac{(\ln B - \ln A)(B+A) - 2(B-A)}{2(\ln B - \ln A)^2} \tag{22}$$

$$\text{Median} = e^{\frac{\ln B + \ln A}{2}} = \sqrt{AB} \tag{23}$$

Triangular Distribution

The triangular distribution is defined by three parameters a, b, and c. The lower limit a and upper limit c establish bounds beyond which sampling is not to occur. The most likely value is specified by the b parameter. With a < b < c, the density function is:

$$f(x) = \frac{2(x-a)}{(c-a)(b-a)}, \quad a \le x \le b \tag{24}$$

and,

$$f(x) = \frac{2(c-x)}{(c-a)(c-b)}, \quad b \le x \le c \tag{25}$$

The mean, variance, and median (respectively) are as follows:

$$E(x) = \frac{a+b+c}{3} \quad (26)$$

$$V(x) = \frac{a(a-b)+b(b-c)+c(c-a)}{18} \quad (27)$$

$$\text{median} = a-\sqrt{\frac{(c-1)(c-b)}{2}}, \quad b \geq \frac{a+c}{2}$$

$$\text{median} = c-\sqrt{\frac{(c-a)(c-b)}{2}}, \quad b \leq \frac{a+c}{2}$$

Beta Distribution

A beta distribution is defined by the limiting endpoints A and B, and shape parameters p and q. The following conditions must be satisfied:

$$p, q \geq 0.001$$
$$0 \leq A < B.$$

The beta distribution is defined by the following density functions:

$$f(\beta) = \frac{\beta}{\int_A^B \beta} \quad (30)$$

where:

$$\beta = x^{p-1}(1-x)^{q-1} \quad (31)$$

User Defined Cumulative Continuous Distribution with Linear Interpolation

A continuous distribution is used when the user knows certain values that the variable will take on, and linearly interpolates between those values. It is commonly used to approximate irregular distributions. The user must specify n, an integer (n > 1) number of ordered pairs to be read in, followed by the n ordered pairs. Within the ordered pairs, the first number is the value of the variable; the second number is the cumulative probability associated with the value. The probabilities in the ordered pairs must increase monotonically starting with 0.0 and ending with 1.0. The variable values must also increase monotonically. LHS then performs a linear interpolation on this distribution function. If only two points are specified, a uniform distribution is generated between the two points.

User Defined Discrete Cumulative Distribution

A discrete cumulative distribution is used when the user has a discrete number of possibilities that may occur. The user must specify an integer, n > 1, which signifies the number of ordered pairs to be read in. The n ordered pairs consist of the value of the variable with the cumulative probability associated with that value. The probabilities in the ordered pairs must increase monotonically starting with a value greater than 0.0 and ending with 1.0. The values must also increase monotonically.

Gamma Distribution

A gamma distribution has a density function defined by

$$\frac{B^{\alpha} X^{\alpha-1} e^{-Bx}}{\Gamma(\alpha)} \quad (32)$$

where

$$\Gamma(d) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy$$

In the input to LHS, the user must specify α and β, both of which are real numbers.

Appendix B: Procedure for Defining Deterministic Defaults for Physical Parameters

The default values for the physical model parameters are required to satisfy the mathematical conditions described in Section 3.3. These mathematical conditions, which express the requirement that the parameter values tend to overestimate dose, lead to set of simultaneous inequalities (Equation 3.8):

$$d_{Di} \equiv m(\mathbf{x_d}, \mathbf{s}_i) \geq d_{Ci} \quad i = 1 \ldots n_s$$

Solving Equation 3.8 requires values for the dose distribution quantile values d_{Ci} for each of the n_s source radionuclides. These quantile values are based on the probability distribution functions F_{Di} for each the n_s radionuclides (Equation 3.7), and these distribution functions depend on the distributions assigned to the model input parameters. Finding defaults therefore entails: 1) identifying parameter distributions; 2) calculating dose distributions; 3) looking for parameter values that solve the inequality constraints in Equation 3.8. If Equation 3.8 has a solution, it will have many solutions. As a final step in defining the default parameters, evaluation functions are defined to help select among alternative solutions identified in Step 3. Details of each of these four steps are provided in this appendix.

