ABSTRACT

LING, XIANBING. Bayesian Analysis for the Site-Specific Dose Modeling in Nuclear Power Plant Decommissioning (Under the direction of Man-Sung Yim.)

Decommissioning is the process of closing down a facility. In nuclear power plant decommissioning, it must be determined that that any remaining radioactivity at a decommissioned site will not pose unacceptable risk to any member of the public after the release of the site. This is demonstrated by the use of predictive computer models for dose assessment.

The objective of this thesis is to demonstrate the methodologies of site-specific dose assessment with the use of Bayesian analysis for nuclear power plant decommissioning. An actual decommissioning plant site is used as a test case for the analyses. A residential farmer scenario was used in the analysis with the two of the most common computer codes for dose assessment, i.e., DandD and RESRAD.

By identifying key radionuclides and parameters of importance in dose assessment for the site conceptual model, available data on these parameters was identified (as prior information) from the existing default input data from the computer codes or the national database. The site-specific data were developed using the results of field investigations at the site, historical records at the site, regional database, and the relevant information from the literature. This new data were compared to the prior information with respect to their impacts on

both deterministic and probabilistic dose assessment. Then, the two sets of information were combined by using the method of conjugate-pair for Bayesian updating.

Value of information (VOI) analysis was also performed based on the results of dose assessment for different radionuclides and parameters. The results of VOI analysis indicated that the value of site-specific information was very low regarding the decision on site release. This observation was held for both of the computer codes used. Although the value of new information was very low with regards to the decisions on site release, it was also found that the use of site-specific information is very important for the reduction of the predicted dose. This would be particularly true with the DandD code.

BAYESIAN ANALYSIS FOR THE SITE-SPECIFIC DOSE MODELING IN NUCLEAR POWER PLANT DECOMMISSIONING

by

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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

NUCLEAR ENGINEERING

Raleigh

2001

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BIOGRAPHY

Xianbing Ling was born on September 9, 1972 in Yixing, Jiangsu Province, the People's Republic of China. After he finished his elementary school and high school educations in his hometown, he was enrolled at Shanghai Jiao Tong University during the academic year from 1990 to 1994, with a major in Nuclear Reactor Engineering. He was granted the Bachelor of Science Degree in Nuclear Reactor Engineering in July 1994. After then, he entered the Graduate School at Shanghai Jiao Tong University for advanced education in the field of Nuclear Engineering. In March 1997 he received Master of Science degree.

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ACKNOWLEDGEMENTS

I would like to express my deep gratitude and appreciation to the faculty and staffs of the Department of Nuclear Engineering at North Carolina State University for providing me with a good opportunity to pursue advanced and qualified education in Nuclear Engineering. I would like to express my special thanks to Dr. Man-Sung Yim. Without his advices, guidance, and supports, I could not have attained so much progress in my graduate study. At this moment, I even cannot find a word to express how grateful I am for his efforts to help me till the last minute of my thesis work. Thank him for his invaluable teaching. Special thanks are also extended to Dr. K. Verghese and Dr. D. S. Reeves for their careful suggestions and comments on my thesis.

Please let me take the opportunity to express sincere thanks to my friends during my study in the Department of Nuclear Engineering at North Carolina State University. They are Wei Lu, Jing Sun, Qunlei Jiang, Jun Li, et al. I cherish the time we have spent together. When some sudden joys or unexplainable bad moods come sometimes, I could always find one of you to share or tell. You make my life here unforgettable.

At this moment, I hope my parents, although far away in China, could share the feelings with me. I am really proud of you, I am really proud to be your son.

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Bayesian Analysis for the Site-Specific Dose Modeling in Nuclear Power Plant Decommissioning

1. Introduction

1.1 Environmental Decision Making in Nuclear Power Plant Decommissioning

Decommissioning is the process of closing down a facility. For a nuclear facility, it means to remove a facility or site safely from service and reduce residual radioactivity to a level that permits: (a) release of the property for unrestricted use and termination of the license; or (b) release of the property under restricted conditions and termination of the license. Currently several nuclear power plants in the United States are in the decommissioning phase [NRC Website, 2001].

One of the essential issues in nuclear power plant decommissioning is to ensure that any remaining radioactivity at a decommissioned site should not pose unacceptable risk to any member of the public after the release of the site. Based on the consideration of acceptable risk, the levels of allowable residual contamination should be determined and the site must be cleaned accordingly [Beyeler, W.E., and Davis, P.A., et al., 1996]. The safety and cost of a decommissioning project will be controlled predominately by this allowable residual contamination level.

Due to the enormous practical difficulties in experimenting with field situations, determination of allowable residual contamination is possible only through predictive analysis (hereafter called “dose assessments”). Dose assessment uses mathematical/computational models as the conceptualization of the actual field situations and estimates the dose from the remaining source of radiation to any potentially exposed individual through various pathways after the release of the site. The principal components of the dose assessments are: (a) models for source term, transport of radionuclides through the environment to a receptor, exposure pathways, and human dose calculation, and (b) the parameters used in those models. As in the case of most

predictive analyses, uncertainty is present in almost every aspect of dose assessment including the conceptualization of the site, assumptions on human exposure pathways, implementation of mathematical models, and development of data for model parameters [Beyeler, W.E., and Brown, T.J., et al., 1998][Kamboj, S., and LePoire, D., et al., 2000]. This uncertainty can be very large depending upon the amount of effort given to the characterization of site and related parameters. Decisions on the required site-cleanup efforts or the acceptance of the residual risk at the site must be made in the light of the uncertainties in the predictive analysis. This renders the problem a classic example of a risk-based decision making problem or an environmental risk management problem. Therefore, analysis of the problem requires a systematic decision analysis framework along with the use of dose assessment methodologies.

The characterization of uncertainty is critical in the application of predictive models to risk-based decision making in nuclear power plant decommissioning. Uncertainties arise due to (i) the limited scientific understanding of important processes; (ii) the inadequacy of mathematical representations which require simplifications of physical processes and their temporal and spatial aggregation; and (iii) the limited ability to measure model parameters and inputs. A systematic analysis of these uncertainties is needed to determine their impact on model predictions and decisions that might be based upon these predictions.

1.2 U.S. NRC's Regulations and Approaches to Dose Assessment

From a regulatory compliance perspective, an essential step required in successful decommissioning is to demonstrate that levels of residual contamination will not exceed the dose limit specified by the government regulations. In 1997, the U.S. Nuclear Regulatory Commission (NRC) published in the Federal Register a final rule incorporating a new Subpart E into 10 CFR Part 20 that includes radiological criteria for license termination. The regulation, as given in Subpart E, 10 CFR 20.1402, "Radiological Criteria for Unrestricted Use", states that a site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from

background radiation results in a Total Effective Dose Equivalent (TEDE) to an average member of the critical group does not exceed 25 mrem (0.25 mSv) per year, including that from groundwater sources of drinking water, and the residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA) [NRC Website-CFR, 2001].

If the dose assessment for a given site determines that the residual radioactivity will result in a dose greater than the regulatory limit, measures must be taken to reduce or remove the radioactivity from the contaminated radioactive material. These measures could include: (a) removing the source material; (b) treating the material to reduce the contamination, (c) letting the material radioactively decay away, or (d) covering the contamination to shield or attenuate the radiation emitted.

Dose assessment relies on the efforts of site characterization and the tools for modeling and analysis. In dose assessments, a reasonable treatment of uncertainty is needed to provide the regulator with the confidence that the actions taken and the decision made to terminate the facility license are consistent with the regulations.

The NRC's hierarchy of dose assessment modeling is shown in Figure 1.1 [Kennedy, W.E., Jr., and Strenge, D.L., 1992].

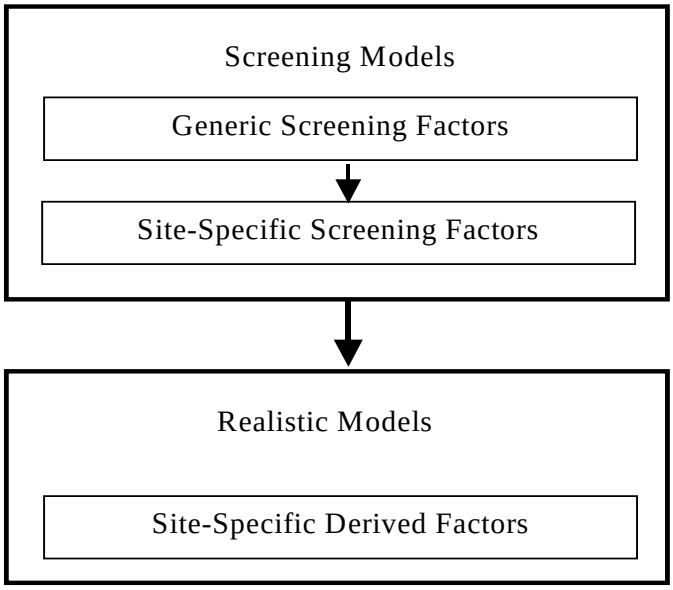

Figure 1.1 NRC's Hierarchy of Dose Assessment Modeling Approaches (NUREG/CR-5512)

During the development of the dose assessment approach, models, scenarios, and parameters should be defined which were expected to be “reasonably conservative”. The models and scenarios are specifically defined such that they would not be “bounding” or unrealistic, while still generally overestimating rather than underestimating potential dose. The model parameters in dose modeling are also evaluated to exclude bounding or unrealistic assumptions. The purpose is two-fold: first, to provide a basis for screening; second, to provide information for more complex decommissioning situations where a clear understanding of the modeling assumptions and construction of the parameters is needed to support changes that lead to more realistic dose assessments. To capture the dose to a critical group, NRC developed a set of exposure scenarios that should serve as conservative representations of a multitude of possible exposure scenarios to humans. These include industrial occupancy, renovation, residential farmer, and drinking water. The purposes and the specific models among those scenarios are different for dose assessment.

The NRC methodology is based on the premise that screening dose assessments are performed with little site-specific information [Kennedy, W.E., Jr., and Strenge, D.L., 1992]. The screening would comply with more restrictive criteria, but would do so based on a decision to not expend resources for a more realistic dose estimate, and would have high assurance that the criteria would be met. However, for more complex situations or more realistic analyses, the methodology ensures that as more site-specific information is incorporated, the uncertainty is reduced and the estimate of the resulting dose generally decreases. This provide assurance that obtaining additional site-specific information is worthwhile because it ensures that a more “realistic” dose assessment will not generally result in a dose higher than that estimated using screening.

The NRC’s dose assessment approach is based on a philosophy of moving from simple, prudently conservative calculations toward more realistic simulations, as necessary. This modeling is part of a process that includes three increasingly detailed methods for calculating screening model dose conversion factors (DCFs) for evaluating exposure to residual radioactivity in soil and structures. Level 1 screening uses very

simple assumptions and default models and parameter values that are intended to be prudently, but not excessively, conservative. Level 1 calculations are intended to produce generic dose estimates that are unlikely to be exceeded at real sites. Level 2 screening allows users to adjust certain parameters and eliminate pathways to more closely approximate conditions at their particular site. Level 3 modeling is based on site-specific models and data and is beyond the scope of the screening methodology. The methodology is designed so that conservatism is reduced and the resulting dose decreases as the process moves from one level to the next upper level. For a Level 1 analysis, site-specific source-term data is used with the default models and parameters. A Level 2 analysis implements the default models with site-specific source-term and parameter data. For a Level 3 analysis, site-specific models are developed and implemented with site-specific source-term and parameter data.

Computer codes used in these efforts include DandD and RESRAD [Yu, C., and Zielen, A.J., et al., 1993][Yim, M.S., 1999]. Sandia National Laboratory developed the DandD computer code. DandD provides a structured interface that allows users to apply screening models to estimate doses under four distinct exposure scenarios: industrial occupancy, renovation, residential farmer, and drinking water. Default parameters were selected based on a rigorous analysis such that defensible screening calculations can be made using information about the source. RESRAD was developed by Argonne National Laboratories in the late 80s, and has been widely used by the Department of Energy (DOE), Environmental Protection Agency (EPA), and the nuclear power industry to estimate doses from residual radioactive material and set site-specific clean modeling platforms, but they are not specifically organized for implementation of the four exposure scenarios given in NUREG/CR-5512 [NRC Report, 1998]. Previous version of RESRAD is also a deterministic code used to perform dose analysis. RESRAD new version, version 6.0, was released in August 2000 for the probabilistic dose analysis by using parameter distributions incorporated in RESRAD code.

Even though they were developed for similar purposes, the results of these computer models vary significantly. These differences are due to differences in the mathematical models used and the supporting parameters as well as their values.

1.3 U.S. NRC's Decision Framework for Plant Decommissioning

A logical, consistent decision process is viewed as a useful tool by the NRC that will support the planning of decommissioning activities and regulatory review of license termination requests along with the use of dose assessment. To support this process, a decision methodology, or framework, is used to support implementation of the dose assessment requirements [NRC Draft NUREG 1549, 1998][NRC NMSS Decommissioning SRP, Appendix C, 2000].

The steps and decision points of the decision framework support assessment of the entire range of dose modeling options from which a licensee may choose, whether it involves using generic screening parameters, changing parameters, or modifying pathways or models. The decision framework, including its steps and decision points, is discussed in this section.

To facilitate the preparation and evaluation of the dose assessments, a phased approach to decision-making for license termination was adopted because of the very wide range of levels of contamination and complexity of analysis and potential remediation necessary at NRC-licensed sites. The phased approach consists of generic screening analysis and of making use of site-specific information as appropriate. Is it worthwhile putting resources to reduce the source level according to the results of generic screening or spend some more efforts to seek site-specific information for more realistic dose analysis? By using decision framework, the risk management decision can be best described and made. These phases are described in broad terms below:

(a) Generic Screening: In this phase, licensees would demonstrate compliance with the dose criteria of the rule by using: (i) pre-defined models, and (ii) generic screening parameters.

Pre-defined models which use generic exposure scenarios and pathways are based on the NUREG/CR-5512, Volume 1, methodology and can be used with minimal justification by licensees who are applying generic screening scenarios and parameters using the DandD software. The generic scenarios and pathways of the pre-defined models

provide the licensee with a simple method to demonstrate compliance using little site-specific information.

The pre-defined models and generic screening parameter distributions are used to calculate a reasonably conservative range of doses that the average member of the screening group could receive. This information was used to develop default deterministic parameters for the DandD model.

(b) Use of Site-Specific Information as Appropriate: if compliance cannot be demonstrated using generic screening analysis, then licensees should proceed to the next phase of analysis in which defensible site specific values are obtained and applied. Examples of site-specific features that may require modeling beyond the defaults include (but are not limited to) known groundwater contamination, large quantities of contamination material (such as slag piles), or buried wastes. Depending on the complexity of the site contamination, the licensee can use site-specific:

(i) By replacing generic screening parameters with site-specific parameter values to allow site-specific factors to be taken into account. Thus, the dose estimates would be more realistic. The models can be pre-defined models. Or

(ii) By using site-specific model assumptions;

(iii) By using some combination of a and b and also remedying the site;

(iv) By using some combination of a, b, and c, and also restricting use of the site.

In any of the cases (i) – (iv), site-specific data are used to support modifying or eliminating a particular scenario or pathway, or to demonstrate that a parameter or group of parameters can be better represented by site-specific values. Alternative exposure scenarios may be appropriate based on site-specific factors that affect the likelihood and extent of potential future exposure to residual radioactivity. Thus use of dose assessment for these situations can range from fairly simple site assessments to fairly complex analyses.

The following general concepts apply to using the phased approach with the decision framework. The approach provides a process for screening sites and for directing additional data collection efforts where necessary.

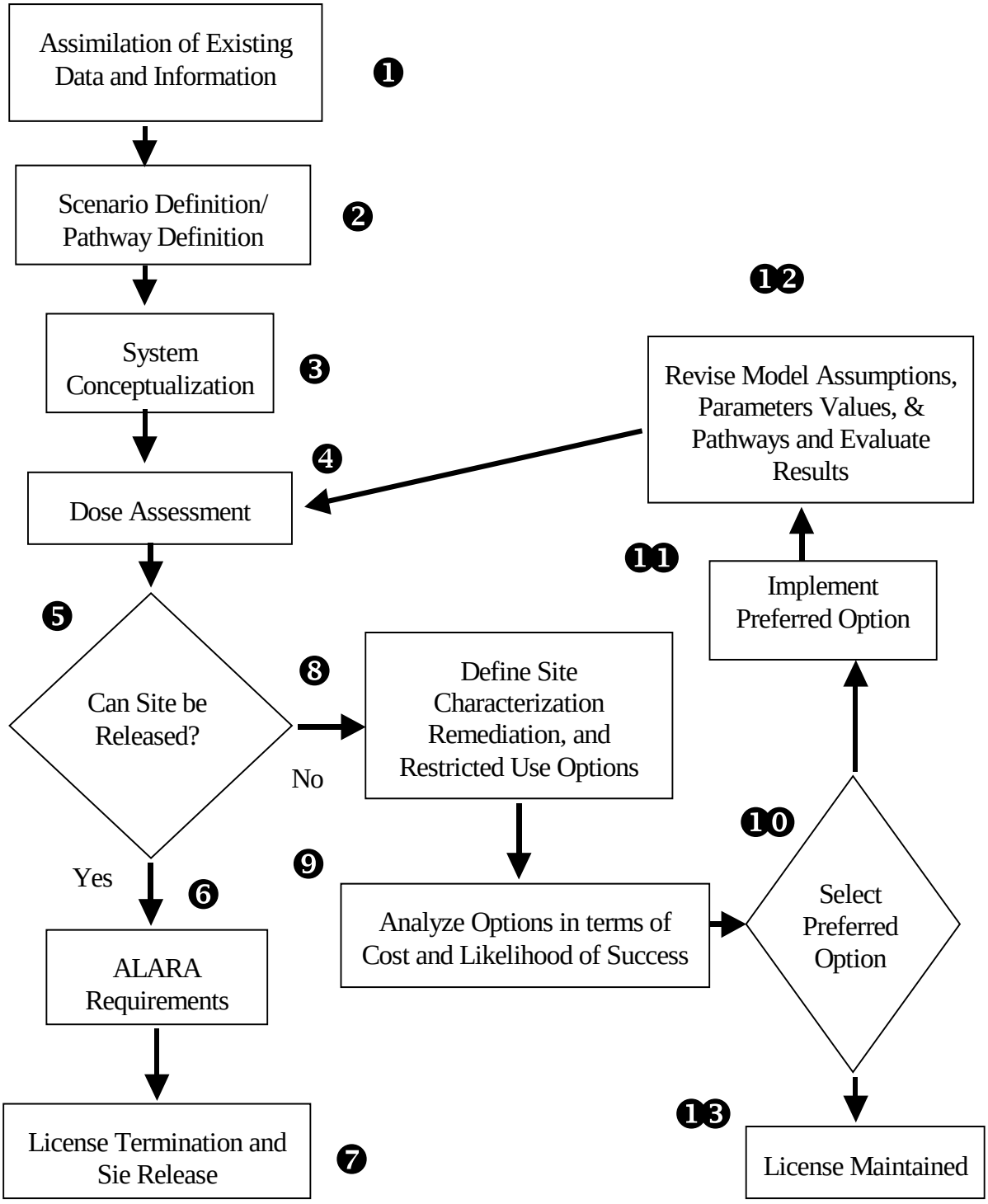

Figure 1.2 Decommissioning and license termination framework

The framework is designed such that the level of complexity and rigor of analysis conducted for a given site should be commensurate with the level of risk that the site poses. Although use of the framework would normally encompass steps 1 through 5, and steps 6 and 7, the amount of work that goes into each of these steps should be based on the expected levels of contamination and the health risks they pose. Note that in this framework, all sites may start at the same level of very simple analyses (not a requirement for successful implementation), but it is expected that only certain sites would progress to very complex dose assessment and options analyses. Some sites may not need to conduct any options analyses (step 8) and some sites may need to evaluate a limited set of relatively simple and inexpensive options. For example, a site with a source of contamination that is obviously simple to remove would not spend time analyzing large suites of alternative data collection and remediation options. On the other hand, a site with high levels of contamination that are widely distributed may use his process to analyze a variety of simple and complex options to define the best decontamination and decommissioning strategy. Thus, the approach ensures that efforts and expenses would be commensurate with the level of risk posed by the site.

The decision framework, described in NUREG-1549, is illustrated in Figure 1.2. The framework can be used throughout the decommissioning and license termination process for sites ranging from the more simple sites to the most complex or contaminated sites.

Step 1: The first step in a dose assessment involves gathering and evaluating existing data and information about the site, including the nature and extent of contamination at the site. Often, minimal information is all that is needed for initial screening analyses. Specifically, information is needed to support the decision that the site is simple and is qualified for screening analysis. However, all information about the site that is readily available should be used. This step also includes definition of the performance objectives that must be met in order to demonstrate compliance with decommissioning criteria.

Step 2: This step involves defining the scenarios and pathways that are important and relevant for the site dose assessment. For all assessments using DandD,

the NRC has already defined the generic scenarios and pathways for screening. For site-specific analysis mode, DandD and RESRAD/RESRAD-BUILD codes may be used, in addition to other codes. These codes should allow the user to both select, and deselect, exposure pathways if certain pathways are not considered relevant due to site conditions.

Step 3: Once scenarios are defined and exposure pathways identified, a basic conceptual understanding of the system is developed, often based on simplifying assumptions regarding the nature and behavior of the natural systems. System conceptualization includes conceptual and mathematical model development and assessment of parameter uncertainty. Using DandD for generic screening, the NRC has pre-defined conceptual models for the scenarios along with default parameter distribution. For site-specific analysis the DandD and/or RESRAD/RESRAD BUILD conceptual model can be used after verification that the actual site conceptual model is compatible with the conceptual model of the code used.

Step 4: This step involves the dose assessment or consequence analysis, based on the defined scenarios, exposure pathways, models, and parameters distributions. For generic screening, reviewers can accept look-up table and use the generic models and default parameter probabilistic density functions (PDFs), simply by running DandD with the appropriate site-specific source term, leaving all other information in the software unchanged. Site-specific assessments allow the user to use other codes and change pathways and parameter distributions based on data and information obtained from the site.