Defining Parameter Distributions

For each of the physical parameters of the scenario model, a distribution was developed to describe the variability in the parameter value over all potential site-specific applications of the model based on: guidelines provided in NUREG/CR-5512; the use of the parameter in the model; the relationship between the diverse site conditions and parameter values; and the expected range of site conditions across applications. (The specific distributions defined for each parameter, along with the data and procedures used to define these distributions, are detailed in Section 5.4 and Section 6.4.)

Calculating Dose Distributions for Individual Source Nuclides

A stratified monte-carlo technique, Latin Hypercube Sampling (LHS, Iman and Shortencarier 1984) , was used to estimate the dose distribution functions from the assigned parameter distribution functions. Monte-carlo techniques, in general, are used to estimate the properties of random variables from a set of sample values for those variables. Samples of the dose distribution functions D_{Ti} were generated by creating samples of the input parameter vector **X**, then calculating the dose value resulting from each of those sampled parameter vectors. For each source nuclide, the dose assessment model m produces a possible dose value $d_{Ti,j}$ for each sample of the parameter vector:

$$d_{Ti,j} = m(\mathbf{x}_j, \mathbf{s}_i) \qquad j = 1 \ldots n_v, \quad i = 1 \ldots n_s \tag{1}$$

where $\mathbf{x}_j$ is the vector of model parameters for sample j, and n_v is the number of sample vectors used to estimate the dose distribution.

LHS is a technique for creating the sample vectors of model parameters based on a stratified sampling of the individual model parameters. For each model parameter, the distribution function for the parameter is used to divide the range of parameter values into n_v intervals such that there is an equal probability of the parameter value occurring in each interval. One sample value is then chosen at random from each interval. Each of the n_v values for a given parameter are then combined with one of the n_v sampled value for all other parameters, producing a set of n_v sample vectors. Each sample vector represents a possible site-specific analysis.

The procedure used to combine parameter values controls the correlations among parameters, or more precisely, among the ranks of the parameter values. This control can be used to insure that accidental (spurious) correlations among parameters are not introduced, or to impose specified correlations among parameters.

Table 1 is a list of the individual radionuclides that might occur in a site source term, including both non-equilibrium and equilibrium (+C) progeny. For each generic source s_i in Table 1, the TEDE value was calculated using each of the sample vectors generated by LHS, and a unit concentration of the radionuclide.

The resulting set of n_v dose values defines the dose distribution function F_{Di}. The dose quantile values, d_{Ci}, for a particular value of P_{crit} can be directly obtained from this distribution function as the $1 - P_{crit}$ quantile of F_{Di}.

Identify Default Parameter Values

The calculations used to approximate the dose distribution functions, and to estimate the dose quantile values

d_{Ci} can also be used to search for solutions to Equation 3.8. For each source radionuclide, the LHS calculations provide a value of the function m for each one of the set of parameter sample vectors. For a given value of P_{crit}, the subset of vectors which satisfy Equation 3.8 for each individual source can be identified:

$$\Phi_i = \left\{ \mathbf{x}_j \middle| d_{Ti,j} \geq d_{Ci} \right\} \qquad (2)$$

The sets Φ_i are all subsets of the original set of sample vectors. Different source will produced different subsets because doses due to different sources will tend to be controlled by different parameters.

Any sample vectors that satisfy Equation 3.8 for all sources are in all filtered sets. The set of samples that are solutions to Equation 3.8 is found by taking the intersection of the filtered sets:

$$\Psi = \bigcap_{i=1,n_s} \Phi_i \qquad (3)$$

This approach requires that the same parameter samples be used for each source radionuclide. This requirement is easy to satisfy if the parameter distributions are the same for all sources within the scenario as assumed here (Equation 3.5). If the parameter distributions vary from source to source, it is possible but practically difficult to use a common sample set. This approach only requires simple sorting and searching operations on the initial sample sets.

For a given value of P_{crit}, solutions may not be found in the set of LHS samples used to estimate the dose distribution. This may have one of two causes:

1. No solution exists to Equation 3.8 because the constraints represented by the different sources are incompatible: one constraint requires values for a particular parameter at one end of its range, while another constraint requires values at the other end. Figure 1(a) illustrates this situation for a model using only two parameters, x_1 and x_2.

2. There are no samples in the region where the solution to Equation 3.8 exists: different constraints establish limits on different parameters, and the joint solution space is a small 'corner' of the original sample space. Figure 1(b) illustrates this situation for a two-parameter model.

It is important to distinguish between these two cases when the LHS sampling fails to produce a solution. In the first case, it is impossible to define defaults that would be appropriate for all source nuclides, and source-dependent default values are required. A solution exists in the second case, but additional samples must be taken in the region of parameter space where the source-independent solution appears to be located.

The results of the LHS sampling can be interpreted to discover whether the source constraints tend to be conflicting (case 1 above), independent (case 2 above) or redundant (several constraints drive the same parameters in the same direction). For a small number (e.g. 10) of source constraints, the correlation coefficient between the ranks of calculated dose for different source constraints can provide this information. For the large number (>100) of constraints in this problem, however, it is impractical to calculate and examine the rank correlation coefficients for all constraint pairs. A different diagnostic technique was therefore used to characterize the set of constraints as generally incompatible, independent, or redundant.

To make this distinction, and to guide the search for parameter vectors that satisfy Equation 3.8 for all sources, the *solution count distribution* (SCD) was generated for the set of sample vectors. For an LHS sample size of n_v, and a given value of P_{crit}, exactly $n_{crit} = P_{crit} \cdot n_v$ sample vectors will satisfy each individual constraint in Equation 3.8. Some vectors will satisfy no constraints, others will satisfy one or more constraints. For each vector, the solution count for that vector is the sum of the number of constraints that it satisfies. If there are n_s constraints, the maximum value for the solution count (indicating that Equation 3.8 is satisfied) is n_s. The minimum value for the solution count is zero. The SCD is the distribution of solution count values over the n_v LHS sample vectors.

If there are n_s constraints, and those constraints are perfectly redundant, then the n_{crit} vectors that satisfy any one constraint also satisfy all remaining constraints. The SCD in this case will show that n_{crit} vectors satisfy exactly n_s constraints, and $n_v - n_{crit}$ vectors satisfy exactly 0 constraints.

If, on the other hand, the n_s constraints are perfectly independent, then any one of the n_{crit} vectors that satisfies the first constraint has the same probability of satisfying the second constraint as any of the $n_v - n_{crit}$ vectors that do not satisfy the first constraint. For a single vector, there is a probability of P_{crit} that it will satisfy the first constraint, a probability of P_{crit} that it will satisfy the second constraint, an so on. Because the n_s constraints are independent, the expected number of constraints satisfied by each vector is $P_{crit} \cdot n_s$. For a set