Step 5: This is the first major decision point in the license termination decision process and involves answering the question of whether the dose assessment results from step 4 demonstrate compliance with the dose criteria in 10 CFR Part 20, Subpart E. NRC establishes the confidence required when interpreting the results from the probabilistic dose assessment. For instance, for screening analysis, licensees may need to demonstrate that the 90^{th}

percentile value of dose is less than 25 mrem/yr. If the results are below the limit, the licensee proceeds with step 6 and 7 to demonstrate ALARA requirements and initiate the license termination process defined by NRC in other guidance documents.

If the results are ambiguous or they clearly exceed the performance objective, proceed to step 8 and 9.

Step 8: Full application of the decision framework involves defining all possible options the licensee might address in order to defend a final set of actions needed to demonstrate compliance with license termination criteria. Options may include acquiring more data and information about the site and source of contamination in order to reduce uncertainty about the pathways, models, and parameters and thus reduce the calculated dose; reducing actual contamination through remediation actions; reducing exposure to radionuclides through implementation for land-use restrictions; or some combination of these options.

Step 9: All of the options identified in step 8 are analyzed and compared in order to optimize selection of a preferred set of option to go forward with. This options analysis may consider cost of implementation, likelihood of success (and the expected costs associated with success or failure to achieve the desired results when the option is implemented), timing considerations and constraints, and potentially other quantitative and/or qualitative selection criteria.

Step 10: The activities in step 8 and 9 provide information for the licensee to choose the preferred options based on considerations of cost, likelihood of success, timeliness, and other considerations. Based on the results of the DandD and RESRAD/RESRAD Build sensitivity analysis, for example, a licensee may identify one or more parameters that may be modified based on acquisition of site-specific information and data. If new data can reduce the uncertainty associated with sensitive parameters, the licensee may be able to defend a new calculated dose that meets the license termination criteria. If no viable

options exist at this time, the licensee may decide to defer actions at this site (step 13) until circumstances allow re-visiting license termination actions.

Step 11: Under step 11, the preferred option is implemented. The licensee commits resources to obtain the information necessary to support revisions to the parameters identified in step 8 and 9.

Step 12: Once data are successfully obtained, the affected parameters for the pre-defined models are revised as appropriate. Also, data may support elimination of one or more of the exposure pathways in the pre-defined scenarios. Once the pathways and parameters are revised, the user would re-visit steps 4 and 5 to determine the impact of the revisions on demonstrating compliance with the performance objectives. If met, the user proceeds to steps 6 and 7. If the performance objective is still exceeded, the assessor returns to steps 8 and 9 to analyze remaining options to proceed.

1.4 Objectives and Organization of the Thesis

Although the NRC's approach provides the conceptual framework for the use of dose assessment, actual use of site-specific dose assessment requires deeper understanding of the problem, dose assessment, the data collection efforts, and their relationships.

The objective of this thesis is to demonstrate the methodologies of site-specific dose assessment for nuclear power plant decommissioning with the use of Bayesian analysis. An actual decommissioning plant site is used as a test case for the analyses. More specific objectives are:

(1) To identify key parameters of importance in site-specific dose assessment as the focus of site-specific data collection efforts.

(2) To demonstrate the development of site-specific data for important parameters of dose assessment.

(3) To demonstrate the use of site-specific data along with the existing information with Bayesian approach based on the characterization of uncertainties of major parameters in dose assessment.

(4) To demonstrate the usefulness of site-specific data in both deterministic and probabilistic dose assessment.

(5) To demonstrate the methodology of Value of Information (VOI) Analysis and to examine the usefulness of the approach in the site-specific dose assessment for nuclear power plant decommissioning.

(6) To examine the importance of addressing the uncertainty in the definition of likelihood function for the Bayesian VOI analysis.

Only the residential farmer scenario was used in the analyses given that the residual contamination was in the surface soil. Both the DandD and RESRAD computer codes were used for the analyses in this thesis.

The organization of this thesis is as follows: Chapter 2 describes the basic theory of Bayesian updating and the methods used in parameter updating. Some definitions and theories applied for value of information and reliability analysis are also presented.

Chapter 3 concentrates on the collection and analysis of input parameters for the DandD and RESRAD codes. The first section of this chapter discusses the key parameters in nuclear power plant decommissioning dose assessment. Then the default inputs for both codes are discussed. The data analysis in this chapter is to provide the prior information required by the Bayesian updating in Chapter 4.

Chapter 4 describes the development of site-specific data for major parameters in dose assessment by using various sources of information, the results of Bayesian updating, the application of the value of information analysis and its results. The issue of the selection of likelihood function in the Bayesian updating is also discussed.

Some conclusions and recommendations are summarized in chapter 5.

2. Bayesian Analysis for Site-Specific Dose Modeling

Accurate estimates of parameters require large amounts of data. When the observed data are limited, as is often the case in engineering, the statistical estimates have to be supplemented (or may even be superseded) by judgmental information. With the classical statistical approach there is no provision for combing judgmental information with observational data in the estimation of the parameters.

The Bayesian method approaches the estimation problem from another point of view [Ang, A. H-S, and Tang, W. H., 1975]. In this case, the unknown parameters of a distribution are assumed (or modeled) to be also random variables. In this way, uncertainty associated with the estimation of the parameters can be combined formally (through Bayes' theorem) with the inherent variability of the basic random variable. With this approach, subjective judgments based on intuition, experience, or indirect information are incorporated systematically with observed data to obtain a balanced estimation. The Bayesian method is particularly helpful in cases where there is a strong basis for such judgments. The basic concepts of the Bayesian approach are discussed in the following sections [Patwardhan, A., and Small, M. J., 1992][Small, M. J., 1997].

2.1 Bayesian Analysis

2.1.1 Discrete Case

The Bayesian approach has special significance to engineering design, where available information is invariably limited and subjective judgment is often necessary. In the case of parameter estimation, the engineer often has some knowledge (perhaps inferred intuitively from experience) of the possible values, of a parameter; moreover, he may also have some intuitive judgment on the values that are more likely to occur than others. For simplicity, suppose that the possible values of a parameter θ were assumed to be a set of discrete values θ_i, i = 1, 2, …, n, with relative likelihood (Probability Mass Function-PMF) $p_i = P(\Theta = \theta_i)$ as illustrated in Figure 2.1 (Θ is random variable whose values represent possible values of the parameter θ).

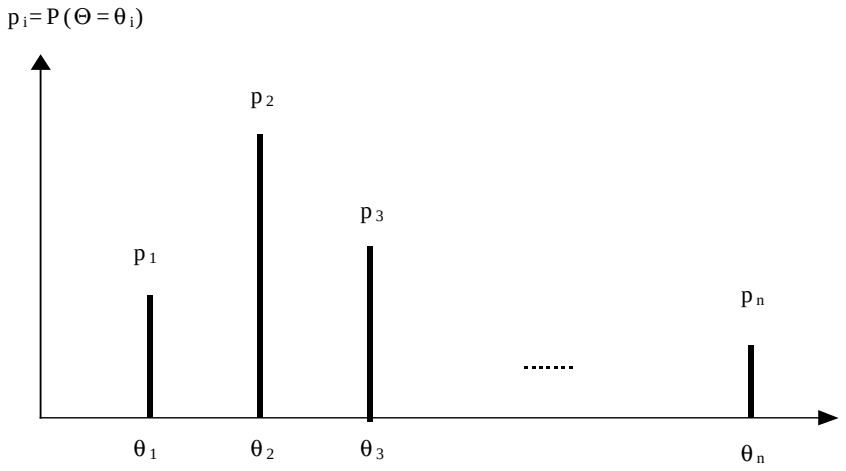

Figure 2.1 Prior PMF of parameter θ

Then if additional information becomes available (such as the results of a series of tests or experiments), the prior assumptions on the parameter θ may be modified formally through Bayes' theorem as follows.

Let ε denote the observed outcome of the experiment. Then applying Bayes' theorem, we obtain the updated PMF for θ as

$$P(\Theta = \theta_i \mid \varepsilon) = \frac{P(\varepsilon \mid \Theta = \theta_i)P(\Theta = \theta_i)}{\sum_{i=1}^{n} P(\varepsilon \mid \Theta = \theta_i)P(\Theta = \theta_i)} \qquad i = 1,2,...,n \qquad (2.1)$$

The various terms in Eq. 2.1 can be interpreted as follows:

$P(\varepsilon \mid \Theta = \theta_i)$ = the likelihood of the experimental outcome ε if $\Theta = \theta_i$; that is, the conditional probability of obtaining a particular experimental outcome assuming that the parameter is θ_i.

$P(\Theta = \theta_i)$ = the prior probability of $\Theta = \theta_i$; that is, prior to the availability of the experimental information ε

$P(\Theta = \theta_i \mid \varepsilon)$ = the posterior probability of $\Theta = \theta_i$; that is, the probability that has been revised in the light of the experimental outcome ε

Denoting the prior and posterior probabilities as $P'(\Theta = \theta_i)$ and $P''(\Theta = \theta_i)$, respectively, Eq. 2.1 becomes

$$P''(\Theta = \theta_i) = \frac{P(\varepsilon \mid \Theta = \theta_i) P'(\Theta = \theta_i)}{\sum_{i=1}^{n} P(\varepsilon \mid \Theta = \theta_i) P'(\Theta = \theta_i)} \tag{2.1a}$$

Eq. 2.1a, therefore, gives the posterior probability mass function of Θ.

The expected value of Θ is then commonly used as the Bayesian estimator of the parameter; that is,

$$\hat{\theta}'' = E(\Theta \mid \varepsilon) = \sum_{i=1}^{n} \theta_i P''(\Theta = \theta_i) \tag{2.2}$$

We may point out that in Eq. 2.2 observational data and judgmental information are both used and combined in a systematic way to estimate the underlying parameter.

In the Bayesian framework, the significance of judgmental information is reflected also in the calculation of relevant probabilities. In the case above, where subjective judgments were used in the estimation of the parameter θ, such judgments would be reflected in the calculation of the probability, for example, P(X ≤ a), through the theorem of total probability using the posterior PMF of Eq. 2.1a. That is,

$$P(X \le a) = \sum_{i=1}^{n} P(X \le a \mid \Theta = \theta_i) P''(\Theta = \theta_i) \tag{2.3}$$

This represents the up-to-date probability of the event (X ≤ a) based on all available information. It may be emphasized that in Eq. 2.3 the uncertainty associated with the error of estimating the parameter (as reflected in $P''(\Theta = \theta_i)$) is combined with the inherent variability of the random variable X.

2.1.2 Continuous Case

In the above section the possible values of the parameter θ were limited to a discrete set of values; this was purposely assumed to simplify the presentation of the concepts underlying the Bayesian method of estimation. In many situations, however, the value of a parameter could be in a continuum of possible values. Thence, it would be appropriate

to assume the parameter to be a continuous random variable in the Bayesian estimation. In this case we develop the corresponding results, analogous Eqs. 2.1 through 2.3, as follows:

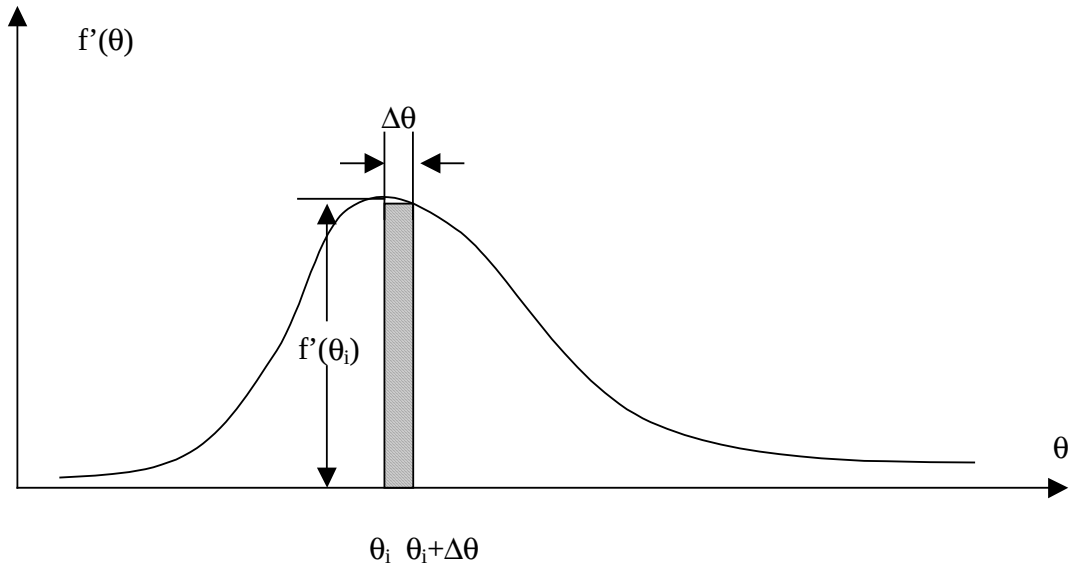

Figure 2.2 Continuous prior distribution of parameter θ

Let Θ be the random variable for the parameter of a distribution, with a prior density function $f'(\theta)$ shown in Figure 2.2. The prior probability that θ will be between θ_i and $\theta_i+\Delta\theta$ then is $f'(\theta_i)\Delta\theta$. Then, if ε is an observed experimental outcome, the prior distribution $f'(\theta)$ can be revised in the light of ε using Bayes' theorem, obtaining the posterior probability that θ will be in $(\theta_i, \theta_i+\Delta\theta)$ as

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

where $P(\varepsilon|\theta_i) = P(\varepsilon|\theta_i < \theta < \theta_i + \Delta\theta)$. In the limit, this yields

$$f''(\theta) = \frac{P(\varepsilon|\theta) f'(\theta)}{\int_{-\infty}^{\infty} P(\varepsilon|\theta) f'(\theta) d\theta} \tag{2.4}$$

The term $P(\varepsilon|\theta)$ is the conditional probability or likelihood of observing the experimental outcome ε assuming that the value of the parameter is θ. Hence $P(\varepsilon|\theta)$ is a function of θ and is commonly referred to as the likelihood function of θ and denoted L(θ). The denominator is independent of θ; this is simply a normalizing constant required to make $f''(\theta)$ a proper density function. Eq. 2.4 then can be expressed as

$$f''(\theta) = kL(\theta) f'(\theta) \tag{2.5}$$

where the normalizing constant $k = [\int_{-\infty}^{\infty} P(\varepsilon|\theta) f'(\theta) d\theta]^{-1}$; and L(θ) = the likelihood of observing the experimental outcome ε assuming a given θ.

We observe from Eq. 2.5 that both the prior distribution and the likelihood function contribute to the posterior distribution of θ. In this way, as in the discrete case, the significance of judgment and of observational data are combined properly and systematically; the former through $f'(\theta)$ and the latter in L(θ).

Analogous to the discrete case, Eq. 2.2, the expected value of θ is commonly used as the point estimator of the parameter. Hence the updated estimate of the parameter θ, in the light of observational data ε, is given by

$$\hat{\theta}'' = E(\theta|\varepsilon) = \int_{-\infty}^{\infty} \theta f''(\theta) d\theta \tag{2.6}$$

The uncertainty in the estimation of the parameter can be included in the calculation of the probability associated with a value of the underlying random variable. For example, if X is a random variable

$$P(X \le a) = \int_{-\infty}^{\infty} P(X \le a|\theta) f''(\theta) d\theta \tag{2.7}$$

Physically, Eq. 2.7 is the average probability of (X≤a) weighted by the posterior probabilities of the parameter θ.

2.2 Combining Information – Bayesian Updating

Combining information is necessary and important in site-specific dose assessment for nuclear power plant decommissioning. As new pieces of information become available through site investigations, the new data should be properly combined with the prior-existing body of knowledge to improve the dose assessment. Bayesian updating is very useful for this purpose. This section discusses different ways of combining information within the Bayesian analysis framework [Ang, A. H-S, and Tang, W. H., 1975].

2.2.1 Combining with Conjugate Pair

This is an ideal case for Bayesian updating. It assumes that the site-specific information are all obtained with same or similar approaches as the national data (prior information) do. Then the site-specific information can be used to update the prior information with Bayesian method. This case in fact simply assumes the distribution of site-specific information as the likelihood function. It's a simple combination of two known PDFs into one posterior PDF. For normal/lognormal distributed prior, likelihood functions, there are analytical results for the posterior distribution with those conjugate distributions. As for normal pairs, the posterior is normal, its statistical parameters μ'' and σ'' are:

$$\text{Mean: } \mu'' = \frac{\mu' \cdot \sigma^2 + \mu \cdot \sigma'^2}{\sigma^2 + \sigma'^2} \tag{2.8}$$

$$\text{Standard deviation: } \sigma'' = \sqrt{\frac{\sigma^2 \cdot \sigma'^2}{\sigma^2 + \sigma'^2}} \tag{2.9}$$

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

Mean (after logarithmic transform):

$$\mu_{\ln}'' = \frac{\mu_{\ln}' \cdot \sigma_{\ln}^2 + \mu_{\ln} \cdot \sigma_{\ln}'^2}{\sigma_{\ln}^2 + \sigma_{\ln}'^2} \tag{2.10}$$

Standard deviation (after logarithmic transform):

$$\sigma_{\ln}'' = \sqrt{\frac{\sigma_{\ln}^2 \cdot \sigma_{\ln}'^2}{\sigma_{\ln}^2 + \sigma_{\ln}'^2}} \tag{2.11}$$

Use Bayesian conjugate pairs for normal and lognormal distributions (the most common types of distribution in engineering analysis), the updated results for each parameter can be obtained.

2.2.2 Combining with Sampling from Normal Population

If the experiment outcome ε in Eq. 2.4 is a set of observed values x_1, x_2, …, x_n, representing a random sample from a population X with underlying density function $f_X(x)$, the probability of observing this particular set of values, assuming that the parameter of the distribution is θ, is

$$P(\varepsilon \mid \theta) = \prod_{i=1}^{n} f_X(x_i \mid \theta) dx$$

Then, if the prior density function of θ is $f'(\theta)$, the corresponding posterior density function becomes, according to Eq. 2.4,

$$f''(\theta) = \frac{[\prod_{i=1}^{n} f_X(x_i \mid \theta) dx] f'(\theta)}{\int_{-\infty}^{\infty} [\prod_{i=1}^{n} f_X(x_i \mid \theta) dx] f'(\theta) d\theta} = kL(\theta) f'(\theta) \tag{2.12}$$

in which the normalizing constant ‘k’ is

$$k = [\int_{-\infty}^{\infty} (\prod_{i=1}^{n} f_X(x_i \mid \theta)) f'(\theta) d\theta]^{-1}$$

and the likelihood function L(θ) is the product of the density function of X evaluated at x_1, x_2, …, x_n, or

$$L(\theta) = \prod_{i=1}^{n} f_X(x_i \mid \theta) \tag{2.13}$$

In the case of a Gaussian population with known standard deviation σ, the likelihood function for the parameter μ, according to Eq. 2.13, is

$$L(\mu) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{1}{2}\left[\frac{x_i - \mu}{\sigma}\right]^2\right) = \prod_{i=1}^{n} N_{\mu}(x_i, \sigma) \qquad (2.14)$$

where $N_{\mu}(x_i, \sigma)$ denotes the normally distributed density function of μ with mean value x_i and standard deviation σ. It can be shown that the product of *m* normal density functions with respective means μ_i and standard deviations σ_i is also a normal density function with mean and variance

$$\mu^* = \frac{\sum_{i=1}^{m} \mu_i / \sigma_i^2}{\sum_{i=1}^{m} 1/\sigma_i^2} \qquad \text{and} \qquad (\sigma^*)^2 = \frac{1}{\sum_{i=1}^{m} 1/\sigma_i^2}$$

For the samples obtained from the same site-specific distribution, they have the same standard deviation. Therefore the likelihood function L(μ) becomes

$$L(\mu) = N_{\mu}\left(\frac{1/\sigma^2 \sum_{i=1}^{n} x_s}{n/\sigma^2}, \frac{1}{\sqrt{n/\sigma^2}}\right) = N_{\mu}\left(\bar{x}, \frac{\sigma}{\sqrt{n}}\right) \qquad (2.15)$$

where $\bar{x}$ is the sample mean.

2.3 Model Uncertainty Analysis - Bayesian Monte Carlo (BMC)

The traditional type of uncertainty analysis, where uncertainties in model input parameters are routed through a predictive model using analytical or numerical methods, yields only a prior, or initial, assessment of uncertainty. The Bayesian Monte Carlo (BMC) approach [Sohn, M. D., Samll M. J., et al., 2000] allows the prior to be updated to a posterior probability using Bayes rule to account for the level of agreement between model predictions and the observed field data. The posterior probability of each realization of the Monte Carlo simulation, given the observed data, is computed as in Eq. 2.4 and 2.13. The likelihood function quantifies the difference between the observations and the model output resulting from inherent variability, measurement error, spatial and

temporal averaging, and imperfect model representation. For example, for unbiased measurements with a normally distributed error, the likelihood of an observation is given as:

$$L(O \mid Y_k) = f(\varepsilon_k - \theta_k)$$
$$= \frac{1}{\sqrt{2\pi}\sigma_\varepsilon} \exp\left(-\frac{1}{2}\left[\frac{O - Y_k}{\sigma_\varepsilon}\right]^2\right) \quad (2.16)$$

where O is observations, Y_k is the model predictions, and σ_ε^2 = the observation error variance.

The selection of the appreciated error structure for the likelihood function is a key consideration for the Bayesian analysis; it requires a careful consideration of the relationship between the model predictions and the observed data. For example, when the relationship is direct, i.e., when model predictions and observed data are available at the same level of temporal and spatial aggregation, then a likelihood estimate based on field and laboratory measurement error is appropriate. In many applications, the correspondence between observed data and model predictions is less direct. In these cases, the error variance in Eq. 2.16 must incorporate the effects of the un-represented variances as well as the error associated with inaccuracy in the measurement methods used to obtain the data.