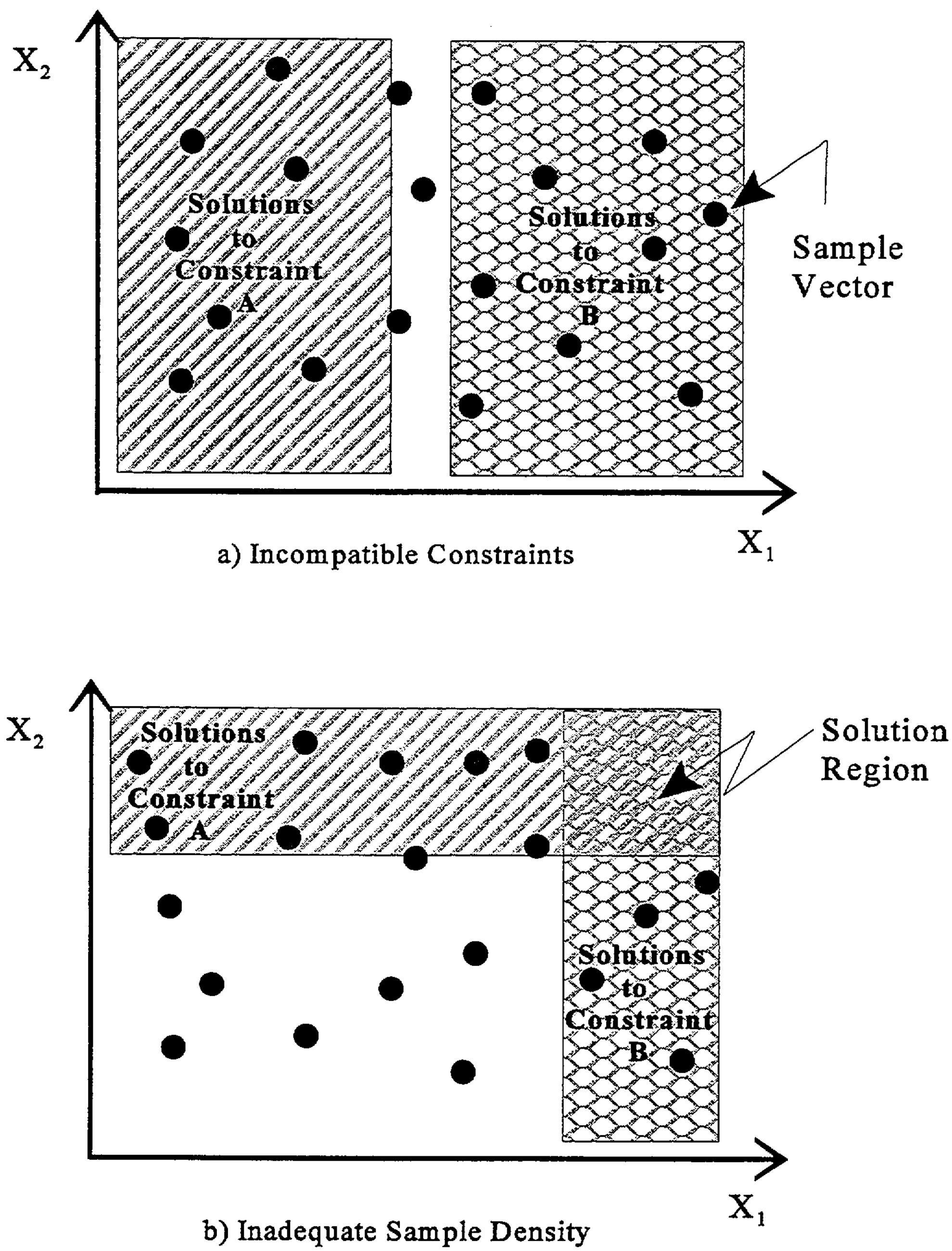

Figure 1 Schematic illustration of two situations in which no joint solution is found in the LHS sample set for a model using two input parameters

of independent *sample vectors*, the distribution of the number of constraints satisfied by each vector should approach the Poisson distribution with an expected value of $P_{crit} \cdot n_s$.

If two constraints are incompatible, then the n_{crit} vectors that satisfy the first constraint do not satisfy the second, and *vice versa*. Generalizing to n_s constraints, each vector will satisfy exactly one constraint, but not satisfy any of the other $n_s - 1$ constraints. For $n_s \cdot n_{crit} \leq n_v$, each vector will satisfy either no constraints or one constraint. In contrast, for n_s *independent* constraints described above, some of the vectors would be expected to satisfy 2 or more constraints according to the Poisson distribution. For $n_s \cdot n_{crit} > n_v$, one or more vectors must necessarily satisfy more than one constraint, so that the n_s constraints cannot be mutually perfectly incompatible. The tendency for vectors which satisfy one constraint to be excluded from solutions to other constraints will instead produce a characteristic clustering in the number of constraints satisfied by each vector: most numbers will be near the expected value of $P_{crit} \cdot n_s$, while vectors that satisfy a larger number of constraints will be much less frequent that predicted for the independent (Poisson) case.

Figure 2 is a schematic illustration of the solution count distributions expected for each of the three cases discussed above. Both the density functions and cumulative distribution functions are shown. The distribution for redundant constraints is bi-modal, with values only occurring at 0 and n_s. The distribution for independent constraints is centered around $P_{crit} \cdot n_s$, and follows a Poisson distribution. The distribution for incompatible constraints is also centered around $P_{crit} \cdot n_s$, but is characteristically narrower than the Poisson distribution.

No actual set of constraints is expected to conform exactly to any one of these ideal cases, but comparing the SCD to these prototypes helps judge the prospective existence of a joint solution to all constraints, and the difficulty in finding such solutions if none are produced by the LHS sampling. Any vectors that satisfy all constraints for a given value of P_{crit} occur at the maximum value of x of n_s on the SCD plot. If there are no joint solutions in a given sample set for a specified value of P_{crit}, the distribution density near n_s for the desired P_{crit}, and the density at n_s for larger values of P_{crit}, indicate the "proximity" of the solution to the vectors in the sample set.

If the initial LHS sampling does not contain solutions for a desired value of P_{crit}, but does not appear to be subject to contradictory constraints, the solution to Equation 3.8 can be pursued by using the results of the initial evaluation to generate new parameter values and combinations. There are a number of strategies for using the performance of the initial LHS sampling to guide the search for solutions to Equation 3.8. The large number of simultaneous constraints, the potential for pathway interactions to create a non-monotonic dependence on parameter values, and the potential for abrupt changes in parameter sensitivity due to changes in pathway dominance all suggest that a robust empirical search procedure would be more effective than analytical approaches.

An empirical approach, based on genetic optimization, was therefore used to generate targeted parameter sets preferentially containing solutions for small values of P_{crit}. Genetic algorithms require no assumptions about the functional form, or even continuity, of the response surface *m*, and have been successfully applied in traditionally difficult non-linear and multimodal optimization problems (Goldberg, 1989).

A basic genetic algorithm creates a new parameter set by combining components from a subset of the original sample set:

1. From the original parameter sample set, a subset of sample vectors is selected based on their solution counts. Vectors having large solution counts are assumed to be "close" to parameter combinations that solve Equation 3.8;

2. To create a new sample vector, a pair of 'parent' vectors from the selected subset is chosen at random, along with a value i_s of a random integer uniformly distributed between 1 and $n_p + 1$, where n_p is the number of components of the parameter vector (i.e. the number of adjustable parameters in the model);

3. The new sample is formed by copying components 1 to $i_s - 1$ from the first parent vector, and components i_s to n_p of the second parent vector.

4. The new sample vectors are also subject to random mutation. A specified percentage of the new vectors are chosen at random. For each chosen vector, a particular parameter is chosen at random,and replaced by a value randomly selected from the original set of sampled values for that parameter.