An additional complication arises from the independent assumption, which is inherent in the use of Eq. 2.13. This assumption, though commonly employed, is often inappropriate. The correlations in the observed data, model predictions, and the difference between them, can violate the independence assumption, causing the information content of an observed dataset to be reduced. In most cases, an approach is employed: the likelihood is defined using statistics that represent the aggregate relationship between the observed data and the model.

Although BMC method is not performed in this thesis because of thesis objective and limitation of time, it is a new approach for future analysis for model uncertainty analysis.

2.4 Bayesian Decision Theory and Reliability Analysis

Reliability certification [Papazoglou, I. A., 1999] or reliability demonstration addresses the need to demonstrate that the reliability related characteristics of an engineered technological system meet certain requirements. The most common form of these requirements is that the reliability of a system, i.e., the probability that the system will perform a required function under stated conditions and for a stated period of time, is greater than a given value. The reliability of a system is estimated from existing or acquired information referring either to its performance as a whole or to the performance of its parts or components. If the reliability of a system considered as a single component is known with certainty, then the certification follows from direct comparison with the required reliability value. Similarly straightforward is the certification in the case where the reliability of the components of the system is known along with their logical interconnection in the system. In the latter case the reliability of the system is expressed as a function of parameters referring to the stochastic behavior of the components.

In many instances, however, uncertainties exist about the reliability of a system and/or of its components. This uncertainty refers to the value of the parameters of the models describing the stochastic behavior of components, and it is due to either incomplete knowledge of these quantities (existing components to operate in a different environment, new design, limited testing, etc.), or to the fact that these quantities are inherently uncertain. A systematic approach for quantifying the uncertainties about the reliability of a system is possible through Bayesian reliability analysis. According to this, approach uncertainties about the parameters of a reliability model are quantified by considering them as random variables distributed according to given probability density function (PDFs). The system reliability being a function of random variables becomes itself a random variable and the problem reduces to one of establishing its PDF. Bayesian reliability analysis also offers a systematic and internally coherent framework for incorporating to the reliability assessment additional information obtained after the initial uncertainty assessments.

2.4.1 Axiomatic Definitions

Bayesian decision theory is a formal mathematical structure that guides a decision maker in choosing a course of action in the face of uncertainty about the consequences of that choice. The course of action recommended by the theory is one which is consistent with the decision maker's preference for various consequences and the uncertainties involved in the problem. More formally, the Bayesian decision problem, as it relates to reliability analysis, is defined in terms of the following:

1. A space A of two possible actions which are available to the decision maker;

$A = \{a_1, a_2\}$

where action a_1 is "Accept the system" and action a_2 is "Do not accept the system". The meaning of the statement "accept the system" is that the system is accepted with respect to its reliability and from the decision maker's point of view. For a producer "accept" means produce the system at the assessed reliability level, for a buyer "accept" means buy it. A similar meaning is assigned to the statement "Do not accept" or "reject" the system.

2. A space of possible "states of the world", $I = \{R\}$, where I is the set of the possible values of the reliability of the system R, and therefore I consists of the interval of the real line (0,1).

3. A family of possible experiments $E = \{e\}$. One of these experiments can be used to obtain more information about the state of the world. E includes a dummy experiment which consists of making an immediate decision with no experimentation. In the context of this analysis an experiment consists in observing a system or components of the system and recording their reliability related performance.

4. A space of possible outcomes $Z = \{z\}$ for the experiments in E. In the reliability context outcomes of experiment consist of times of observation and successful or not in the completion of the mission during these times.

Each combination (e, z, a, R) determines a consequence. In other words the combination of: (1) the choice of an experiment e; (2) the observation of an outcome z; (3) the choice of an action *a*; and (4) the realization (by the system) of a reliability R, will

have a certain consequence to the decision maker that chose this particular course of action.

The axioms and the basic theorems of Bayesian decision theory, can be summarized as follows:

Proposition 1. There exist a preference relation $\succ$ over the set of all consequences $C = \{c\}$ such that if c_i and c_j belong to C then one of the following three alternatives is true.

(1). $c_i \succ c_j$ (c_i "is preferred to" c_j).

(2). $c_j \succ c_i$ (c_j "is preferred to" c_j).

(3). Both (1) and (2) (indifference between c_i and c_j).

Proposition 2. The decision maker can express his preference for consequences by a real-valued function u(.) such that $c_i \succ c_j$ if and only if $u(c_i) > u(c_j)$. The function u(.) is called the utility function.

Proposition 3. The existing uncertainties about the reliability of the system and the relative likelihood of the experimental outcomes can be expressed by means of a probability measure $P(\tilde{R}, \tilde{z})$ on I×Z. From $P(\tilde{R}, \tilde{z})$ one can obtain the marginal probability measure $P(\tilde{R})$ on I, called the prior probability distribution of the reliability (i.e., prior to experimentation). If an experiment e results in an outcome z, the decision maker's prior knowledge is modified by means of Bayesian theorem to yield the posterior probability distribution. The reliability of posterior information can be obtained based on the posterior probability distribution function.

From the foregoing it can be shown that if the decision maker is to act consistently with his preference for consequences and the existing uncertainties, he should choose the act that maximizes the expected utility of the consequence of that act, the expectation being taken with respect to $P(\tilde{R}, \tilde{z})$.

The following section briefly describes the method of choosing the best course of action according to decision theory.

2.4.2 The Nature of the Utility Function

A general assumption on the nature of the utility function that will be made can be stated in the form of the following proposition.

Proposition 4. The utility function u(c), which is defined on C=E×Z×A×I, can be expressed as the sum of a function $u_s(.,.)$ on E×Z and a function u(.,.) on A×I,

$$u(c) = u_s(e,z) + u(a,R) \tag{2.17}$$

Utility function $u_s(e,z)$ refers to the sampling part and describes the preferences of the decision maker on choosing experiment e and observing outcome z. Utility function u(a,R) describes the preferences of the decision maker on deciding *a* for a system with reliability R. The general characteristics of u(a,R) are as follows:

1. If act a_1 is chosen then it is assumed that a rational decision maker would prefer a larger reliability than a smaller one, so that

$$u(a_1,R_1) \geq u(a_1,R_2) \text{ if and only if } R_1 \geq R_2 \tag{2.18}$$

2. If act a_2 is chosen, the decision maker's preferences could be based on two different arguments. On one hand, one could argue that once a decision of not accepting the system has been made, no consequence from a particular reliability (small or large) of the system can actually be realized. Therefore the particular value of the reliability of the system that it would have obtained if the system was accepted is unimportant to the decision maker, and the utility function is constant for all R.

$$u(a_2,R) = constant. \qquad \forall R, R \in I \tag{2.19}$$

On the contrary one could argue that the choice of action a_2 (do not accept), combined with a large reliability that the system would exhibit if adopted represents an opportunity loss for the decision maker, in the sense that the decision maker by choosing action a_2 lost the opportunity to accept a reliable system. If this argument represents the decision maker's preference then it is obvious that the utility function $u(a_2, R)$ does not take the same value for every possible value of R, and further, a larger reliability (larger opportunity loss) is less preferred to a smaller one (smaller opportunity loss), i.e.,

$$u(a_2,R_1) \geq u(a_2,R_2) \text{ if and only if } R_1 \leq R_2 \tag{2.20}$$

It will always be assumed that there exists an "equilibrium" value of the reliability, R_0 such that

$$u(a_1,R_0) \geq u(a_2,R_0) \quad R_0 \in (0, 1) \tag{2.21}$$

With regard to the utility function $u_s(e,z)$ it is usually convenient to think of this utility in terms of its negative value defined by the following equation,

$$c_s(e,z) = - u_s(e,z) \tag{2.22}$$

called the "cost" of performing the experiment e and observing the result z. it is apparent that whatever the point of view, both $u_s(e,z)$ and $c_s(e,z)$ depend exclusively on the nature of the space E.

2.4.3 Prior Analysis

As it was stated repeatedly in the foregoing, the purpose of decision theory is to suggest the best course of action, i.e., the optimum experiment e* and the optimum act a* given the results of this experiment. Before examining how the information resulting from an experiment can be used and which experiment should be selected, it would be helpful to examine the two limiting cases of experimentation: (1) the dummy experiment (called also the null experiment) which consists of no experimentation at all; and (2) the ideal experiment which, if performed, would yield perfect information that is, eliminate any uncertainties about the reliability of the system.

The reason for analyzing the null experiment is that this experiment represents an actual alternative to the decision maker. It is possible that the decision maker will decide on the basis of the existing information only, available in terms of the prior probability measure on I. Further, exactly the same analysis is applicable after an experiment has been performed and an outcome z has been observed. The only difference would be that instead of the prior measure $p'(R)$ on I the probability measure $P''(R)$ will be used.

If perfect information were available to the decision maker, then the optimum act a_R (conditional on R) would be,

$$a_R = \begin{cases} a_1 & \text{if and only if } R \geq R_0 \\ a_2 & \text{if and only if } R < R_0 \end{cases} \tag{2.23}$$

The exact value of the reliability of R is not known to the decision maker at the moment of the decision. With the definitions of the prior expected utilities $\bar{u}_1'$ and $\bar{u}_2'$, the prior optimum act a* can be written as,

$$a^* = \begin{cases} a_1 & \text{if and only if } \bar{u}_1' \geq \bar{u}_2' \\ a_2 & \text{if and only if } \bar{u}_1' < \bar{u}_1' \end{cases} \tag{2.24}$$

This equation determines the best course of action on the basis of the prior information alone.

2.4.4 The Conditional Value of Sample Information (CVSI)

It is now assumed that the decision maker can perform a real experiment *e*, which yields information. In other words the results of the experiment will be to "update" the prior measure F′(R) to a posterior measure F″(R) (or the prior PDF f′(R) to a posterior PDF f″(R)). Let a_z^* denote the optimal act after the experiment has been performed and the outcome z has been observed and with the definition of $\bar{u}_1''$ and $\bar{u}_2''$, the optimal act can be written as,

$$a^* = \begin{cases} a_1 & \text{if and only if } \bar{u}_1'' \geq \bar{u}_2'' \\ a_2 & \text{if and only if } \bar{u}_1'' < \bar{u}_1'' \end{cases} \tag{2.25}$$

Now the decision maker by choosing: to perform the experiment and to act after observing the outcome according to a″*, instead of choosing: not to perform the experiment and to act according to a′*; has increased his utility after the fact by the following amount

$$CVSI \equiv E[u(a''^*)] - E[u(a'^*)] \tag{2.26}$$

By virtue of the equations of optimum act for prior and posterior analysis, the Conditional Value of Sample Information (CVSI) can be written as,

$$CVSI = \begin{cases} 0 & if\ \bar{u}_1'' > \bar{u}_2''\ and\ \bar{u}_1' > \bar{u}_2' \\ \bar{u}_1'' - \bar{u}_2'' & if\ \bar{u}_1'' > \bar{u}_2''\ and\ \bar{u}_1' < \bar{u}_2' \\ \bar{u}_2'' - \bar{u}_1'' & if\ \bar{u}_1'' < \bar{u}_2''\ and\ \bar{u}_1' > \bar{u}_2' \\ 0 & if\ \bar{u}_1'' < \bar{u}_2''\ and\ \bar{u}_1' < \bar{u}_2' \end{cases} \tag{2.27}$$

Of course CVSI can be evaluated only conditionally on outcome z or after the experiment has been performed.

3. Site-Specific Dose Assessment – Use of Data

3.1 Dose Assessment for Nuclear Power Plant Decommissioning

Dose assessment is to project the dose to potentially exposed humans from the presence of radioactive source materials. Activities required for a dose assessment include characterizing the source term, developing a conceptual model for a given site, selecting a computer code that is compatible with the site conceptual model, developing supporting input data for the selected computer code, executing the code, and interpreting the results for the necessary decisions. The computer codes that are capable of performing dose assessment for a decommissioning nuclear power plant have been identified by the NRC as described in section 1.2. Therefore, main work to be done in decommissioning dose assessment exercise is to develop an appropriate site conceptual model and prepare appropriate data for the input parameters.

Contamination in a decommissioning nuclear power plant can exist in a wide diversity of conditions. For example, radionuclides in soil can originate from intentional disposal, accidental spill, or long-term accumulation of material deposited from airborne releases during plant operation. The complexity of the environmental setting also influences the potential pathways and components that may need to be considered in modeling human exposures. Therefore, the conceptual model must be broad enough to account for many different, and potentially complex, pathways and conditions for the given residual soil contamination. These potential situations range from simply inhaling air that contains re-suspended contaminated soil to ingesting drinking water from a contaminated well or fish from contaminated surface water, or a variety of plant and animal products that may be grown in the contaminated soil.

Although the source term and site-conceptual model can vary between sites, there are generic issues/questions in dose assessment for decommissioned sites: (1) how does the residual radioactivity move through the environment?; (2) where and how can humans be exposed to the environmental concentrations?, and; (3) what are the exposure group's habits that will determine dose? (e.g., what do they eat and where does it come from?

How much? Where do they get water and how much? How much time do they spend on various activities? etc.) Therefore, the type of required input parameters remain the same between different sites. These parameters include physical, behavioral, and metabolic parameters. The physical parameter is classified as any parameter whose value, for a given site and a given group of exposed individuals, would not change if a different group of individuals were considered. All other parameters are behavioral. Within behavioral parameters, a further distinction is made between parameters describing interaction with the site in the context of the scenario, and metabolic parameters. Under the ICRP 43 recommendation [ICRP Publication 43, 1985], values for metabolic parameters would not depend on site conditions nor on the composition of the generic screening group. Distributions were not defined for metabolic parameters. In the residential scenario model, the breathing rate parameters were classified as metabolic.

There are about 222 input parameters required to execute DandD and more than 120 parameters for RESRAD. Therefore developing appropriate input data for all of these parameters is a formidable task. However, the screening methodology developed by NRC provides a default set of input values for these parameters. The NRC's screening analysis is designed to allow termination decisions to be made without requiring site-specific data. So the data set must therefore be "prudently conservative", meaning that the dose estimate is likely to decrease if more site information is included in the dose calculation.

For example, for the behavioral parameters, prudently conservative values were established by defining a generic screening group for the scenario. This screening group provides a reasonable upper bound on the behavior of the site-specific critical groups that might be defined in consideration of particular site features. Default values for behavior parameters represent the behavior of the average member of the screening group, and are defined by the average value of the parameter distribution from the efforts of uncertainty characterization for each parameter.

For physical parameters, probability distributions are defined which describe the parameter values that might be used if site-specific data were collected. The range of possible parameter values leads to a range of possible doses resulting from exposure to a specified radionuclide concentration. The probability distributions describing the range of

possible parameter values allow decisions to be made in the absence of such values by calculating the range of possible doses that might result if site data were collected and selecting a set of default values from that range of doses.

As discussed in sections 1.2 and 1.3, if site-specific data can be developed, this will likely serve to reduce the conservatism in the predicted dose, which, in term, can reduce the cost of overall decommissioning project. Since developing site-specific data itself will require resources, use of resources should be managed to be effective following the spirit of the NRC decision framework.

It is important in the site-specific dose assessment to identify key parameters among the large number of parameters involved. If generic key parameters in nuclear power plant decommissioning dose assessment can be identified, the efforts for the development of site-specific data should be focused on these parameters for the maximum benefit.

3.2 Key parameters in Decommissioning Modeling

The focus of dose assessment in this thesis is the radiation dose calculations resulting from contaminated soil. Dose from contaminated soil could involve many different types of human activities. But the residential farmer scenario is likely to represent a prudently bounding scenario. Accordingly, identification of key parameters will also be confined to the same scenario. The results, however, are expected to provide a representative picture of key parameters for dose assessment of nuclear power plant decommissioning because the residential farmer scenario is mostly applicable for any environmental contamination.

3.2.1 Identification of Key Parameters

Identification of key parameters was performed through parameter sensitivity analysis. Parameter sensitivity is a measure of the degree to which the uncertainty of a parameter affects the output. Information on parameter sensitivities helps users to focus on those parameters whose variability would result in a relatively large impact on TEDE

during data collection. This approach can make assessment more effective, efficient, and economic.

The sensitivity of a parameter in this study is defined as TEDE relative differences. The TEDE relative difference for a parameter is described by [Yim, M.S., 1999]:

$$\left|\frac{TEDE_{ch} - TEDE_{d}}{TEDE_{d}}\right| \times 100\%$$

where $TEDE_{ch}$ is the peak effective dose equivalent calculated when the parameter's input is changed and $TEDE_{d}$ is the peak dose equivalent value when the default value is used.

3.2.2 Radionuclides of Interest

The inventory of residual nuclides, their half-life and their chemical properties are key factors to determine whether a radionuclide is important for dose evaluation. Residual radionuclide concentration, distributions and inventories were studied at several nuclear plants, such as Pathfinder, Humboldt Bay, and Trojan nuclear power plant,. Within 10 to 20 years after shutdown, abundant radionuclides were Co-60, Fe-55 and Cs-137; after about 20-30 years, the abundant radionuclides generally include Ni-63, Cs-137, Co-60, and Sr-90; and after about 100 to 200 years, Am-241, Pu-238, Pu-239, and Cm-244 become dominant. Residual radionuclide analysis of Trojan Nuclear Power Plant that was shut down in November 1992, indicates that as of November of 1997, five radionuclides H-3, Fe-55, Co-60, Eu-152, Eu-154 comprised approximately 99% of the remaining radioactivity in the activated bioshield concrete. Three radionuclides Fe-55, Co-60 and Ni-63 accounted for approximately 99% of the radioactivity in the primary systems, while in the auxiliary systems, four radionuclides, Fe-55, Co-60, Ni-63 and Pu-241 comprised 98% of the radioactivity. Surface and subsurface soil samples contained Co-60, Sr-90, Cs-134, and Cs-137. Other radionuclides such as C-14 and Ni-59 were also found in the embedded pipes in addition to above listed radionuclides.

As shown above, the major residual radionuclides from different power plants are limited in number. These include H-3, C-14, Mn-54, Fe-55, Ni-59, Ni-63, Co-58, Co-60,

Zn-65, Sr-90, Nb-94, Cs-134, Cs-137, Eu-152, Eu-154, Pu-238, Pu-239, Pu-241, Am-241, and Cm-242. This list is also consistent with the radionuclides specified in 10 CFR Part 61 concerning low-level radioactive waste disposal. However, the number of radionuclides for study was further reduced based on the following principles [Yim, M.S., 1999]:

- The radionuclides must be present in the library of both of DandD code and RESRAD code – This eliminates Eu-152 and Cm-242.
- The activity typically observed in nuclear power plants is measurable or at a level to be of concern for dose modeling – This eliminate H-3 and Nb-94.
- The radionuclides of similar characteristics that do not affect the results are eliminated for the simplicity of the analysis – This eliminates Mn-54, Fe-55, Co-58, Ni-63, Zn-65, and Cs-134, ad Pu-238.

By further excludes Eu-154, Pu-241, and Cm-243 because of limit of information, the list of radionuclides analyzed in this study includes: Cs-137, Sr-90, Pu-239, Co-60, C-14, Am-241 and Ni-59.

3.2.3 Key Parameters for Residential Farmer Scenario

The results of sensitivity analysis show that the key parameters of importance vary with selected nuclides and with computer code used for dose modeling (DandD 1.0 and RESRAD 5.65). These key parameters are shown in Table 3.1 [Yim, M.S., 1999].

The main reason for the difference in key parameters between the DandD code and the RESRAD code is the difference in conceptual approaches and models used in the environmental transport of radionuclides in each code. Due to this difference, exposure pathways of importance identified for various nuclides were sometimes quite different.

Table 3.1 Comparisons of Key Parameters from Individual Parameter Sensitivity Analysis

Source term	DandD (% represents sensitivity)	RESRAD (% represents sensitivity)
Cs-137	Partition coefficient (40.3%) Saturation ratio of unsat. zone (33.9%) Depth of unsat. zone (33.6%) Density of unsat. zone (32.5%) Infiltration rate (31.1%) Surface soil density (26.5%) Human consumption of fish (25.1%)	Time spent indoors (14.7%) Indoor shielding (14.6%) Time spent outdoors (on-site) (10.4%) Soil-to-plant transfer (4.5%) Area of contamination (3.4%)
Sr-90	Human diet from garden (30.0%) Soil to plant transfer (leafy vegetables) (29.0%) Human consumption of milk (14.5%)	Soil-to-plant transfer (29.7%) Human consumption of fruits, vegetables, grains (21.8%) Area of contamination (6.2%)
Pu-239	Partition coefficient (38.5%) Depth of unsat. zone (33.3%) Saturation ratio of unsat. zone (33.3%) Density of unsat. zone (32.3%) Infiltration rate (28.8%) Surface soil density (27.4%) Human consumption of fish (20.1%)	Soil-to-plant transfer (21.1%) Human diet fruits, vegetables, grains (19.3%) Depth of soil mixing layer (12.4%) Soil ingestion rate (6.6%)
Co-60	Time spent indoors (19.1%) Indoor shielding (19.1%) Outdoor shielding (6.2%) Time spent outdoors (on site) (5.8%) Human diet from the garden (4.3%)	Time spent indoors (16.8%) Indoor shielding (16.8%) Time spent outdoor (on site) (12%)
C-14	Human diet - fish (26.0%) Fish bioaccumulation (26.0%) Consumption period/Human diet (25.85%) Infiltration rate (23.68%) Partition coefficient (19.04%)	Density of contaminated zone (31.98%) Thickness of evasion layer of C-14 in soil (22.93%) Area if contamination (20.66%) C-14 evasion flux rate from soil (19.16%)
Am-241	Garden diet (29.57%) Human diet - fruit (12.23%) Consumption period – fruit (11.51%) Human diet - grain (10.07%)	Density of saturated zone (32.37%) Drinking water intake (30.70%) Soil-to plant transfer factor (22.33%) Precipitation rate (16.80%) Partition coefficient (11.23%)
Ni-59	Human diet from garden (25.2%) Density of unsaturated zone (23.3%) Partition coefficient (20.5%) Human consumption of root vegetables (19.5%)	Soil to plant transfer (27.9%) Human diet fruits, vegetables, grains (15.0%) Area of contamination (13.5%)

Table 3.1 also tells that for the residential farmer scenario the number of key parameters that affect the dose modeling results or the derivation of site-specific Derived Concentration Guideline Level (DCGL) *[See note.]* is relatively small. Among these parameters, several of them are more generic in nature rather than being site-specific due to the inherently uncertain nature of dose modeling. These generic parameters include time spent indoors and outdoors and indoor and outdoor shielding.

To predict the amount of time an individual in a population spends in different microenvironment requires a detailed knowledge of that person's occupation and habits. This is considered non-site-specific. Also shielding factor varies for a structure depending on the type of structure and the size and location of the source. The type of structure to be built on the site is basically unknown and is less site-specific.

The remaining list of key site-specific parameters on which site-specific dose modeling should be focused is:

For RESRAD:

- Soil-to-plant transfer factor for key nuclides (Cs-137, Sr-90, Pu-239)
- Human consumption rate of fruits, vegetables, and grains
- Area of contamination
- Human consumption rate of garden diet, milk, fish

Note: Derived Concentration Guideline Level (DCGL) is used for demonstrate radiological criteria for unrestricted use defined in Subpart E, 10 CFR 20.1042. The DCGL is the concentration of residual radioactivity distinguishable from background, which, if distributed uniformly throughout a survey unit, would result in a Total Effective Dose Equivalent (TEDE) as specified in a regulation (25 mrem per year) to an average member of the critical group. The target in a decontamination and decommissioning (D&D) project is a contamination level below the DCGL. Therefore the DCGL value has a significant impact on D&D cost and possibly the worker dose. The DCGL values are calculated based on "dose modeling" using exposure pathway analysis computer codes. These computer models represent decision-making tools which project of future conditions based on mathematical models and current knowledge

For DandD:

- Partition coefficient for key nuclides (Cs-137, Pu-239)
- Soil-to-plant transfer factor for key nuclides (Sr-90)
- Saturation ratio of unsaturated zone
- Depth of the unsaturated zone
- Density of the unsaturated zone
- Water infiltration rate
- Surface soil density

3.3 Uncertainty Characterization of Key Parameters from the National Database

A parameter is uncertain if there is lack of knowledge about its true value. This is always the case with the parameters used in the dose assessment due to the difficulty in capturing the real-world situations of the parameters for the long-term predictive analysis. Uncertainty of a parameter can be due to inherent variability of the system being studied over time, space, or some populations of individuals and/or uncertainty due to lack-of-knowledge or subjectivity as a property of the analyst. Mathematically the variability and uncertainty of a parameter can be described by a probability distribution function.

For each of the key input parameters identified, the corresponding probability distribution function has been developed by the Sandia National Laboratory and Argonne National Laboratory considering the range of conditions expected across the nation. Development of these distributions based on the national database is described in NUREG/CR-5512, Volume 3 and NUREG/CR-6697. These results are used in this study as prior information of the parameter uncertainty before attempting any site-specific investigations. These are given in the Tables 3.2 and 3.3.

Table 3.2 Default value or distribution type (if available) in NUREG/CR-5512, Volume 1*

Parameters	Cs	Sr	Pu	Co	C	Am	Ni	Description
Partition Coefficient Kd (ml/g)	2.65 ± 1.01	1.50 ± 0.92	2.98 ± 0.82	3.00 ± 1.18	1.32 ± 0.79	3.16 ± 1.37	1.57 ± 1.48	LOGN: lnμ ± lnσ
Soil-to-plant Transfer (pCi/kg / pCi/kg)								
Leafy	-3.194 ±1.253	0.5878 ±1.335	-7.706 ±0.9042	-2.43 ±1.548	-0.3567 ± 0.9042	-5.203 ±0.9042	-3.381 ±1.163	LOGN: lnμ ± lnσ
Root	-5.298 ±1.411	-2.59 ±1.335	-10.01 ±0.9042	-4.2 ±1.194	-0.3567 ±0.9042	-8.294 ±0.9042	-3.3863 ±0.9163	
Fruit	±-5.298 ±1.411	-2.59 ±1.335	-10.01 ±0.9042	-4.2 ±1.194	-0.3567 ±0.9042	-8.294 ±0.9042	-3.3863 ±0.9163	
Grain	±-5.298 ±1.411	-2.59 ±1.335	-10.01 ±0.9042	-4.2 ±1.194	-0.3567 ±0.9042	-8.294 ±0.9042	-3.3863 ±0.9163	
Area of contamination (m^2)	2,400 (Constant)							
Thickness of unsaturated zone (m)	1.0 (Choose conservative value from sampling)							
Infiltration (m/yr)	0.18 (Based one the high end of the range of infiltration rates for humid areas of the U.S.)							
Density of Unsaturated Zone (g/cm^3)	1.63 (Choose conservative value from sampling)							
Porosity of Unsaturated Zone	0.3 (Associated with only partially compacted soils)							
Consumption rate of fruits, vegetables, and grains (kg/yr) – Conservative values based on Nationwide Food Consumption Survey								
Leafy	11							
Grain	69							
Beef	59							
Poultry	9							

* by Sandia National Laboratory [Beyeler, W.E., and Brown, T.J., et al., 1998].

Table 3.3 Default distribution types and parameters in NUREG/CR-6676*

Parameter	RESRAD							
	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59	Remark
Partition Coefficient Kd (ml/g)	6.1±2.33	3.45±2.12	6.86±1.89	5.46±2.53	2.4±3.22	7.28±3.15	6.05±1.46	LOGN: $\ln\mu \pm \ln\sigma$
Soil-to-plant Transfer (pCi/kg / pCi/kg)	-3.22 ±0.9933	-1.2 ±0.9933	-6.91 ±0.9163	-2.53 ±0.9163	-0.36 ±0.9042	-6.91 ±0.9163	-3 ±0.9163	No type assigned
Area of contamination (m^2)	10,000							No type assigned
Thickness of unsaturated zone (m)	Bounded LOGN: 2.296 ± 1.276							$\ln\mu \pm \ln\sigma$
Contaminated zone b parameter	Bounded LOGN: 1.06 ± 0.66							$\ln\mu \pm \ln\sigma$
Precipitation (m/yr)	1							No type assigned
Saturated zone hydraulic conductivity (m/s)	Bounded LOGN: 2.3 ± 2.11							$\ln\mu \pm \ln\sigma$
Saturated zone hydraulic gradient	Bounded LOGN: -5.11 ± 1.77							$\ln\mu \pm \ln\sigma$
Density of Unsaturated Zone (g/cm^3)	Truncated NORM: 1.52 ± 0.23							NORM: $\mu \pm \sigma$
Density of Saturated Zone (g/cm^3)	Truncated NORM: 1.52 ± 0.23							NORM: $\mu \pm \sigma$
Porosity of Unsaturated Zone	Truncated NORM: 0.425 ± 0.0867							NORM: $\mu \pm \sigma$
Porosity of Saturated Zone	Truncated NORM: 0.425 ± 0.0867							NORM: $\mu \pm \sigma$
Consumption rate of fruits, vegetables, and grains (kg/yr)								
Leafy	14							No type assigned
Fruit, vegetable, and Grain	Mode: 178, Min: 135, Max: 318							Triangular
Meat and Poultry	63							No type assigned

* by Argonne National Laboratory [Kamboj, S., and LePoire, D., et al., 2000].

3.4 Default Input Values of Key Parameters (DandD vs. RESRAD)

Characterizing the variability and uncertainty of a parameter as a probability distribution enables the decision of selecting default input values of parameters to produce conservative dose estimates in the deterministic analysis. The default input values for the deterministic analysis (DandD 1.0 and RESRAD 6.0) are shown in Table 3.4. Due to the differences in the model, the required input parameters are somewhat different as seen in the table. The default values of the DandD code have been determined for the purpose of NRC's screening analysis as described in the Appendix A. These values correspond to the 90^{th} percentile value of the dose estimate for a representative source term, using parameter distributions that describe variability in parameter values over all sites, as the values that. The default input values of RESRAD were determined as reasonably conservative estimates of each individual parameter based on engineering judgments.

Table 3.4 Parameter used in DandD and RESRAD (Default values)

Parameter	DandD							RESRAD						
	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59
Partition Coefficient Kd(ml/g)	10.5	31.4	13.6	1510	4.34	1430	37	1000	30	2000	1000	0	20	1000
Soil-to-plant Transfer(pCi/kg / pCi/kg)								0.04	0.3	0.001	0.08	5.5	0.001	0.05
Leafy	0.018	64	4.5E-4	0.04	0.32	0.0055	0.034							
Root	0.031	0.46	4.5E-5	2.9	0.7	0.00025	2.5							
Fruit	0.14	0.26	4.5E-5	0.022	0.7	0.00025	0.34							
Grain	0.0066	0.085	4.5E-5	0.011	0.22	0.00025	0.038	/						
Element Independent														
Area of contamination(m^2)	2,400							10,000						
Thickness of unsaturated zone(m)	1.2288							4						
Contaminated zone b parameter	/							5.3						
Infiltration rate(m/yr)	0.2526							Precipitation rate (m/yr): 1.0						
Saturated zone hydraulic conductivity(m/s)	/							100						
Saturated zone hydraulic gradient	/							0.02						
Density of Unsaturated Zone(g/cm^3)	1.4312							1.5						
Density of Saturated Zone(g/cm^3)	/							1.5						
Porosity of Unsaturated Zone	0.4599							0.4						
Porosity of Saturated Zone	/							0.4						
Consumption rate of fruits, vegetables, and grains(kg/yr)														
Leafy	21.4							14						
Grain	14.4							Fruit, vegetable, and Grain: 160						
Beef	39.8							Meat and Poultry: 63						
Poultry	25.3													

3.5 Availability of Data for Key Parameters for Site-Specific Analysis

It is reasonable to use the default values when performing dose assessment without any site-specific information: these default inputs are developed as applicable to all the nuclear power plants nationwide as the conservative point estimate for the uncertainty distribution. As for a specific nuclear power plant site in a particular area, these default values could be too conservative. Understanding various features of a given particular site enables the development of site-specific data. And use of site-specific data could lead to the higher DCGL for a site compared to the case with default inputs although this requires additional expense. Therefore it is prudent to consider the usefulness/value of these new data preparation efforts before expending resources.

Site-specific information for the parameters can be obtained from various sources. These include actual site field investigations. Some information about physical characteristics of the site [Radian International, 1999][RP & ES Department, 1999], such as thickness of unsaturated zone, can only be obtained from the field exercises. Some information can be available from historic records or regional databases, such as precipitation rate. Information on soil type can be available from the regional database or from the actual field investigations. Determination of soil type enables the characterization of various soil-type specific information such as porosity and the b parameter for infiltration. The soil-type dependent radionuclide-specific parameters such as the partition coefficient and soil-to-transfer factor could be developed based on the relevant information available from the literatures[Sheppard, M. I., and Thibault, D.H., 1990][Nisbet, A.F., and Woodman, R.F.M., 2000]. Some of the human food consumption-related parameters can be developed from the national database such as EPA's Exposure Factors Handbook [EPA, 1995]. Use of these pieces of information for a site-specific analysis is described in Chapter 4.

4. Application of Decision Analysis for A Site-Specific Analysis – A Test Case

4.1 Conceptual Site Model

4.1.1 Brief Descriptions of the Site

An actual nuclear power plant site undergoing decommissioning is used for the demonstration of the methodology for this study. The site is located in the North Central Midwest region and occupies approximately 570 acres. Figure 4.1 depicts the site boundaries and owner-controlled area.

According to the soil survey by U.S.D.A. for the location of the plant site, the soil type in the plant's protected area is classifies as AgB (Alpena gravelly –sandy loam with 0-6% slope). On the average, the warmest normal maximum and normal minimum temperatures both occur in July (76.6 °F and 57.0 °F). The coldest normal maximum temperatures usually occur in January (26.7 °F). However, the coldest normal minimum temperatures (12.8 °F) occur in February. Overall, the precipitation is very evenly distributed, averaging between the 2 and 3 inches eight month of the year. Annually, the plant site receives an average of 31.7 inches of precipitation. Groundwater at the plant site moves north into the lake. The soil is well drained at the plant site. Before plant construction, the water table elevation was approximately 580 ft MSL (Mean See Level). A thick sequence of limestone is overlaid by 50 feet of compact clay till, interbedded with artesian sand zones. The top 10 feet of limestone is fractured bedrock, resulting in artesian groundwater conditions. The fractured bedrock provides a direct connection with the lake, allowing the ground water gradient to quickly respond to short-term lake water level variations.

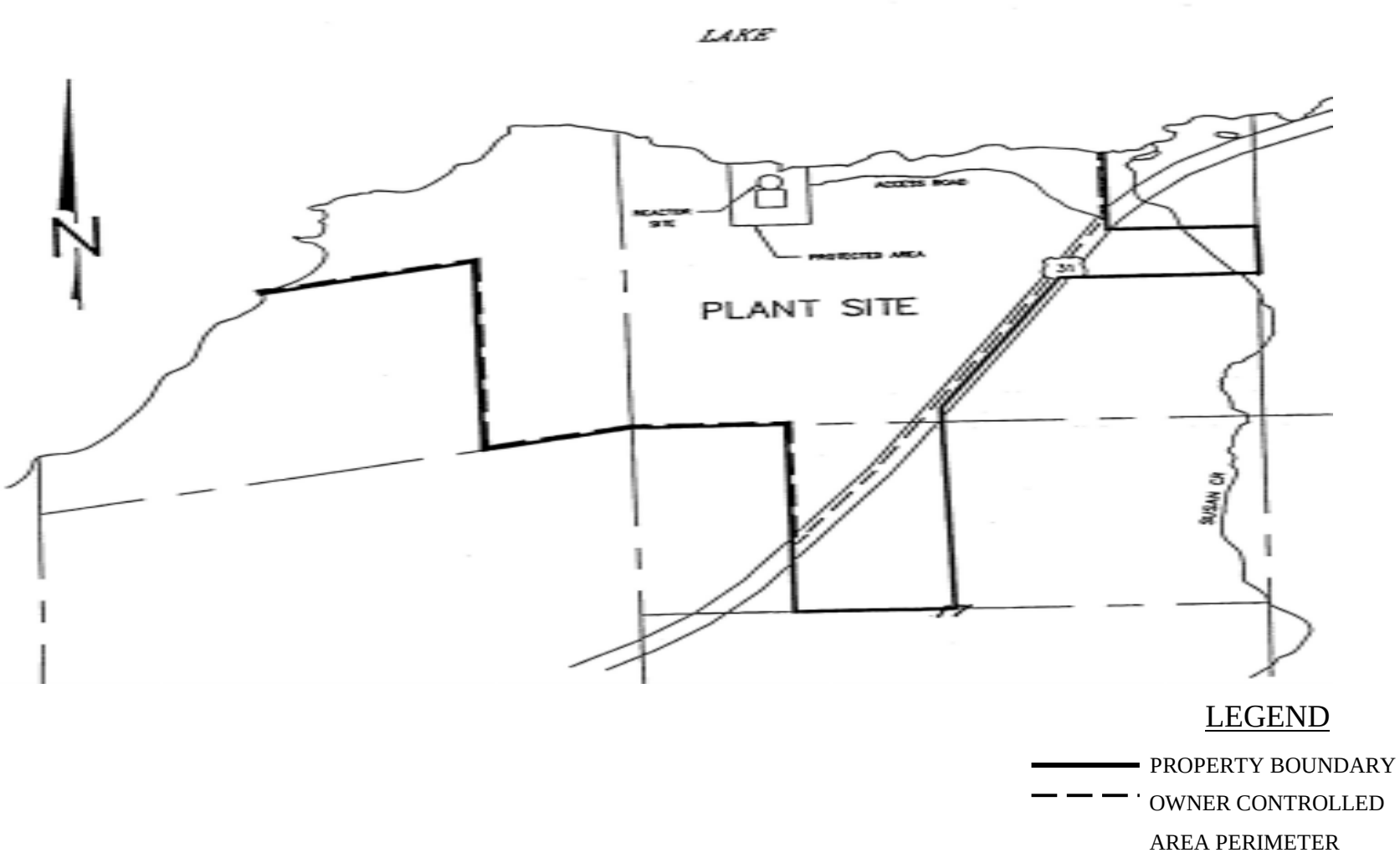

Figure 4.1 A nuclear power plant site boundary and owner-controlled area used in the study

The survey for soil contamination level is described in section 4.3. Environmental radioactivity concentrations were established by the collection of soil samples. Detectable level of Cs-137 can be found in most soil samples around the country. Cs-137 is a fission product produced from atmospheric testing of nuclear weapons and the operation of nuclear reactors. The concentrations of Cs-137 differ widely due to the varying affinity of different soil types for cesium. Cs-137 and Co-60 were detected in excess of the action level at two on-site locations. Trace quantities of both Cs-137 and Co-60 were identified at other locations on site above background levels, but all were less than 10% of the site release criteria. Mn-54 and Cs-134 were the only other man-made nuclides identifies at trace concentrations in the soil samples. Due to the relatively short half-life of Mn-54 (312 days) and undetectable concentration level of Cs-134, the two nuclides are excluded from the analysis in this thesis.

NUREG/CR-5849 presents classifications for characterization of plant areas for radiological significance, Affected Area and Unaffected Area. Based on a review of operating history and scoping survey results, the following plant areas are considered Affected Areas:

Radiation Controlled Area – All structures and soil in the Radiation Control Area. Radioactive materials were used and stored in the Radiation Control Area.

Protected Area – Structures and soil located in areas outside the Radiation Control Area but with the protected Area (fenced in area) of the site. This includes the fenced in area around the rad-waste building. Radioactive materials have been transported and stored at these locations. Scoping survey results have identified some areas having plant related radioactivity in the soil and groundwater.

The remaining areas of the plant property are considered to be the Unaffected Area. In this thesis, only the contamination in protected area at the site is considered.

4.1.2 Conceptual Models for the Nuclear Power Plant Site

Residual radioactive materials in buildings, and contaminated soil from licensed operation can exist in a wide diversity of conditions. For example, radionuclides in soil

can originate from intentional disposal, accidental spills, or long-term accumulation of material deposited from airborne releases during plant operation. The complexity of the environmental setting also influences the potential pathways and components that may need to be considered in modeling human exposures.

The site conceptual model is a qualitative description of the important environmental transport and exposure pathways and their interrelationships. For the use of a computer code in dose assessment, the appropriateness of the assumptions made in the computer code should be examined with respect to the site conceptual model.

Examination of the contamination at the site indicates that the radioactivity is mostly dispersed near the surface soil. Also the physical characteristics of the site were not complex to be adopted into the modeling framework of DandD and RESRAD.

Numerous potential exposure pathways can be identified for residual radioactive contamination in surface soil through residential farmer scenario [NRC, 1998]. These include:

- External exposure to penetrating radiation from volume soil sources while outdoors
- External exposure to penetrating radiation from volume soil sources while indoors
- Inhalation exposure to re-suspended soil while outdoors
- Inhalation exposure to re-suspended soil while indoors
- Inhalation exposure to re-suspended surface sources of soil tracked indoors
- Direct ingestion of soil
- Inadvertent ingestion of soil tracked indoors
- Ingestion of drinking water from contaminated ground water
- Ingestion of plant products grown in contaminated soil
- Ingestion of plant products irrigated with contaminated ground water
- Ingestion of animal products grown onsite (i.e., after the animals ingest contaminated drinking water, plant products, and soil)
- Ingestion of fish from a contaminated surface water source

Although DandD and RESRAD have different approaches to treat above pathway due to difference in the conceptual basis of the codes, most of the exposure pathways can be analyzed by both the codes as shown in Table 4.1. RESRAD was developed more for a site-specific analysis. DandD was designed to be used as a screening code for the generic contaminated site of 15 cm in thickness with no cover. In principle DandD is applicable to any site and none or very few site-specific data are required. Detailed comparison of models used between DandD and RESRAD are discussed in Appendix A.

Table 4.1 Residential Farmer Scenario Pathways Considered by DandD and RESRAD

Pathway	DandD	RESRAD
External exposure from volume soil sources while outdoors	Yes	Yes
External exposure from volume soil sources while indoors	Yes	Yes
Inhalation exposure to re-suspended soil while outdoors	Yes	Yes
Inhalation exposure to re-suspended soil while indoors	Yes	Yes
Inhalation exposure to re-suspended surface sources of soil tracked indoors	Yes	No
Inhalation-Radon progeny	No	Yes
Ingestion of soil – Direct	Yes	Yes
Inadvertent ingestion of soil tracked indoors	Yes	No
Ingestion of drinking water from a ground water source	Yes	Yes
Ingestion of plant products grown in contaminated soil	Yes	Yes
Ingestion of plant products grown with contaminated ground water	Yes	Yes
Ingestion of animal products grown on-site	Yes	Yes
Ingestion of fish	Yes	Yes

4.2 Screening Analysis Results

In this section, use of the DandD and RESRAD code for screening analysis with default inputs for seven radionuclides, i.e., Cs-137, Sr-90, Pu-239, Co-60, C-14, Am-241, and Ni-59, is described. In this calculation, the contamination concentrations of different radionuclides are set to 1 pCi/g to predict the Derived Concentration Guideline Level (DCGL) that corresponds to 25 mrem yearly doses. The contaminated area is set to 2,400 square meters for both the codes. Table 4.2 lists the Total Effective Dose Equivalent (TEDE) calculated by the DandD and RESRAD deterministic codes.

Table 4.2 The Screening analysis peak dose results and DCGL with DandD and RESRAD deterministic code

Radionuclide	DandD		RESRAD		Peak TEDE Ratio DandD to RESRAD
	Peak TEDE (mrem/yr)	DCGL (pCi/g)	Peak TEDE (mrem/yr)	DCGL (pCi/g)	
Cs-137	28.3	0.883	2.046	12.22	13.83
Sr-90	59.4	0.421	4.202	5.95	14.14
Pu-239	288	0.0868	0.4306	58.06	668.83
Co-60	6.87	3.64	8.482	2.95	0.81
C-14	6.46	3.87	0.579	43.18	11.16
Am-241	13.9	1.8	17.84	1.4	0.78
Ni-59	0.0061	4100	0.0011	22727.27	5.55

Both codes are capable of analyzing all of the important exposure pathways in the residential farmer scenario. But the results indicate that DandD is much more conservative than RESRAD. The closest pair of value is for Co-60. This is because Co-60 is treated similarly by both codes. However, for some of the key individual radionuclides such as Cs-137 and Pu-239, significant differences were found.