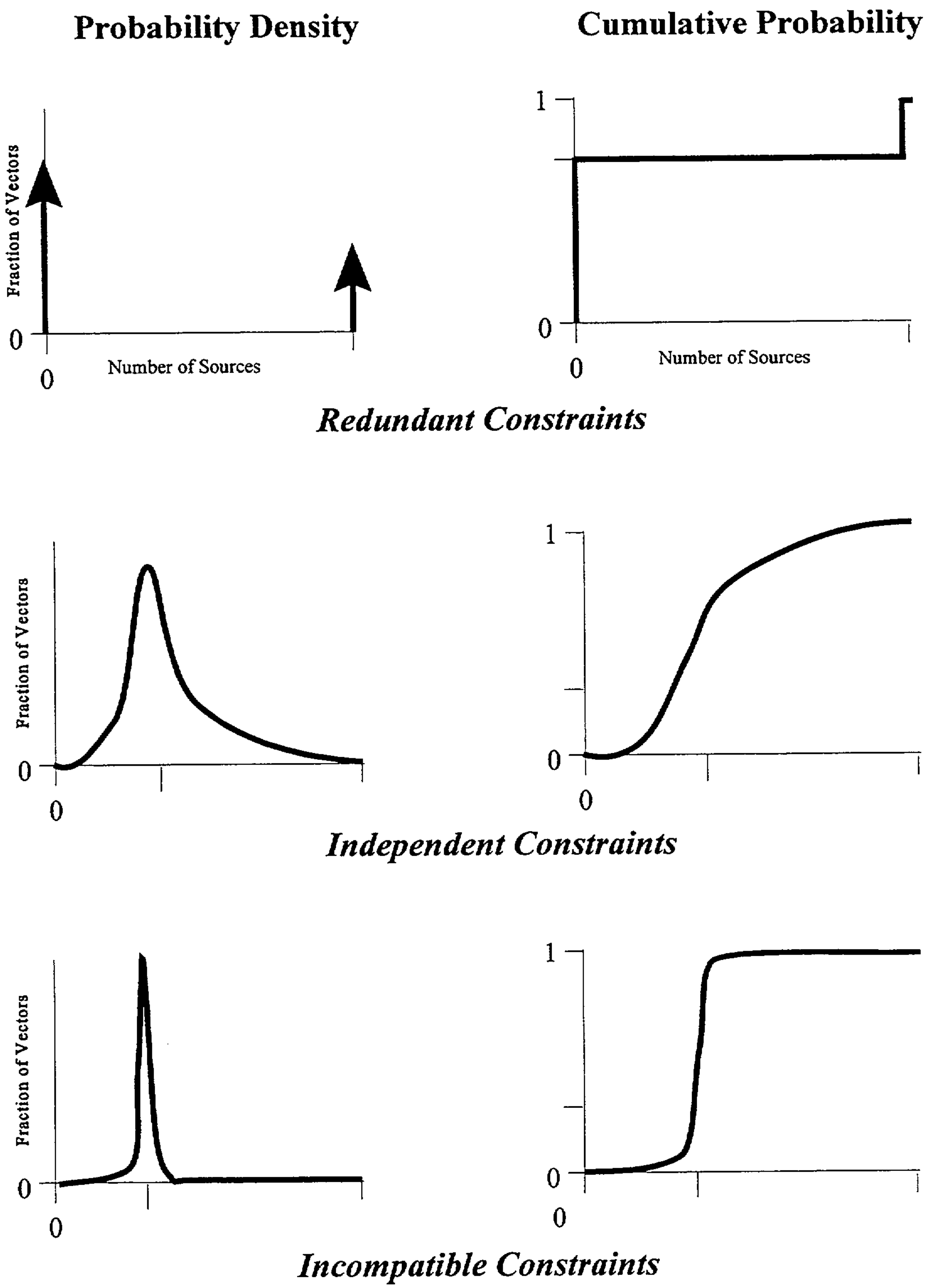

Figure 2 Solution count distributions (SCDs) for three idealized relationships among source constraints

Dose values are then calculated for the new set of sample vectors for each of the source radionuclides, and the set is examined for solutions to Equation 3.8. If none are found, the genetic algorithm can be applied to the second generation of vectors, along with their solution counts. With each iterative application, the algorithm is expected to produce vectors with increasing solution counts, ultimately producing one or more vectors that satisfy Equation 3.8.

The basic genetic algorithm described above rates parameter vectors based on the total number of source nuclides for which the vector is a solution. New vectors are generated based on random combinations of the parameter values of highly-rated vectors. This algorithm was found to produce vectors with large solution counts after a few iterations, but the maximum solution count increased at an unacceptably slow rate during later iterations.

To speed the search for solutions, the algorithm was modified to exploit information that is not used in the basic genetic algorithm. A solution vector must produce a dose value in the selected quantile for each of the source nuclides. For a given nuclide, the dose will be more strongly dependent on some parameters than on others. These features of the problem were used to speed the solution search by modifying the way vectors were selected and combined to produce new candidate vectors. The first 'parent' vector was selected based on the solution count distribution, as in the basic algorithm. The second 'parent' was selected based on a modified solution count, in which only the source nuclides *not* satisfied by the first 'parent' vector are counted. This modified or residual solution count was used to determine the probability of selecting a vector as the second parent.

Once the parents were selected, the parameter values for the new vector were selected by combining the 'important' parameters from each parent, rather than by selecting parameters at random. 'Important' parameters were those whose values were significantly correlated with dose for any of the source nuclides satisfied by the vector. Parameters having no significant correlation with any source nuclide were set to the median values of their distributions.

The resulting 'child' vector has parameter values that were assembled in a way that increases the number of distinct nuclides whose constraints are satisfied. Parents vectors are paired based on their distinctive contributions, and parameter values are chosen to preserve the desirable characteristics of each parent. Compared to the random parameter combination used in the basic genetic algorithm, this 'genetic engineering' algorithm resulted in a much more rapid increase in the solution count values with successive iterations.

The performance of the two algorithms is compared in Figure 3. The distribution of solution counts for the vectors produced using each algorithm is summarized as a function of iteration. After 5 iterations, the largest solution count value produced by the basic genetic algorithm was 92 out of 105 sources. In addition, the rate of increase of the maximum solution count was discouragingly slow given that a solution to Equation 3.8 requires a solution count of 105. In contrast, the genetic engineering algorithm produced 63 vectors with a solution count of 105 after only three iterations.

Ranking Identified Solutions

Equation 3.8, if it has a solution, will in general be solved anywhere in some subdomain of the sample parameter space. If the procedure described above produces multiple solution vectors, additional criteria can be used to rank the solutions as potential default parameter values.

With respect to inversion probability, P_{crit} defines an upper limit, but the actual inversion probability associated with a solution may be much smaller than this limit, as discussed in Section 3.4. Individual source probabilities are not available, so that the inversion probability strictly cannot be calculated using Equation 3.2. The range (over the various source constraints) of conditional inversion probabilities *can* be calculated from Equation 3.3 however, and may be used to discriminate among solution vectors. For a given value of P_{crit}, solutions that tend to have small values of the conditional inversion probability will generally have parameter values that are more 'extreme' than solutions that tend to have large values, (assuming the model is monotonic)[1]. The average inversion probability (AIP) over all sources was used to evaluate alternative solution vectors.

With respect to the parameter values themselves, default values that are generally closer to the center of their distributions may be preferred to values near the tail of their distributions. The probability of obtaining a parameter value 'beyond' the potential default value is an intuitive measure of the reasonableness of the default value. For each parameter in the solution vector,

[1]Solutions that *consistently* have small values of conditional inversion probability are of course also solutions for smaller values of P_{crit}.