4.3 Preparation of Data for Site-Specific Analysis

4.3.1 Source Term Characterization

The spatial distributions of the soil contamination levels are needed as the site's source term. To determine whether the site can be released with license termination, the residual source term determined from the site survey will need to be compared with the DCGL, the target cleanup level. Before making the decision on compliance, the probability that the contamination level could exceed DCGL can also be determined.

The soil concentrations for major radionuclides at the plant site are available for the locations where the soil samples were taken. Assuming that the data from these samples represent the variability of the contamination at the site, the probability distributions of soil concentration of Cs-137 and Co-60 were constructed. In many locations, the measured concentrations were less than the minimum detectable activity (<MDA). In this case, the sample concentrations were conservatively assumed to be at the lower limit of detection (LLD). These were estimated to be 0.15 pCi/g, 0.13 pCi/g, and 0.44 pCi/g for Cs-137, Co-60, and Am-241, respectively. The raw data of soil concentrations for Cs-137 and Co-60 at different locations in the sampled area are listed in Appendix B.

The distribution of C-14, Ni-59, Sr-90, and Pu-239 were estimated using the scaling factors (Table 4.3) provided by the plant with respect to the concentrations of Cs-137, Co-60, and Am-241. The standard deviations of these concentrations were assumed to have the same value of its base nuclide after the logarithmic transform ($\sigma_{lnx)}$. The concentrations of all nuclides were assumed to follow the lognormal distribution. Due to lack of data for Am-241, the mean and standard deviation of its concentration was assumed to be at the LLD and σ_{lnx} of 1.00 (after the logarithmic transform) as a hypothetical test case. The resulting concentration distributions are shown in Table 4.4.

Table 4.3 Scaling factors for selected radionuclides at the plant site
(10,000 m^2 area with soil contaminated to 1 m depth)

Radionuclide	pCi/g Nuclide per pCi/g Am-241	pCi/g Nuclide per pCi/g Co-60	pCi/g Nuclide per pCi/g Cs-137
Cs-137	/	/	1
Sr-90	/	/	0.064
Pu-239	1.0848214	/	/
Co-60	/	1	/
C-14	/	0.0039205	/
Am-241	1	/	/
Ni-59	/	0.0004691	/

Table 4.4 The results of estimated concentrations for selected radionuclides at the plant site

Radionuclide	Base nuclide	μ_{lnx}	σ_{lnx}	Geometric Mean μ_g (pCi/g)	Geometric Standard deviation σ_g	Mean μ (pCi/g)
Cs-137	/	-1.4743	1.1082	0.2289	3.0289	0.4231
Sr-90	Cs-137	-4.2230	1.1082*	0.01465	3.0289	0.02708
Pu-239	Am-241	-1.2396	1.00*	0.2895	2.7183	0.4773
Co-60	/	-1.7602	0.9657	0.1720	2.6266	0.2742
C-14	Co-60	-7.3017	0.9657*	6.7439E-4	2.6266	1.075E-3
Am-241	/	-1.3210	1.00*	0.2669	2.7183	0.44*
Ni-59	Co-60	-9.4249	0.9657*	8.0691E-5	2.6266	1.2863E-4

* This is made by assumptions.

4.3.2 Site-Specific Data for Radionuclide Independent Parameters

1). Area of contamination

The DandD default is 2,400 m^2. RESRAD default is 10,000 m^2. The DandD default value is chosen in analysis.

2). Thickness of unsaturated zone

From the bolehole logs provided by the plant, 16 data points are available: 3, 5, 7, 5, 7, 10, 11, 9.5, 10, 6, 5, 11, 6, 7, 7, and 6 (in feet). Changing its unit to meter and analyzing the data as lognormally distributed, the probability distribution function (and cumulative distribution function) is developed as shown below (Figure 4.2).

Geometric mean μ_g: 2.0813 m

Geometric standard deviation σ_g: 1.4242

Mean μ: 2.2156 m

90% value: 3.2740 m

95% value: 3.7230 m

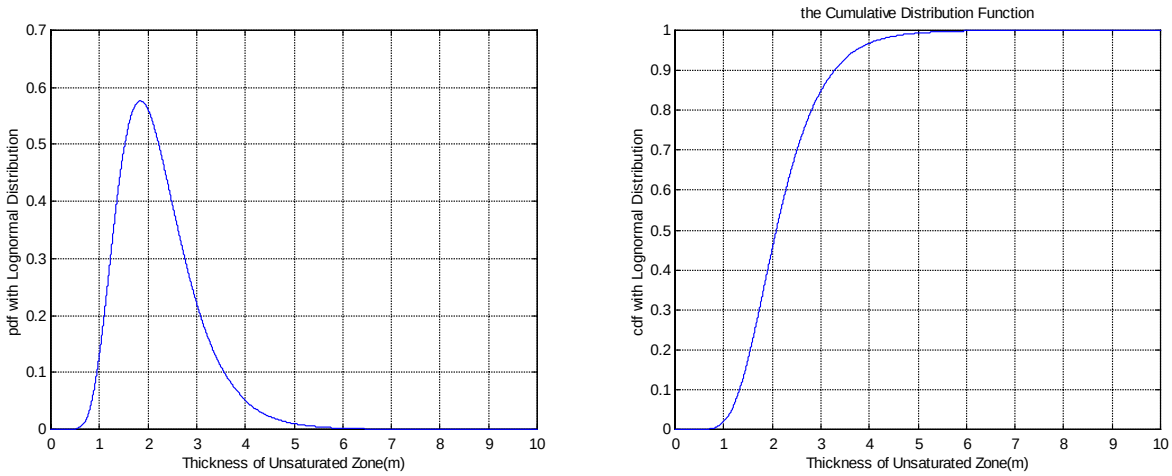

Figure 4.2 Distribution for the thickness of unsaturated zone

3). Contaminated zone b parameter (Not applicable to DandD)

For the given soil type of the site (i.e., sandy loam), the b parameter can be given a value of 4.9 based on the information available from ANL. However, considering the variability/uncertainty in the application of this value at the site, a uniform distribution within +/-10% variation, i.e., uniform (4.41, 5.39), is assumed for the probabilistic analysis.

4). Precipitation rate

Information on the precipitation rates at the site is available from the Plant Environmental Report for Decommissioning. The mean monthly precipitation rate reported was (12 data points): 2.2, 1.43, 2.05, 2.4, 2.7, 2.75, 2.8, 3.4, 3.83, 3.02, 2.72, and 2.4 (in inch). The data become, after converting them to annual rate in meters: 0.6706, 0.4359, 0.6248, 0.7315, 0.8230, 0.8382, 0.8534, 1.0363, 1.1674, 0.9205, 0.8291, and 0.7315.

These data were treated as lognormally distributed. The probability distribution function and cumulative distribution function developed are as following (Figure 4.3).

Geometric mean μ_g: 0.7830 m/yr

Geometric standard deviation σ_g: 1.2891

Mean μ: 0.8084 m/yr

90% value: 1.0837 m/yr

95% value: 1.1883 m/yr

Although this parameter cannot be used directly as input to DandD, its corresponding input parameter, infiltration rate, can be calculated by:

$$I = (1 - C_e)[(1 - C_r)P_r + I_{rr}]$$

where C_e is evapo-transportation coefficient (0.5), C_r is runoff coefficient (0.4 for the site's soil type), P_r is precipitation rate (0.8084 m/yr), and I_{rr} is irrigation rate (0.2 m/yr). Therefore, the infiltration rate for DandD site analysis is 0.3425 m/yr.

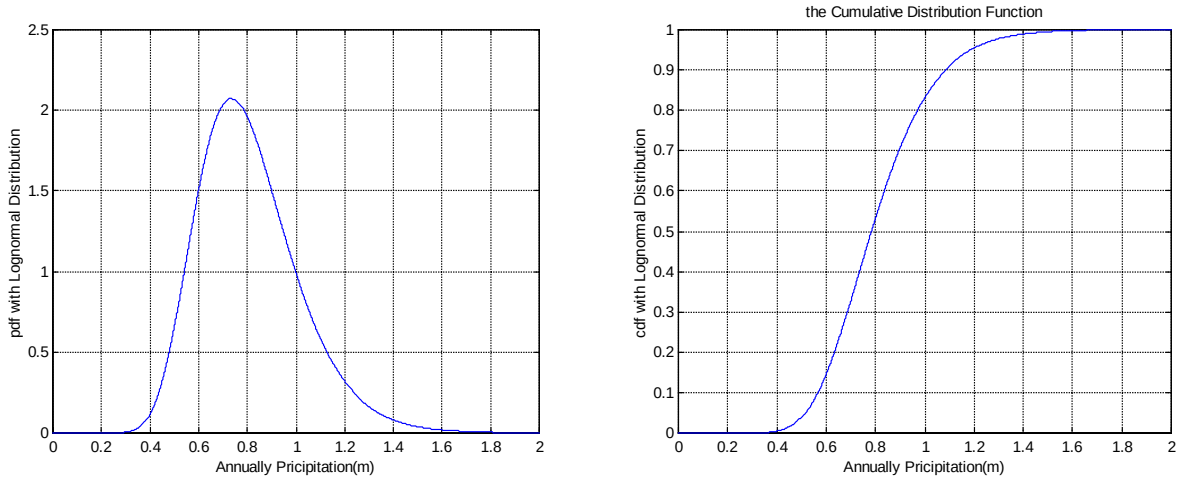

Figure 4.3 Distribution for the Annual precipitation rate

5). Saturated zone hydraulic conductivity (Not applicable to DandD).

The average value obtained from site investigation was 199 km/yr (6.31e-3 m/s).

Assuming that the parameter obeys lognormal distribution with mean value μ = 6.31e-3 m/s and using the typical expected uncertainty range of the parameter from the literature (as geometric standard deviation σ_g = 2.0), the probability distribution of the parameter was developed. According to this, the geometric mean is μ_g = 0.005812 m/s. The probability distribution function and cumulative distribution function are shown in Figure 4.4.

90% value: 0.0098 m/s

95% value: 0.0113 m/s

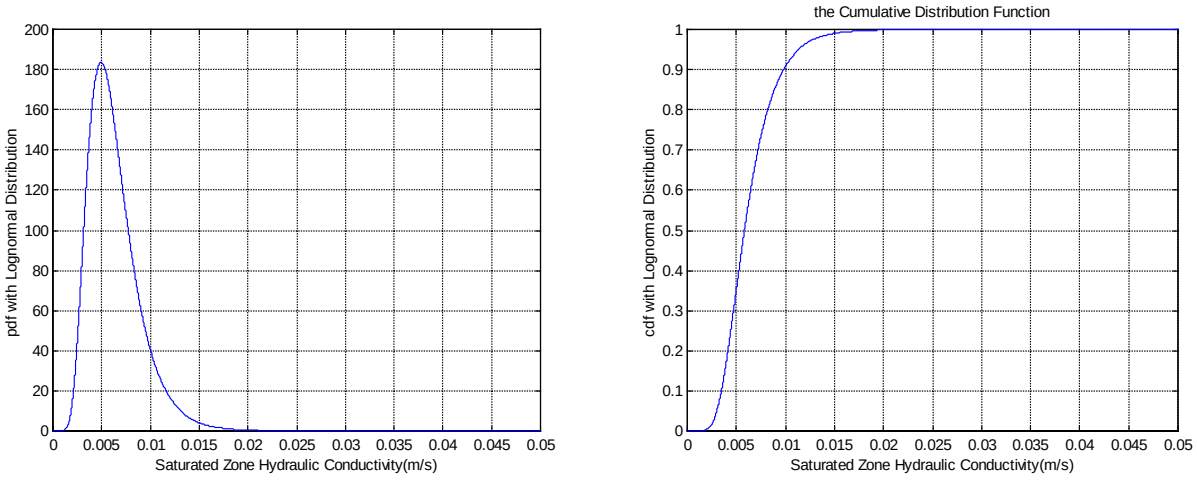

Figure 4.4 Distribution for saturated zone hydraulic conductivity

6). Saturated zone hydraulic gradient (Not applicable to DandD)

The site investigation determines the value of this parameter as 0.056 (m/m). However, considering the variability/uncertainty in the application of this value at the site, a uniform distribution with +/-5% variation, i.e., uniform (0.053, 0.059), is assumed for the probabilistic analysis.

7). Total porosity of unsaturated zone

The estimated values of porosity for different soil textures can be found in literature [Carsel and Parrish, 1988]. The soil type of the site is sandy loam. For this soil texture,

the total porosity is expected to have the mean value $\mu = 0.41$ with the standard deviation $\sigma = 0.09$. The corresponding probability distribution function and cumulative distribution function are shown in Figure 4.5.

90% value: 0.5253

95% value: 0.5580

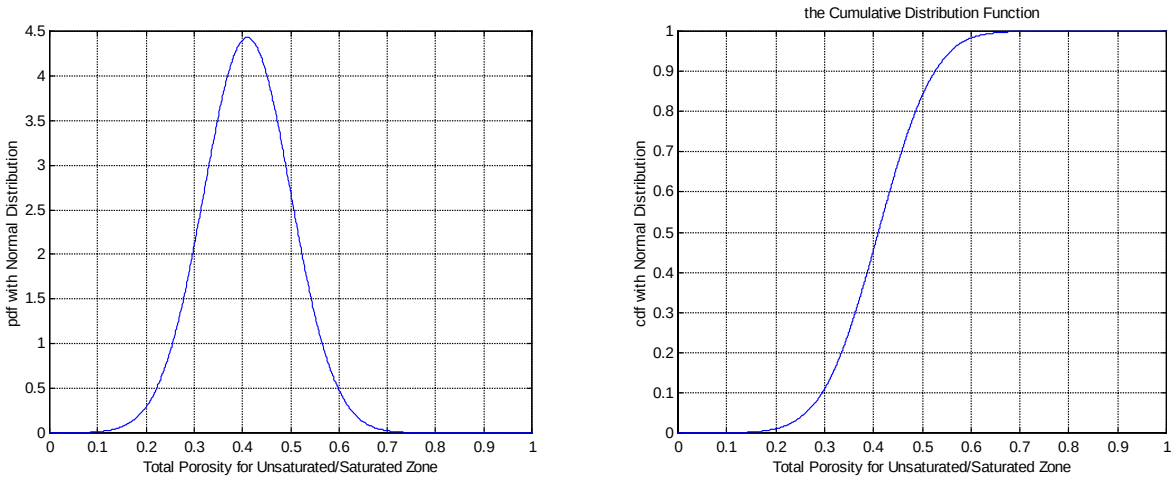

Figure 4.5 Distribution for total porosity

8). Total porosity of saturated zone

This was assumed to be the same as the porosity of the unsaturated zone.

9). Density of unsaturated zone

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

$$\rho = (1-e)\rho_s$$

where ρ is the soil bulk density (g/cm^3), e is the porosity (0.41), and ρ_s is the soil particle density (2.65 g/cm^3). So the mean value for density is 1.56 g/cm^3. For simplicity, assume its standard deviation is 0.25. Its probabilistic distribution function and cumulative distribution function are shown in Figure 4.6.

90% value: 1.8840 g/cm^3

95% value: 1.9750 g/cm^3

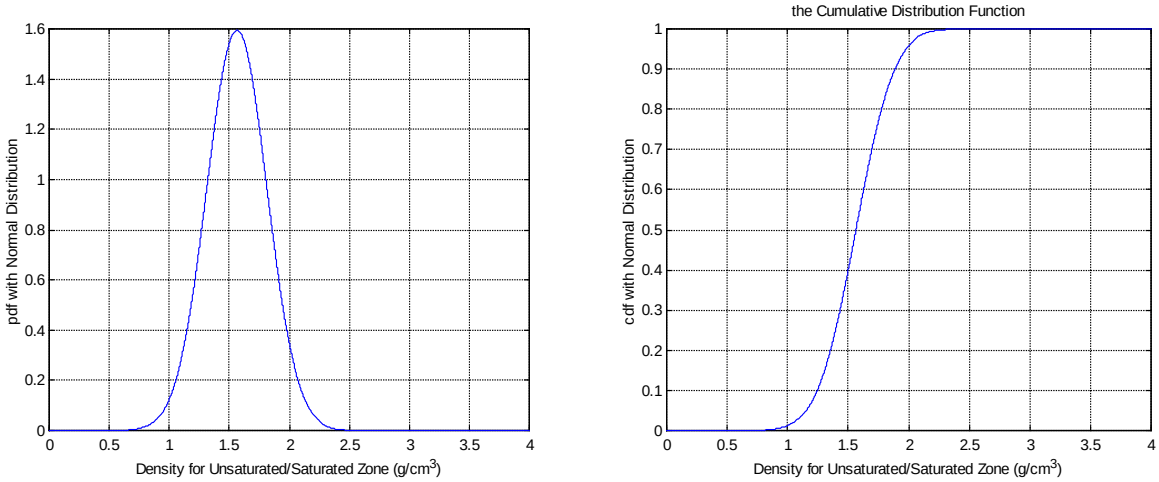

Figure 4.6 Distribution for density

10). Density of saturated zone

This was assumed to be the same as the density of the unsaturated zone

11). Consumption rate

The average food consumption rates for the plant location can be obtained from the national database. For the North Central region, the site-specific consumption rates can be generalized as the following tables.

Table 4.5 Human consumption rate of fruits, vegetables, and grains(g/d per capita)

	US population	North Central	Mean (North Central)	Standard deviation (North Central)
Total produce	282.6±3.5	282.4±6.7	282.4	6.7
Leafy	39.2±0.8	37.1±1.5	37.1	1.5
Exposed	86.0±1.5	87.8±2.9	87.8	2.9
Protected	150.4±2.3	150.1±4.3	150.1	4.3
Other	7.0±0.3	7.3±0.5	7.3	0.5
Total Grain	200.0±3.0	192.8±5.6	192.8	5.6
Breads	147.3±1.4	150.9±2.7	150.9	2.7
Cereals	29.9±1.3	28.7±2.4	28.7	2.4
Other	22.9±1.7	13.3±3.2	13.3	3.2

Table 4.6 Human consumption rate of meat, animal products, and fish (g/d)

	North Central	
	Male	Female
Beef	86.8	55.9
Pork	26.5	18.8
Lamb	0.4	0.4
Veal	0.4	0.4
Variety meats/games	11.9	8.0
Processed meats	26.3	15.8
Poultry	51.7	44.7

The data represent only the regional variability and does not include interpersonal variability. Therefore, the data could reflect a much narrower distribution than the actual site-specific information. For the purpose of demonstrating the effects of a very narrow distribution, this study used the above data treating them as normally distributed.

Because DandD and RESRAD have different definitions for the consumption rate, and the information in the above tables are quite different from the classifications defined by DandD and RESRAD, the information was combined for both codes to produce the following results.

A. Leafy

For both DandD and RESRAD input.

Mean μ: 13.5 kg/yr

Standard deviation σ: 0.55

90% value: 14.2 kg/yr

95% value: 14.4 kg/yr

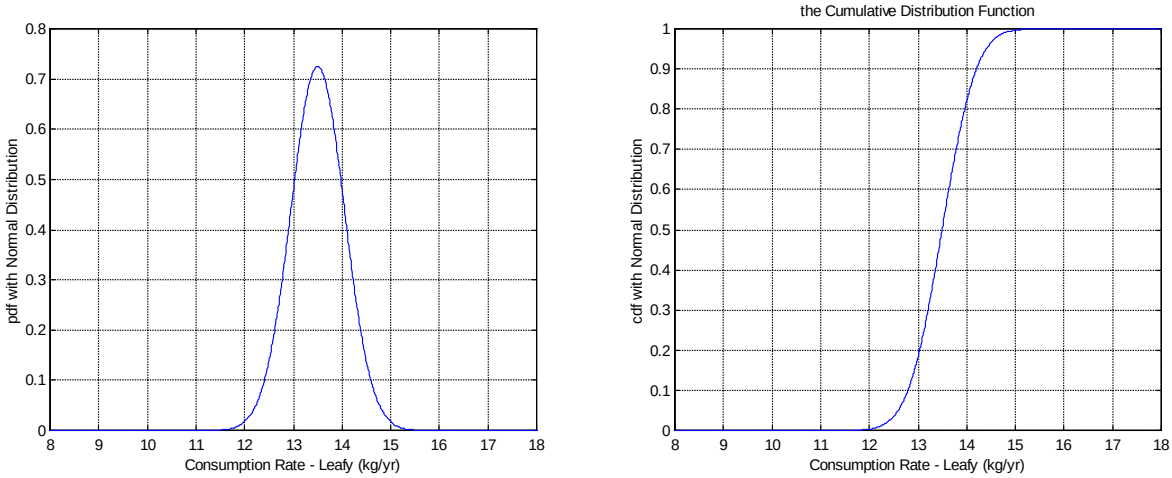

Figure 4.7 Distribution for consumption rate – leafy

B. Grain/Fruits, vegetables, and grain

For DandD, grain consumption rate is an input.

Mean μ: 15.33 kg/yr

Standard deviation σ: 0.7

90% value: 16.23 kg/yr

95% value: 16.48 kg/yr

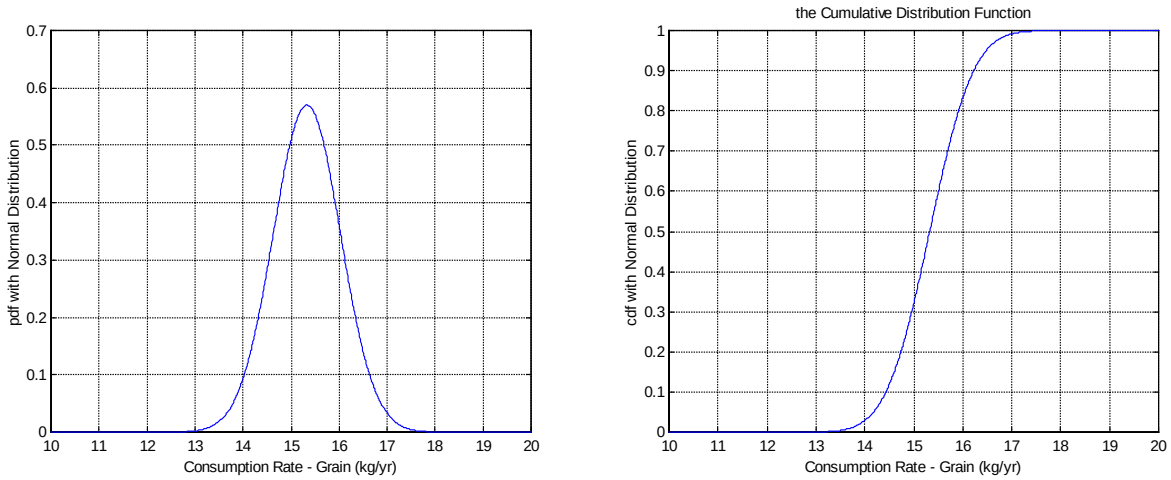

Figure 4.8 Distribution for consumption rate – grain

For RESRAD, fruits, vegetables, and grains consumption rate is an input.

Mean μ: 173.4 kg/yr

Standard deviation σ: 1.68

90% value: 175.55 kg/yr

95% value: 176.16 kg/yr

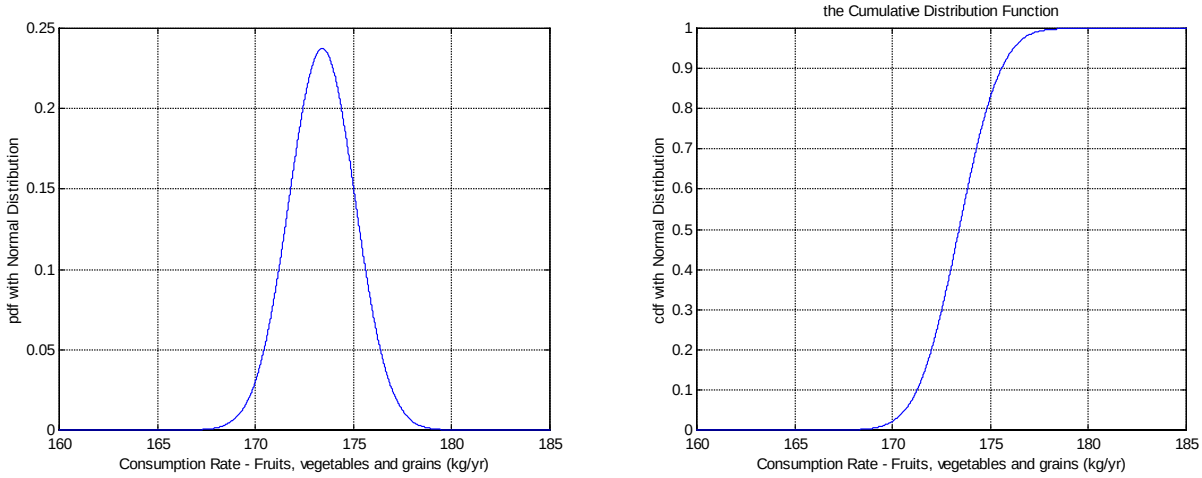

Figure 4.9 Distribution for consumption rate – fruits, vegetables, and grains

C. Beef

For DandD, beef consumption rate is an input.

Mean μ: 26.04 kg/yr

Standard deviation σ: 0.8

90% value: 27.07 kg/yr

95% value: 27.36 kg/yr

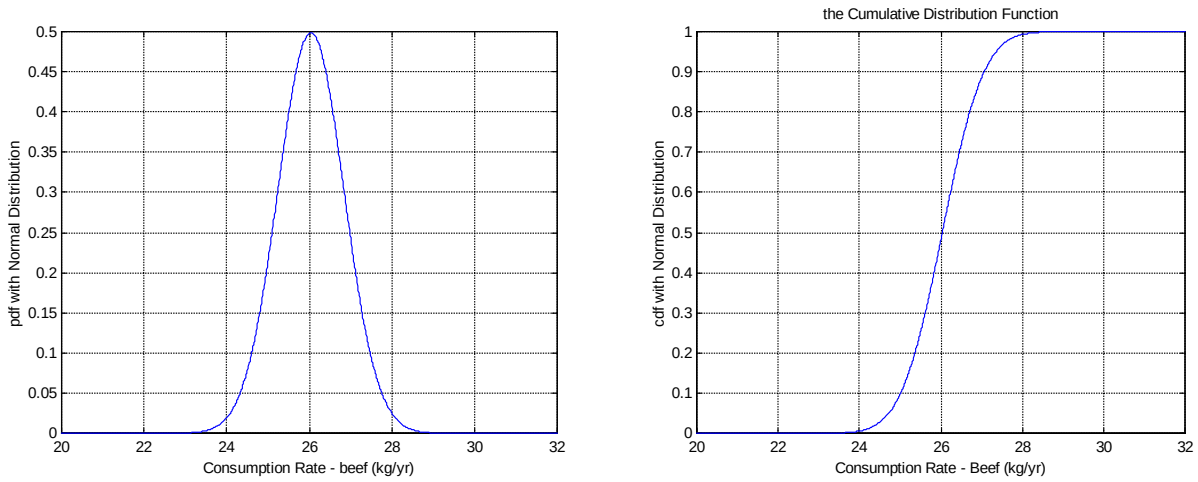

Figure 4.10 Distribution for consumption rate – beef

D. Poultry

For DandD, beef consumption rate is an input.

Mean μ: 37.47 kg/yr

Standard deviation σ: 0.8

90% value: 38.50 kg/yr

95% value: 38.79 kg/yr

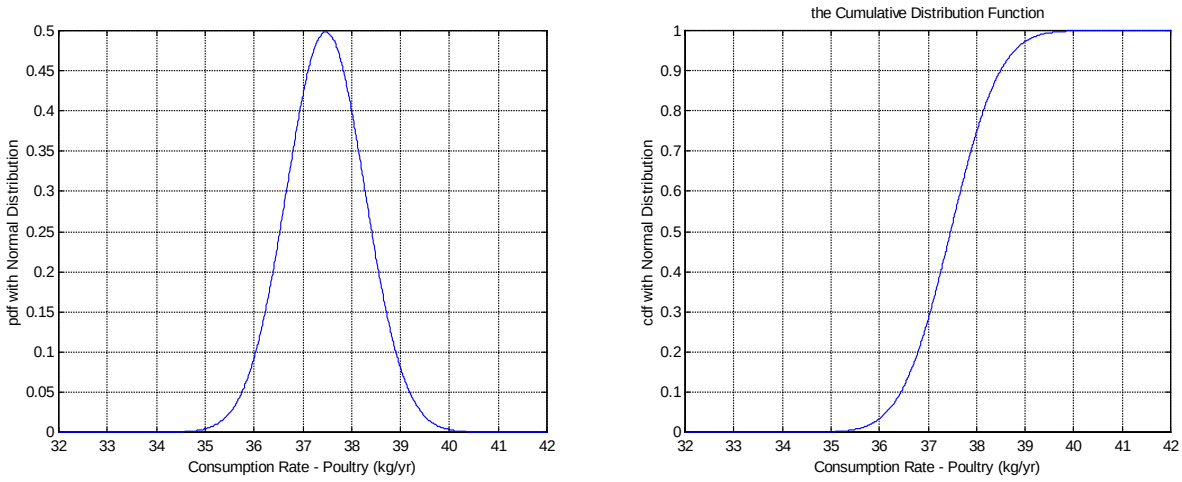

Figure 4.11 Distribution for consumption rate – poultry

E. Meat and poultry

For RESRAD, meat and poultry consumption rate is an input.

Mean μ: 63.51 kg/yr

Standard deviation σ: 1.2

90% value: 65.05 kg/yr

95% value: 65.48 kg/yr

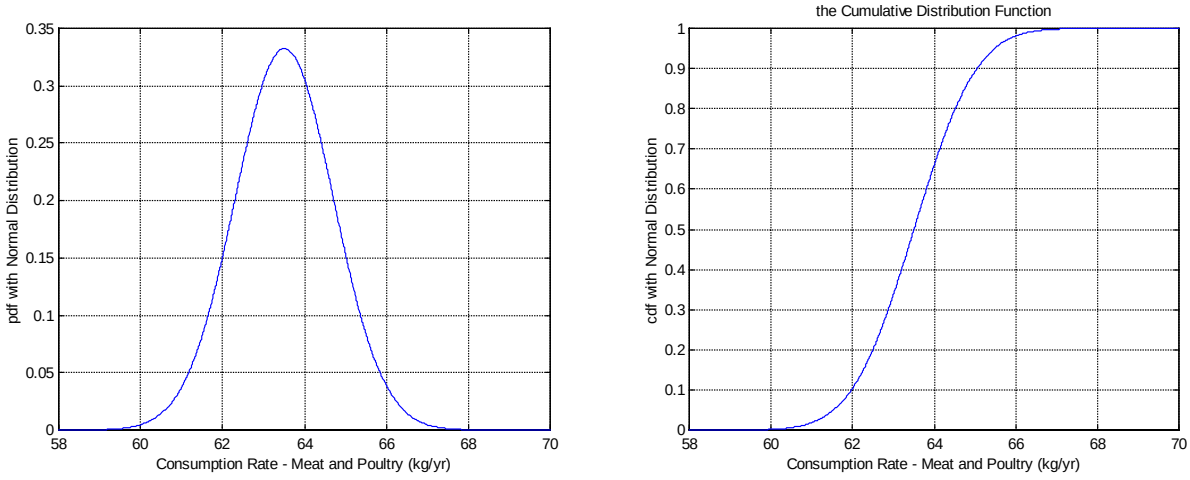

Figure 4.12 Distribution for consumption rate – meat and poultry

4.3.3 Site-Specific Data for Radionuclide-Specific Parameters

In this thesis, only 7 radionuclides were analyzed considering their importance in nuclear plant decommissioning (see section 3.2). These are Am-241, C-14, Co-60, Cs-137, Ni-59, Pu-239, and Sr-90.

As for the nuclide-specific parameters in this section, the partition coefficient and soil-to-plant transfer factor are discussed here as both are important in dose assessment. When relevant information was unavailable for some radionuclides, assumptions were made based on engineering judgments.

1). Partition coefficient Kd

The partition coefficient Kd for the given soil type is obtained from the observations by M. I. Sheppard and D. H. Thibault. The Kd values were assumed to be lognormally distributed. Table 4.7 lists the lognormal distributions of Kd values for different radionuclides for the given soil type of the site (i.e., sandy loam).

Table 4.7 The Kd values in loam soil (L/kg)

Element	# of observations	μ^a	σ^b	exp(μ)	Range
Am	20	9.17	1.4	9600	400 to 48309
C		2.996	1.0[c]	20	
Co	23	7.17	1.3	1300	100 to 9700
Cs	54	8.434	1.3	4600	560 to 21687
Ni		5.704	1.0[c]	300	
Pu	21	7.09	1.2	1200	100 to 5933
Sr	43	2.996	1.7	20	0.01 to 300

Note: a Mean of the natural logarithms of the observed values

b Standard deviation of the natural logarithms of the observed values

c Assumed as 1.0

2). Soil-to-plant transfer factor

The soil-to-plant transfer factors were found to be very important in dose assessment, especially with the RESRAD code (see section 3.2). The parameter is radionuclide and soil type dependent. However, the data from the literature, as both nuclide and soil type specific information, are available only for Cs-137 and Sr-90. Therefore, only these two nuclides were analyzed for this parameter.

Tables 4.8 and 4.9 list the soil-to-plant transfer factors of Cs-137 and Sr-90 for the given soil-type of the site for different types of plants [Nisbet and Woodman, 2000]. From these data, the subgroup average soil-to-plant transfer factors are estimated for the use in the DandD code. These are listed in pairs, i.e., the natural logarithm of the mean and the natural logarithm of standard deviation.

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

Table 4.8 Soil-to-plant transfer factor for Cs in loam (Bq/kg/Bq/kg)

Crops	Number of observations	Number of studies	Geometric mean	Geometric Standard Deviation	95% confidence interval, lower	95% confidence interval, upper
Cereals	358	23	1.4e-2	5.67	4.5e-4	4.2e-1
Tubers	173	14	2.9e-2	3.18	2.9e-3	2.8e-1
Green vegetables	100	12	1.2e-1	3.24	1.2e-2	1.2
Brassicas	40	9	2.8e-2	2.19	5.9e-3	1.3e-1
Root vegetables	52	11	3.7e-2	5.10	1.5e-3	9.0e-1
Legumes	74	11	1.1e-2	4.16	6.4e-4	1.8e-1
Onions	11	2	8.5e-3	2.64	1.3e-3	5.7e-2

Table 4.9 Soil-to-plant transfer factor for Sr in loam (Bq/kg/Bq/kg)

Crops	Number of observations	Number of studies	Geometric mean	Geometric standard deviation	95% confidence interval, lower	95% confidence interval, upper
Cereals	88	13	1.5e-1	2.55	2.2e-2	9.4e-1
Tubers	33	10	2.1e-1	2.05	5.3e-2	8.6e-1
Green vegetables	75	7	2.4	1.97	6.5e-1	9.1
Brassicas	28	7	2.2	2.75	3.0e-1	1.6e+1
Root vegetables	29	7	1.6	2.91	1.9e-1	1.3e+1
Legumes	58	4	1.4	2.19	3.0e-1	6.5
Onions	8	2	8.8e-1	2.22	1.8e-1	4.2

In comparison to DandD, the soil-to-plant transfer factor is described in RESRAD as a single value input for a nuclide ignoring the variations in different types of plants. Table 4.10 lists the soil-to-transfer factor data and other site-specific parameters discussed above in this thesis for DandD and RESRAD.

Table 4.10 Parameter used in DandD and RESRAD (Site-specific)

Parameter	Site-specific data						
	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59
Partition Coefficient Kd(ml/g)	8.434±1.3	2.996±1.7	7.09±1.2	7.17±1.3	2.996±1.0	9.17±1.4	5.704±1.0

Soil-to-plant Transfer (pCi/kg / pCi/kg)	DandD							RESRAD						
	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59
Leafy(LOGN)	-2.12 ±1.18	0.88 ±0.68	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Root (LOGN)	-3.30 ±1.63	0.47 ±1.07	N/A	N/A	N/A	N/A	N/A							
Fruit (LOGN)	-3.54 ±1.16	-1.56 ±0.72	N/A	N/A	N/A	N/A	N/A							
Grain (LOGN)	-4.27 ±1.74	-1.90 ±0.94	N/A	N/A	N/A	N/A	N/A							

Element Independent		
Area of contamination(m^2)	Use DandD default: 2,400 m^2	
Thickness of unsaturated zone(m)	LOGN: 0.733 ± 0.3536	
Contaminated zone b parameter	/	4.9(Deterministic)
Precipitation(m/yr)	LOGN: -0.245 ± 0.254	
Saturated zone hyd. Cond.(m/s)	/	LOGN: -5.148 ± 0.405
Saturated zone hydraulic gradient	/	0.056(Deterministic)
Density of Unsaturated Zone(g/cm^3)	NORM: mean = 1.56, std = 0.25	
Density of Saturated Zone(g/cm^3)	NORM: mean = 1.56, std = 0.25	
Porosity of Unsaturated Zone	NORM: mean = 0.41, std = 0.09	
Porosity of Saturated Zone	NORM: mean = 0.41, std = 0.09	
Consumption (kg/yr)		
Leafy	NORM: mean = 13.5, std = 0.55	
(Fruits, vegetables)Grain	NORM: mean = 15.33, std = 0.7	NORM: mean = 173.4, std = 1.68
Beef	NORM: mean = 26.04, std = 0.8	NORM: mean = 63.51, std = 1.2
Poultry	NORM: mean = 37.47, std =0.8	

Remark: LOGNormal distribution: $\ln\mu \pm \ln\sigma$; The data are unavailable for the shaded area, sensitivity analysis will be applied (with 30% increment of μ_g)

4.3.4 Bayesian Updating of Input Data with Site-specific Parameters

The information obtained from the site-specific investigations including the information from expert judgments (i.e., the new data developed in section 4.3.3.) represents new pieces of information for the parameters of interest in dose assessment. This is in addition to the prior information available from the national database.

If the new information is complete in representing the variability and uncertainty of a parameter at the site, the information can be directly used as inputs to the dose assessment without considering any prior information. However, in reality, the new information obtained is not based on a complete characterization of the parameter at the given site conditions, but rather represents a limited understanding of the behavior of the parameter at the site. In this case, combination of the new information with the prior national data can be useful to reduce the uncertainty of the parameter at the site conditions.

Bayesian updating is very useful for the combination of information as described in section 2.2. Bayesian methods allow the subjective knowledge and experience of experts to be combined with the pre-existing information on the data to yield a better informed assessment of the uncertainty of a parameter. However, a key assumption usually employed in Bayesian updating is that the likelihood of observing the new information given the prior information is known. In reality, the likelihood is dependent upon the errors in both the old information and the new information (e.g., measurement errors, spatial and temporal variability, any unrecognized and/or correlated errors). It is difficult to recognize these errors thus to define the correct likelihood function.

In this thesis, a bounding approach for the selection of likelihood function is employed and compared for their effect on the final results. As a very optimistic case, it is assumed that the likelihood of observing the new information given the prior national data is represented by the probability distributions of the parameters developed from site-specific investigations. This implies that there is no error in obtaining the new information other than what is represented by the probability distributions of the parameters. To present the other end of the bounding approach, errors in obtaining the

new information were conservatively estimated and used for the updating. This latter approach is described in section 4.7.

In this section, the first/optimistic approach was used to combine the new information for the site (in section 4.3.3) with the prior national data (in section 3.3). Since most of the data are in either normal or lognormal distributions, Bayesian conjugate pair method was applicable to the updating. The relevance of using this approach is discussed in section 4.7 with the descriptions of the comparisons of the results from the bounding approach.

The updated results for each parameter are described in the following. Only those figures with comparable curves between the prior and posterior case are shown. For the case of the DandD code (which is deterministic), the updated input data of a parameter was the mean or geometric mean of the probability distribution.

A. Physical (Non Radionuclide-Specific) Parameters

1). Area of contamination (m^2)

Deterministic: no Bayesian updating. Use 2,400 m^2.

2). Thickness of unsaturated zone (m)

Prior: Lognormal (2.296 ± 1.276)

Site-specific: Lognormal (0.733 ± 0.3536)

Posterior: Lognormal (0.8445 ± 0.3408)

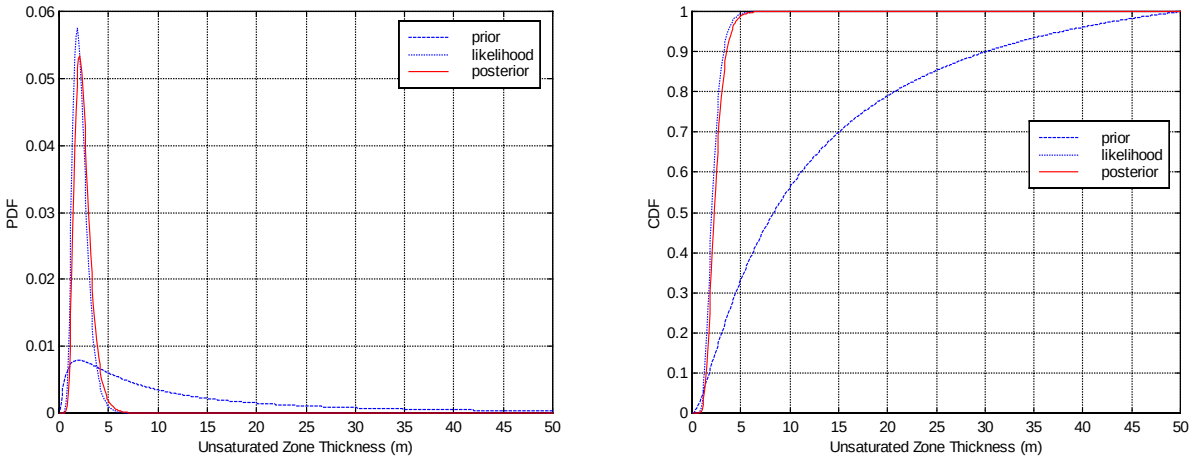

Figure 4.13 Bayesian updating for the thickness of unsaturated zone

3). Contaminated zone b parameter

No updating was performed due to lack of prior information. Uniform distribution between 4.41 and 5.39 was used.

4). Precipitation rate (m/yr)

Prior: No distribution assigned.

Site-specific: Lognormal (-0.245 ± 0.254)

Posterior: No updating, assumed as same as site-specific distribution.

5). Saturated zone hydraulic conductivity (m/s)

Prior: Lognormal (2.3 ± 2.11)

Site-specific: Lognormal (-5.148 ± 0.405)

Posterior: Lognormal (-4.8833 ± 0.3977)

6). Saturated zone hydraulic gradient

Uniform distribution within range of 0.0055 and 0.0057.