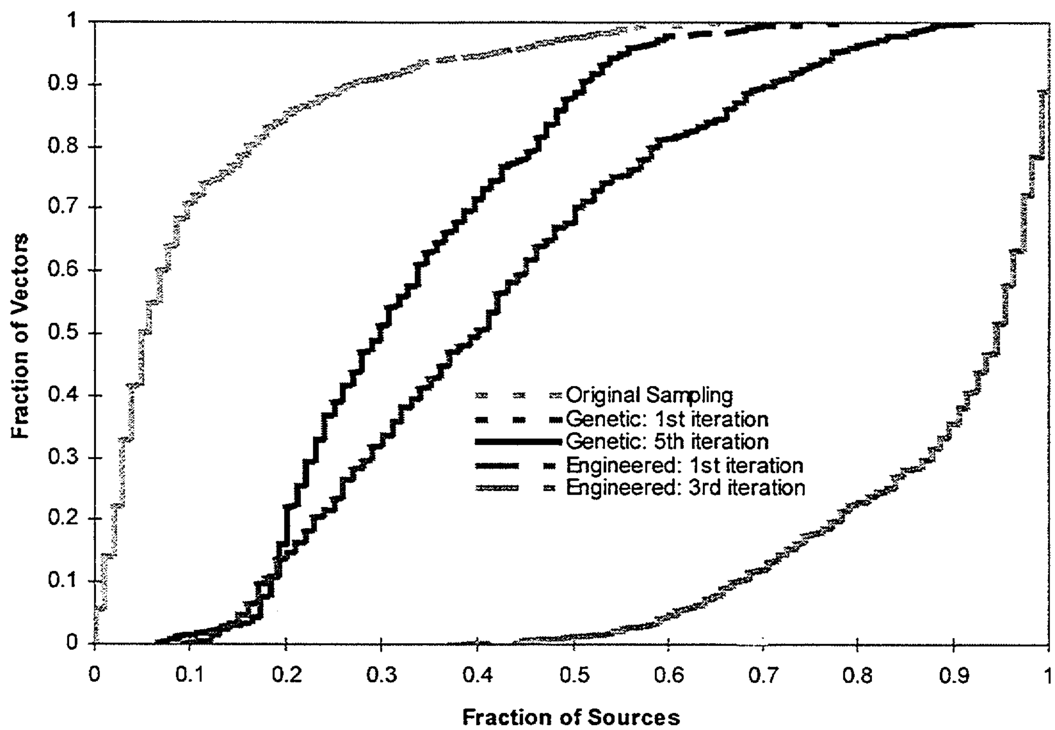

Figure 3 Solution count distributions (SCDs) for sample vector sets generated using the basic genetic and genetic engineering algorithms

the probability of obtaining a more extreme site specific value was calculated using the input parameter distributions. A 'more extreme' value is a larger value for defaults above the median, or a smaller value for defaults below the median. The product of these probabilities over all parameters, called the joint parameter exceedance probability (JPEP), was used as a second measure of reasonableness in evaluating alternative solution vectors. Other global measures might be considered, such as the minimum exceedance probability over all parameters, or the minimum conditional inversion probability over all sources.

Note that it is also possible to incorporate ranking functions into the solution search procedure. The analytical problem is then to maximize the value of the ranking function subject to the constraints defined by the simultaneous inequalities of Equation 3.8, rather than to simply find a combination of parameters that solves these inequalities. It is also possible to use ranking function values, along with solution count values, to control parent selection in the genetic (engineering) algorithm. This approach would require combining, in some way, an absolute requirement based on solution count with a continuous requirement based on the ranking function, and was not explained.

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-5512, Volume 3

2. TITLE AND SUBTITLE

Residual Radioactive Contamination From Decommissioning
Parameter Analysis
Draft for Comment

3. DATE REPORT PUBLISHED

MONTH	YEAR
October	1999

4. FIN OR GRANT NUMBER

W6227

5. AUTHOR(S)

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6. TYPE OF REPORT

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Sandia National Laboratories, P.O. Box 5800, MS 1345, Albuquerque, NM 87185

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555 -0001

10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

NUREG/CR-5512 is a multi-volume report describing a generic model which estimates potential radiation dose from exposure to residual radioactive contamination after the decommissioning of facilities licensed by the U.S. Nuclear Regulatory Commission. Individual volumes describe the generic scenarios, models, and parameter values for screening calculations, and the software that implements these calculations. This third volume describes the analysis used to define default parameter values for the Building Occupancy and Residential scenarios and the results of that analysis. Screening calculations are designed to support dose-based decisions without requiring information about specific site conditions. The range of conditions that might exist at licensed sites was used to develop distributions describing the variability in site-specific parameter values. These distributions were then used to derive distributions of potential dose values for unit concentrations of individual source radionuclides. Parameter values were then identified which produce dose values in the upper quantiles of the distributions for all source radionuclides. The resulting parameter values define a generic screening calculation that has a limited risk of underestimating a site-specific dose calculation based on the generic scenarios, models, and screening group. The distributions that underlie these parameter values provide a basis for developing site-specific parameter values.

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

Decommission
Decontamination
License Termination
software
DandD
screening
dose assessment

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)
unclassified

(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)

Printed on recycled paper

Federal Recycling Program

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001