7). Total porosity of unsaturated zone

Prior: Normal (0.425 ± 0.0867)

Site-specific: Normal (0.41 ± 0.09)

Posterior: Normal (0.4178 ± 0.0624)

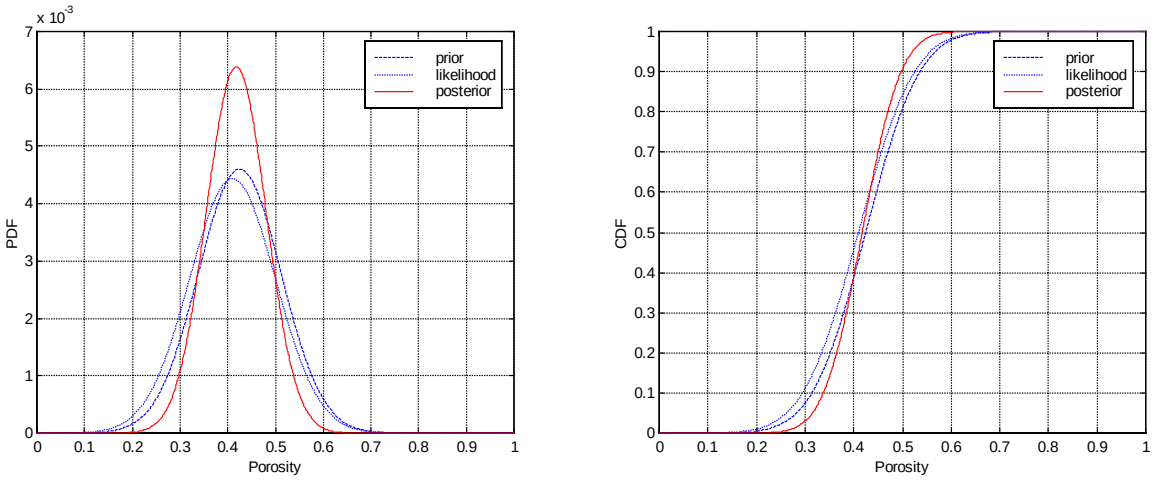

Figure 4.14 Bayesian updating for total porosity

8). Total porosity of saturated zone

As same as unsaturated zone.

9). Density of unsaturated zone (g/cm^3)

Prior: Normal (1.52 ± 0.23)

Site-specific: Normal (1.56 ± 0.25)

Posterior: Normal (1.5383 ± 0.1693)

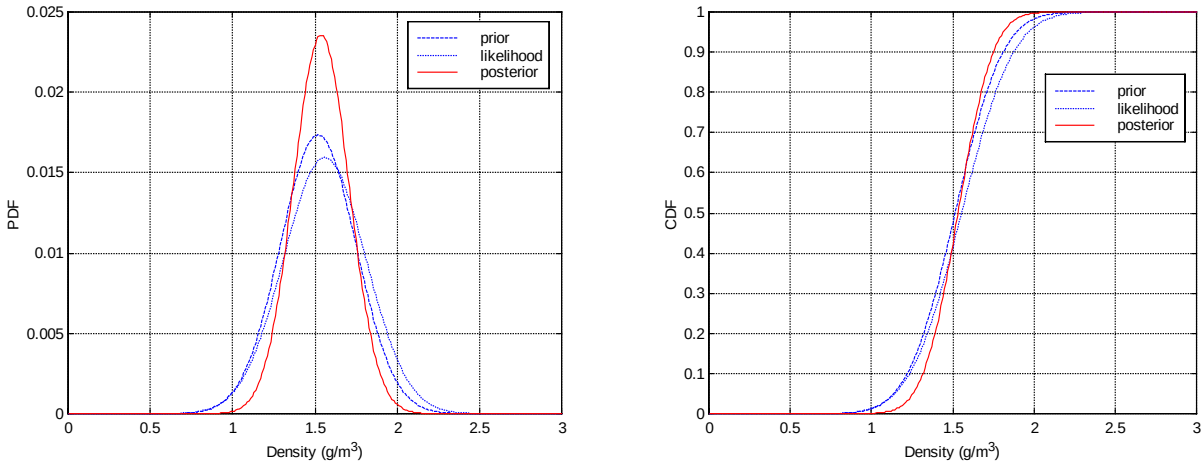

Figure 4.15 Bayesian updating for density

10). Density of saturated zone (g/cm^3)

As same as unsaturated zone.

11). Consumption rate (kg/yr)

None of the inputs for consumption rate was updated because no distribution type was assigned for leafy and meat/poultry. For fruit, vegetable and grain, its type is triangular (see Table 3.3). However, they are analyzed with the assumptions of having same distributions and parameters as normally distributed site-specific data.

B. Radionuclide Dependent Parameters

1). Partition coefficient Kd (ml/g)

1.1) Cs-137: Prior: Lognormal (6.1 ± 2.33)

Site-specific: Lognormal (8.434 ± 1.3)

Posterior: Lognormal (7.88 ± 1.14)

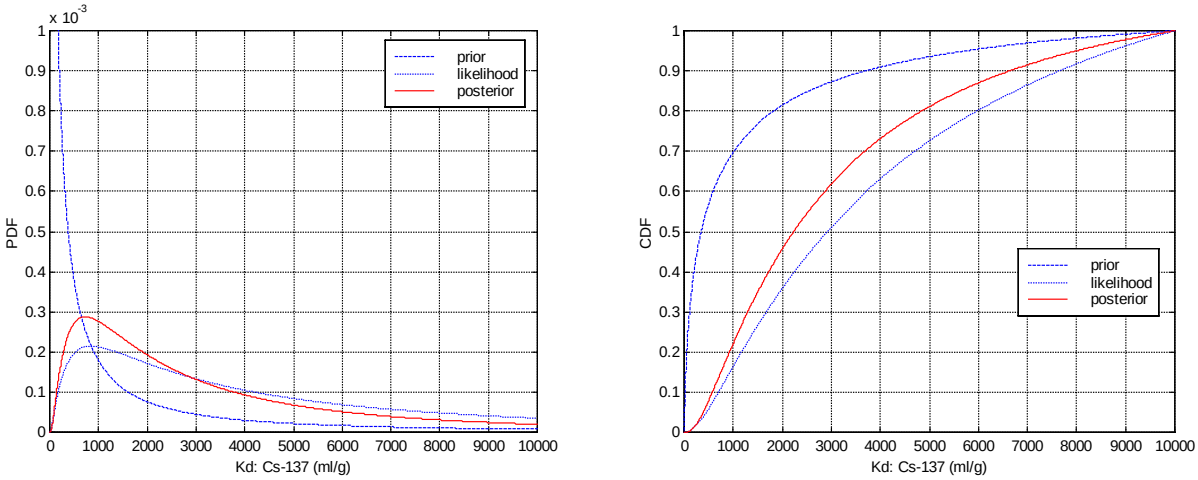

Figure 4.16 Bayesian updating for Kd: Cs-137

1.2) Sr-90: Prior: Lognormal (3.45 ± 2.12)

Site-specific: Lognormal (2.996 ± 1.7)

Posterior: Lognormal (3.1737 ± 1.3263)

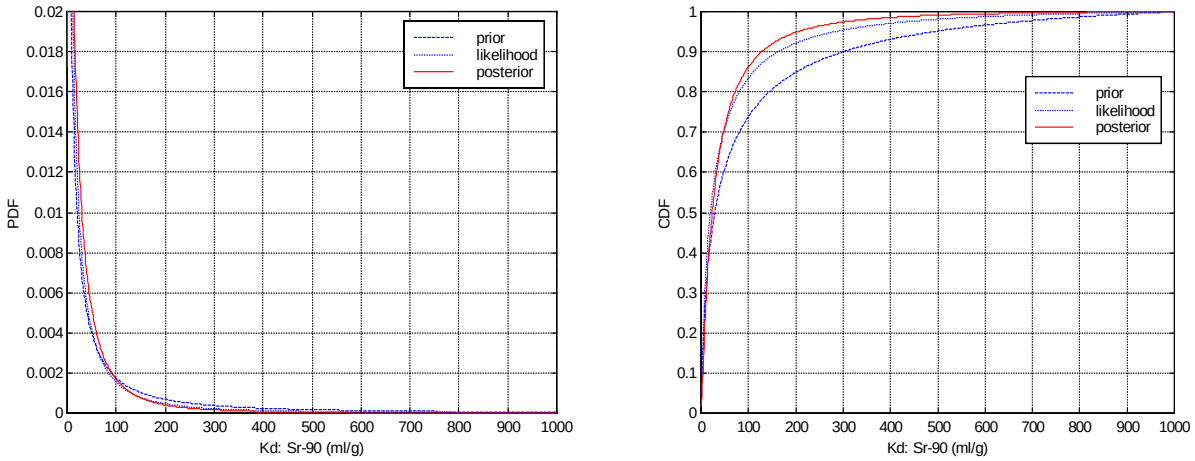

Figure 4.17 Bayesian updating for Kd: Sr-90

1.3) Pu-239: Prior: Lognormal (6.86 ± 1.89)

Site-specific: Lognormal (7.09 ± 1.2)

Posterior: Lognormal (7.0239 ± 1.0131)

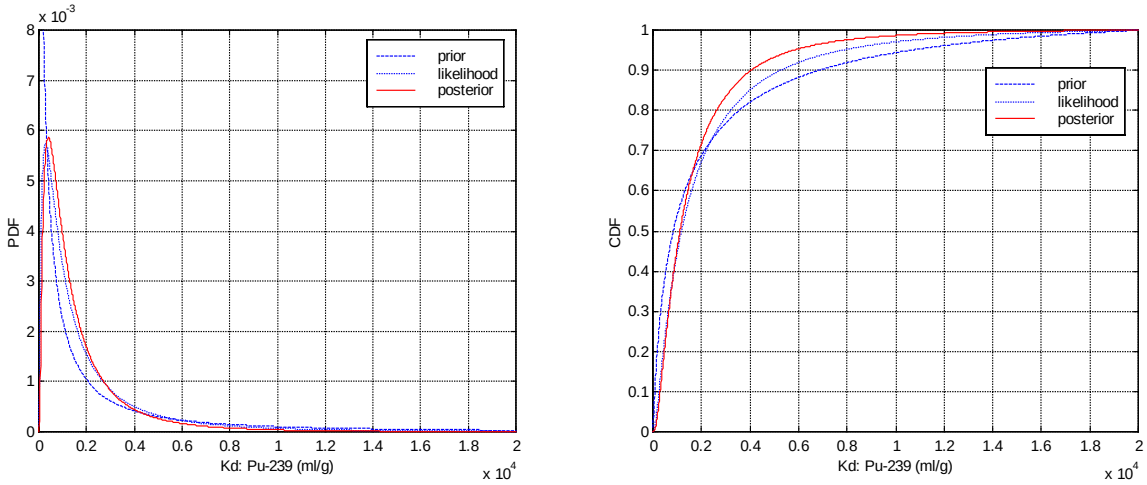

Figure 4.18 Bayesian updating for Kd: Pu-239

1.4) Co-60: Prior: Lognormal (5.46 ± 2.53)

Site-specific: Lognormal (7.17 ± 1.3)

Posterior: Lognormal (6.8128 ± 1.1563)

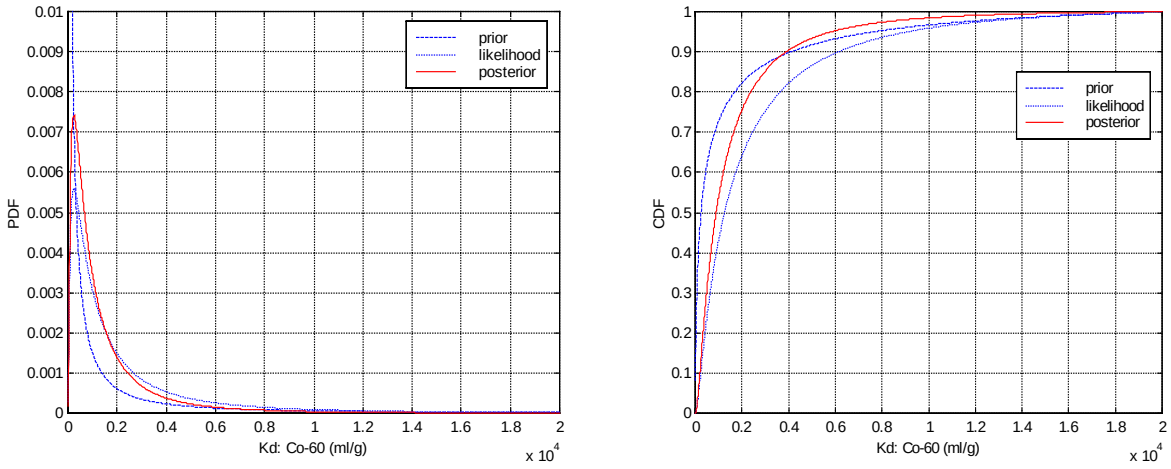

Figure 4.19 Bayesian updating for Kd: Co-60

1.5) C-14: Prior: Lognormal (2.4 ± 3.22)

Site-specific: Lognormal (2.996 ± 1.0)

Posterior: Lognormal (2.9436 ± 0.955)

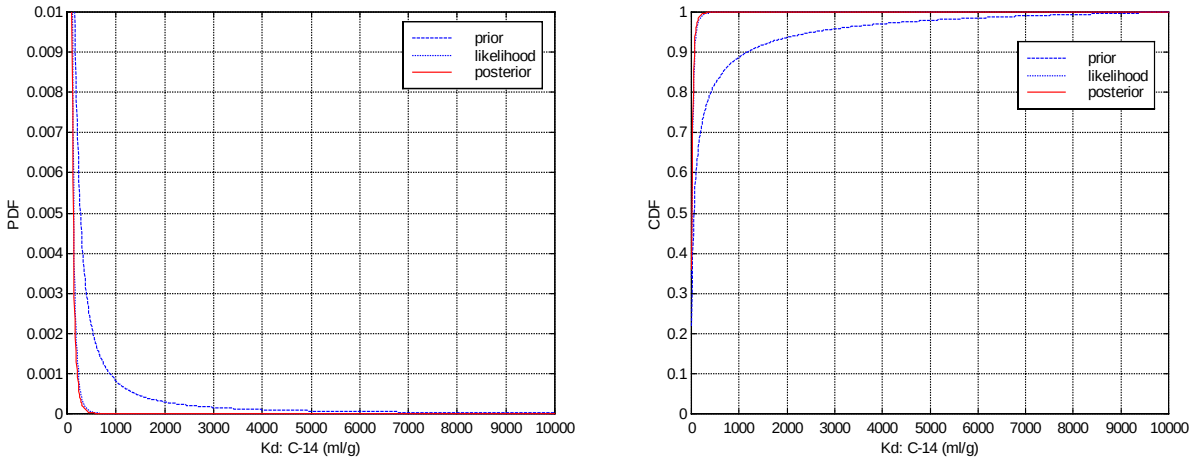

Figure 4.20 Bayesian updating for Kd: C-14

1.6) Am-241: Prior: Lognormal (7.28 ± 3.15)

Site-specific: Lognormal (9.17 ± 1.4)

Posterior: Lognormal (8.8582 ± 1.2793)

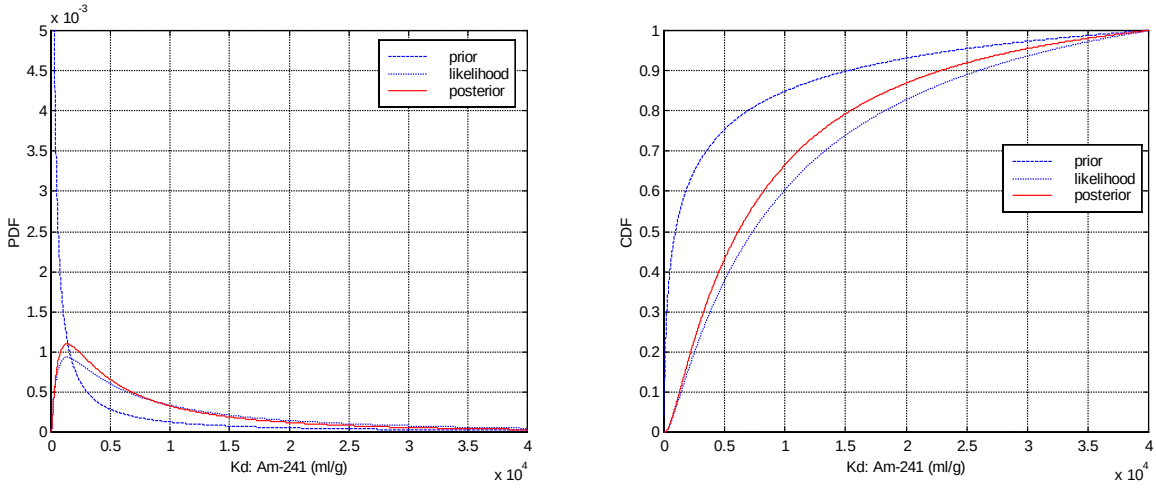

Figure 4.21 Bayesian updating for Kd: Am-241

1.7) Ni-59: Prior: Lognormal (6.05 ± 1.46)

Site-specific: Lognormal (5.704 ± 1.0)

Posterior: Lognormal (5.8145 ± 0.825)

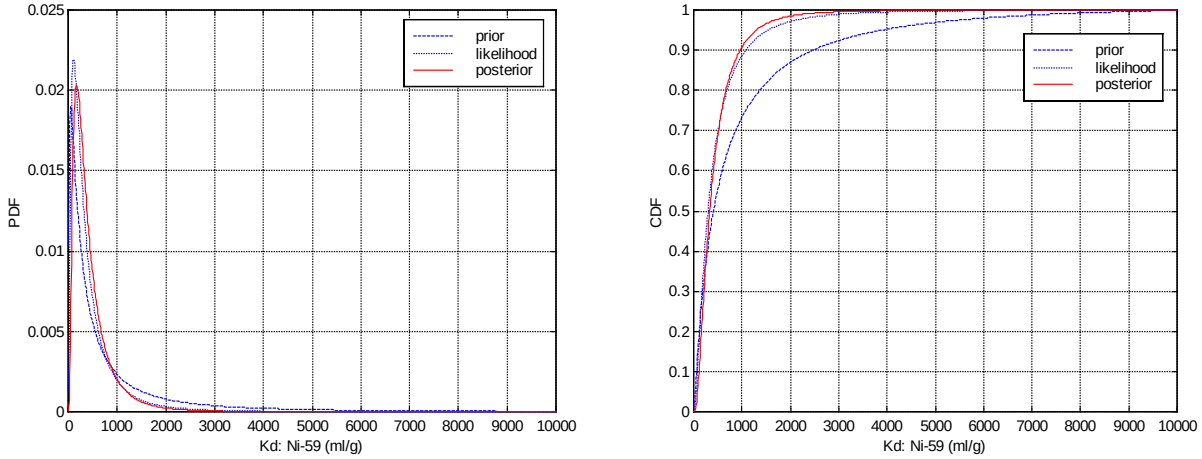

Figure 4.22 Bayesian updating for Kd: Ni-59

2). Soil-to-plant transfer factor (pCi/kg/pCi/kg)

Some site-specific information for the soil-to-plant transfer factor is only directly applicable to the DandD (for Cs-137 and Sr-90, see Table 4.10). The mean or geometric

mean of the updated probability distribution functions was used in the posterior DandD analysis. As for the RESRAD posterior probabilistic analysis, the sensitivity analysis is performed by assuming that the geometric mean of the posterior distribution increases by 30% from that of the prior distribution (see Table 3.3), while the geometric standard deviation remains unchanged.

Table 4.11 lists the “updated” parameter values for both DandD and RESRAD.

Table 4.11 Parameters after Bayesian Updating

Parameter	Site-specific data						
	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59
Partition Coefficient Kd(ml/g)	7.88±1.14	3.1737±1.3263	7.0239±1.0131	6.8128±1.1563	2.9436±0.955	8.8582±1.2793	5.8145±0.825

Soil-to-plant Transfer (pCi/kg / pCi/kg)	DandD							RESRAD						
	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59	Cs-137	Sr-90	Pu-239	Co-60	C-14	Am-241	Ni-59
Leafy (LOGN)	0.12	2.41	/	/	/	/	/	-2.958 ±0.9933	-0.938 ±0.9933	-6.648 ±0.9163	-2.268 ±0.9163	-0.907 ±0.9042	-6.648 ±0.9163	-2.738 ±0.9163
Root (LOGN)	0.0369	1.6	/	/	/	/	/							
Fruit (LOGN)	0.029	0.21	/	/	/	/	/							
Grain (LOGN)	0.014	0.15	/	/	/	/	/							

Element Independent		
Area of contamination(m^2)	2,400	
Thickness of unsaturated zone(m)	2.2156	LOGN: 0.8445 ± 0.3408
Contaminated zone b parameter	/	Uniform: 4.8-5.0
Infiltration Rate(m/yr)	0.3425	Precipitation(m/yr): LOGN: -0.245 ± 0.254
Saturated zone hydraulic conductivity(m/s)	/	LOGN: -4.8833 ± 0.3977
Saturated zone hydraulic gradient	/	0.056
Density of Unsaturated Zone(g/cm^3)	NORM: 1.5383 ± 0.1693	
Density of Saturated Zone(g/cm^3)	NORM: 1.5383 ± 0.1693	
Porosity of Unsaturated Zone	NORM: 0.4178 ± 0.0624	
Porosity of Saturated Zone	NORM: 0.4178 ± 0.0624	
Consumption (kg/yr)		
Leafy	NORM: 13.5 ± 0.55	
(Fruits, vegetables)Grain	NORM: 15.33 ± 0.7	NORM: 173.4 ± 1.68
Beef	NORM: 26.04 ± 0.8	NORM: 63.51 ± 1.2
Poultry	NORM: 37.47 ± 0.8	

Remark: LOGNormal distribution: $\ln\mu \pm \ln\sigma$, NORMal distribution: $\mu \pm \sigma$.

4.4 Dose evaluation with DandD Deterministic Code

After the new site-specific data was used for the Bayesian updating of prior information, the new posterior data are used as inputs for dose assessment. In this section, the results are compared between the new posterior input data and prior default inputs for the deterministic analysis with the DandD code. Table 4.6 through 4.12 lists the results for each radionuclide of interest. The relative importance of each parameter is calculated by,

$$Relative \quad importance = \left| \frac{(TEDE_{updated} - TEDE_{default}) \Big/ TEDE_{default}}{(Value_{updated} - Value_{default}) \Big/ Value_{default}} \right| \qquad (4.1)$$

1. Cs-137

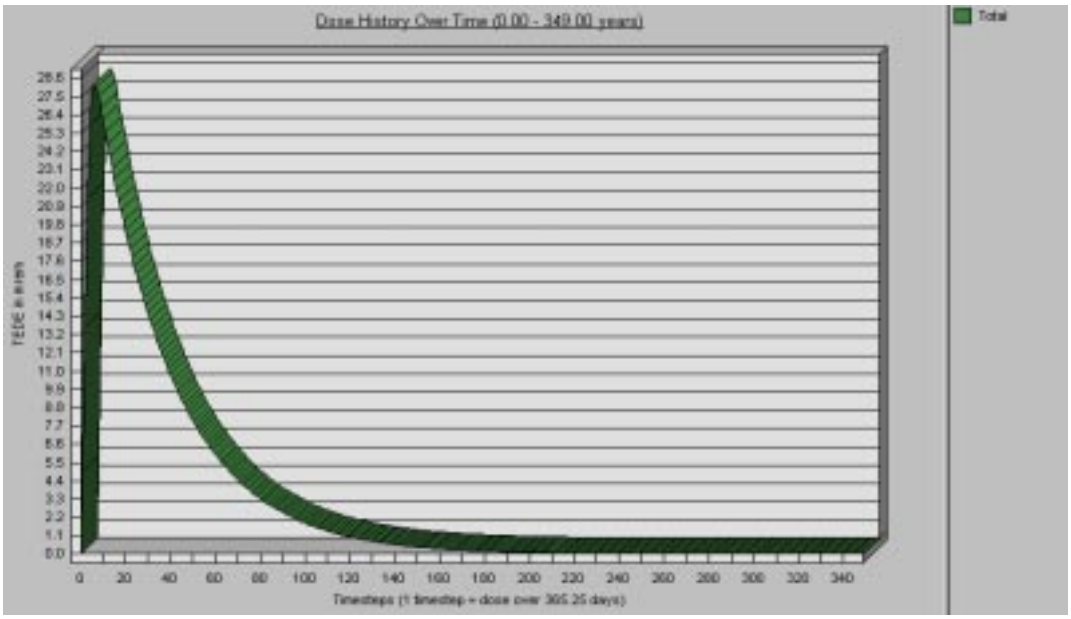

Figure 4.23 Dose values over time in year for default distributions (Cs-137)

Table 4.12 Dose results with updated information for Cs-137

Default peak TEDE: 28.3 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		1.2288	2.2156	16.9	0.5016
Infiltration Rate (m/yr)		0.2526	0.3425	38.2	0.9829
Density of Unsaturated Zone (g/cm^3)		1.4312	1.5383	26.6	0.8027
Porosity of Unsaturated Zone		0.4599	0.4178	28.3	0
Consumption rate	Leafy	21.4	13.5	28.1	0.0191
	Grain	14.4	15.33	28.3	0
	Beef	39.8	26.04	28.1	0.0204
	Poultry	25.3	37.47	28.3	0
Partition Coefficient Kd (ml/g)		10.5	2643.87	2.03	0.0037
Soil-to-plant Transfer Factor (pCi/kg / pCi/kg)	Leafy	0.018	0.12	28.3	0
	Root	0.031	0.037	28.3	0
	Fruit	0.14	0.029	28.3	0
	Grain	0.0066	0.014	28.3	0

2. Sr-90

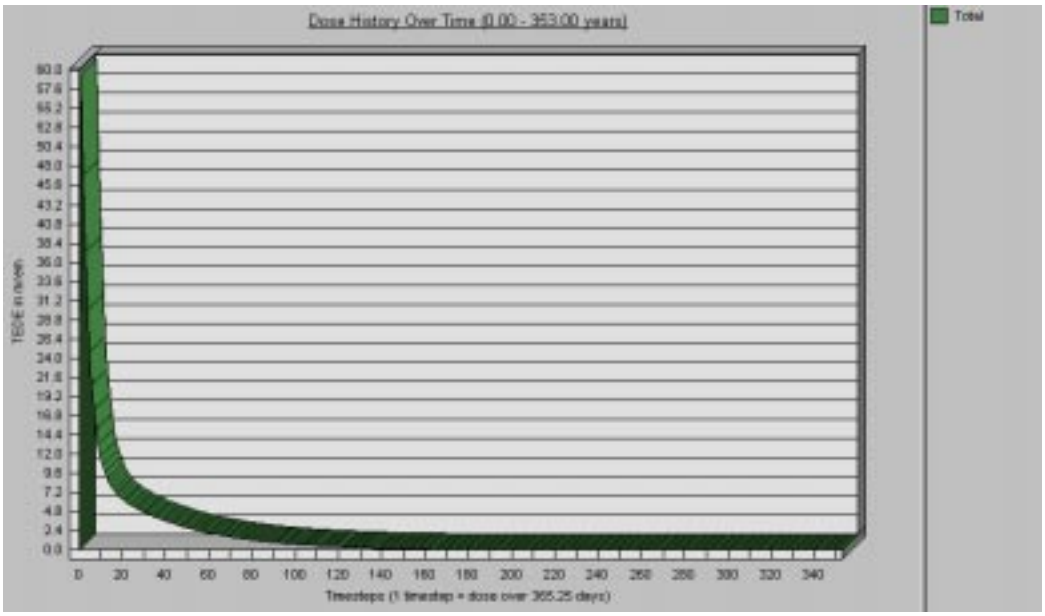

Figure 4.24 Dose values over time in year for default distributions (Sr-90)

Table 4.13 Dose results with updated information for Sr-90

Default peak TEDE: 59.4 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		1.2288	2.2156	59.4	0
Infiltration Rate (m/yr)		0.2526	0.3425	59.5	0.0047
Density of Unsaturated Zone (g/cm^3)		1.4312	1.5383	59.4	0
Porosity of Unsaturated Zone		0.4599	0.4178	59.4	0
Consumption rate	Leafy	21.4	13.5	49.2	0.4652
	Grain	14.4	15.33	59.5	0.0261
	Beef	39.8	26.04	59.3	0.0049
	Poultry	25.3	37.47	59.5	0.0035
Partition Coefficient Kd (ml/g)		31.4	23.9	59.5	0.007
Soil-to-plant Transfer Factor (pCi/kg / pCi/kg)	Leafy	64	4.21	4.25	0.9938
	Root	0.46	1.6	60.7	0.0088
	Fruit	0.26	0.21	59.3	0.0088
	Grain	0.085	0.15	59.6	0.0044

3. Pu-239

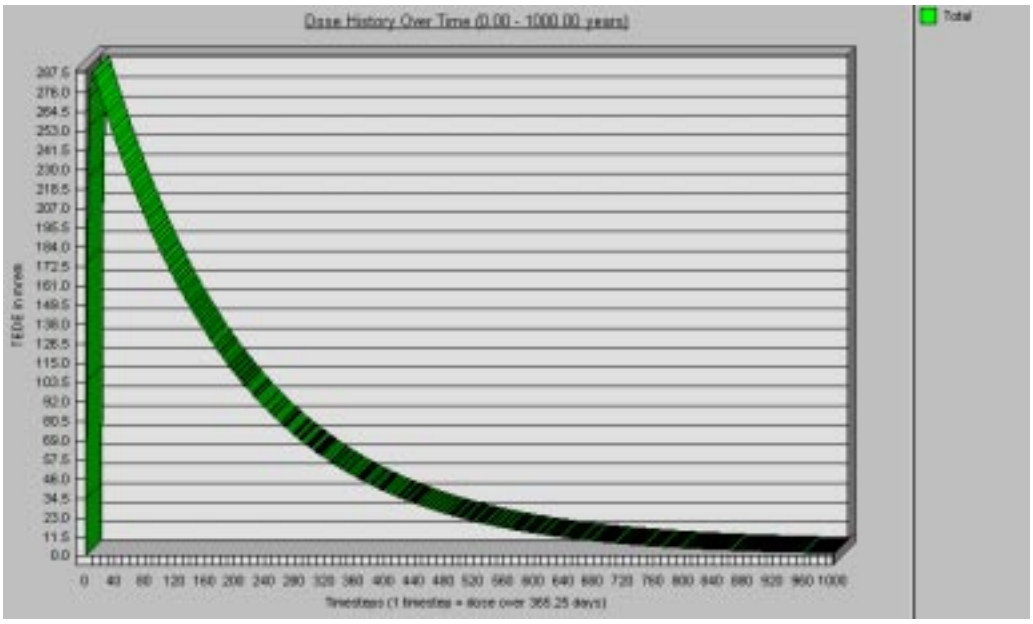

Figure 4.25 Dose values over time in year for default distributions (Pu-239)

Table 4.14 Dose results with updated information for Pu-239

Default peak TEDE: 288 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		1.2288	2.2156	173	0.4972
Infiltration Rate (m/yr)		0.2526	0.3425	383	0.9268
Density of Unsaturated Zone (g/cm^3)		1.4312	1.5383	272	0.7424
Porosity of Unsaturated Zone		0.4599	0.4178	289	0.0379
Consumption rate	Leafy	21.4	13.5	275	0.1223
	Grain	14.4	15.33	289	0.0538
	Beef	39.8	26.04	288	0
	Poultry	25.3	37.47	288	0
Partition Coefficient Kd (ml/g)		13.6	1123.16	13.5	0.0117
Soil-to-plant Transfer Factor		Site-information are unavailable			

4. Co-60

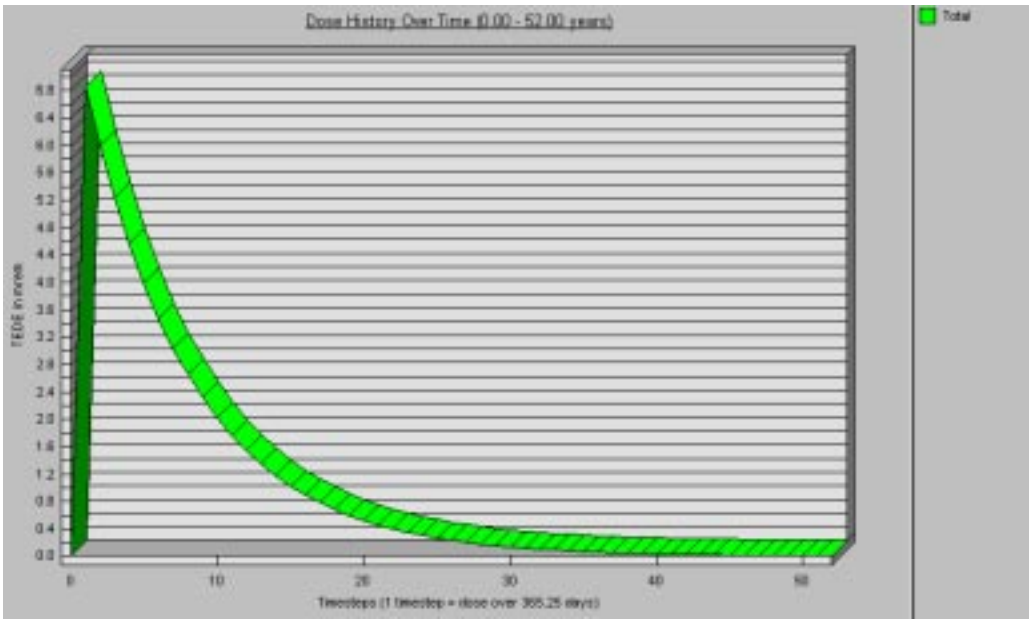

Figure 4.26 Dose values over time in year for default distributions (Co-60)

Table 4.15 Dose results with updated information for Co-60

Default peak TEDE: 6.87 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		1.2288	2.2156	6.87	0
Infiltration Rate (m/yr)		0.2526	0.3425	6.87	0
Density of Unsaturated Zone (g/cm^3)		1.4312	1.5383	6.87	0
Porosity of Unsaturated Zone		0.4599	0.4178	6.87	0
Consumption rate	Leafy	21.4	13.5	6.86	0.0039
	Grain	14.4	15.33	6.87	0
	Beef	39.8	26.04	6.86	0.0042
	Poultry	25.3	37.47	6.87	0
Partition Coefficient Kd (ml/g)		1510	909.41	6.87	0
Soil-to-plant Transfer Factor		Site-information are unavailable			

5. C-14

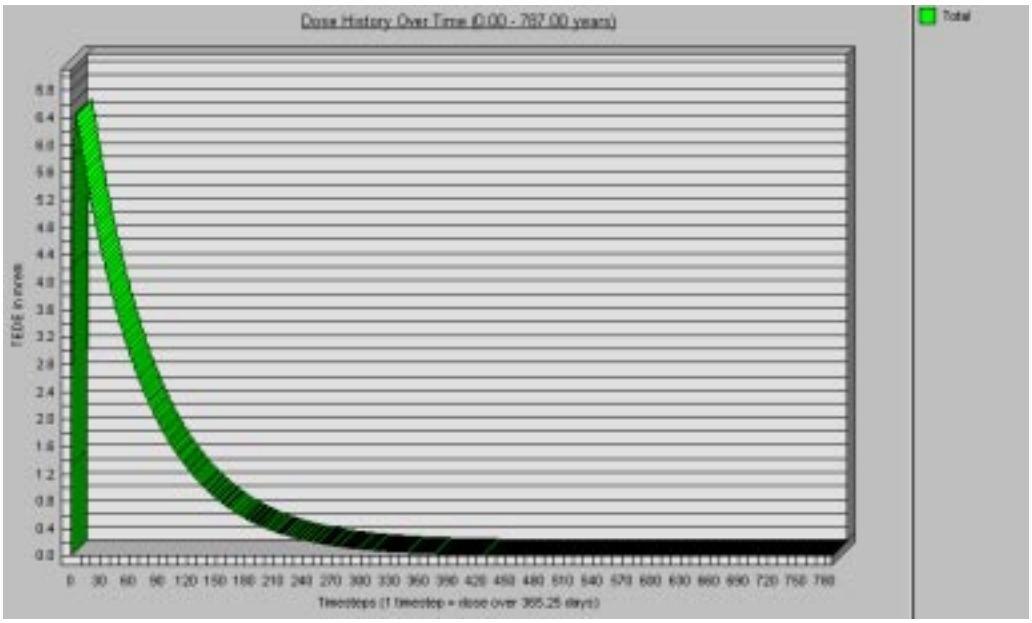

Figure 4.27 Dose values over time in year for default distributions (C-14)

Table 4.16 Dose results with updated information for C-14

Default peak TEDE: 6.46 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		1.2288	2.2156	4.04	0.4665
Infiltration Rate (m/yr)		0.2526	0.3425	8.27	0.7873
Density of Unsaturated Zone (g/cm^3)		1.4312	1.5383	6.14	0.6620
Porosity of Unsaturated Zone		0.4599	0.4178	6.49	0.0507
Consumption rate	Leafy	21.4	13.5	6.44	0.0084
	Grain	14.4	15.33	6.46	0
	Beef	39.8	26.04	6.33	0.0582
	Poultry	25.3	37.47	6.47	0.0032
Partition Coefficient Kd (ml/g)		4.34	18.98	1.77	0.2152
Soil-to-plant Transfer Factor		Site-information are unavailable			

6. Am-241

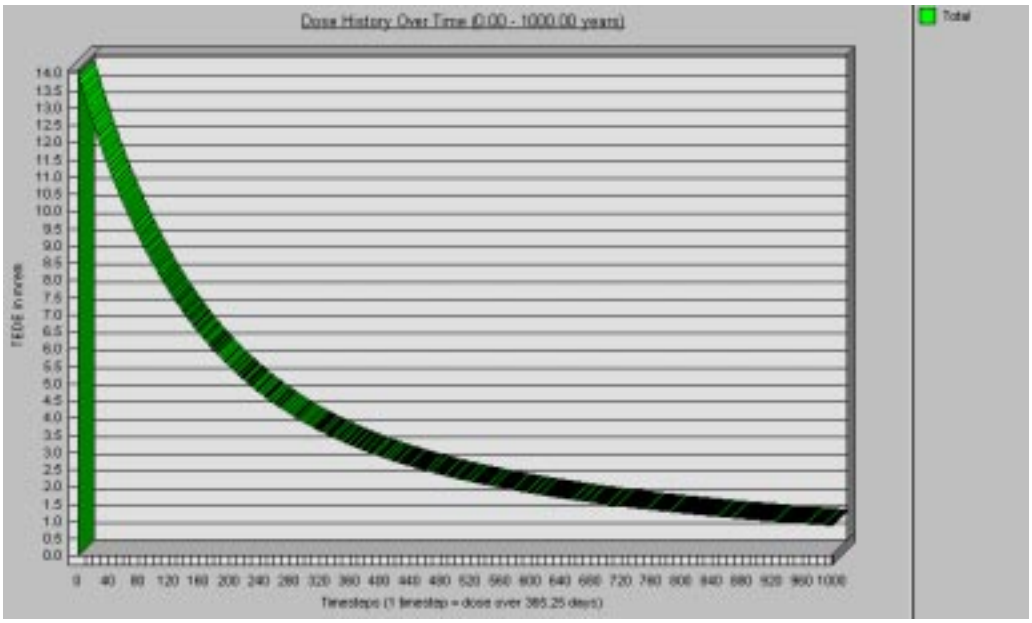

Figure 4.28 Dose values over time in year for default distributions (Am-241)

Table 4.17 Dose results with updated information for Am-241

Default peak TEDE: 13.9 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		1.2288	2.2156	13.9	0
Infiltration Rate (m/yr)		0.2526	0.3425	13.9	0
Density of Unsaturated Zone (g/cm^3)		1.4312	1.5383	13.9	0
Porosity of Unsaturated Zone		0.4599	0.4178	13.9	0
Consumption rate	Leafy	21.4	13.5	13.5	0.078
	Grain	14.4	15.33	14.2	0.3342
	Beef	39.8	26.04	13.9	0
	Poultry	25.3	37.47	13.9	0
Partition Coefficient Kd (ml/g)		1430	7031	13.9	0
Soil-to-plant Transfer Factor		Site-information are unavailable			

7. Ni-59

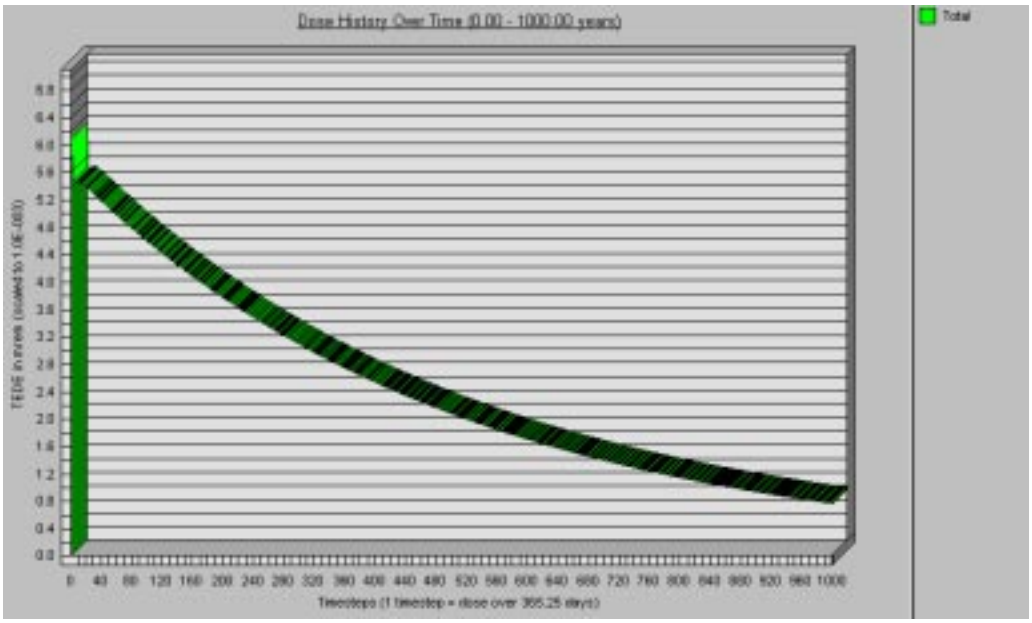

Figure 4.29 Dose values over time in year for default distributions (Ni-59)

Table 4.18 Dose results with updated information for Ni-59

Default peak TEDE: 0.0061 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		1.2288	2.2156	0.00604	0.0122
Infiltration Rate (m/yr)		0.2526	0.3425	0.00705	0.4376
Density of Unsaturated Zone (g/cm^3)		1.4312	1.5383	0.00609	0.0219
Porosity of Unsaturated Zone		0.4599	0.4178	0.0061	0
Consumption rate	Leafy	21.4	13.5	0.00606	0.0178
	Grain	14.4	15.33	0.00613	0.0762
	Beef	39.8	26.04	0.00608	0.0095
	Poultry	25.3	37.47	0.0061	0
Partition Coefficient Kd (ml/g)		37	335.12	0.00597	0.0026
Soil-to-plant Transfer Factor		Site-information are unavailable			

The relative importance of various parameters for different radionuclides is summarized in Table 4.19. The table only lists those parameters with the relative importance greater than a cutoff threshold, 0.20. Based on the results of the table, some less important parameters can be excluded for the further analysis (e.g., value of information analysis).

Table 4.19 Relative important parameters for different radionuclides in analysis (DandD)

Radionuclide	Important parameter	Importance value
Cs-137	① Thickness of unsaturated zone	0.5016
	② Infiltration rate	0.9829
	③ Density of unsaturated zone	0.8027
Sr-90	① Consumption rate-Leafy	0.4652
	② Soil-to plant transfer factor	0.9938
Pu-239	① Thickness of unsaturated zone	0.4972
	② Infiltration rate	0.9268
	③ Density of unsaturated zone	0.7424
Co-60	None	/
C-14	① Thickness of unsaturated zone	0.4665
	② Infiltration rate	0.7873
	③ Density of unsaturated zone	0.6620
	④ Partition coefficient Kd	0.2152
Am-241	① Consumption rate-Grain	0.3342
Ni-59	① Infiltration rate	0.4376

4.5 Dose evaluation with RESRAD Probabilistic Code

4.5.1 Dose Results

Using the posterior probability distribution functions of the parameters, new calculations were made with the RESRAD probabilistic code (RESRAD 6.0). Figures 4.30 through 4.36 show the results of the calculations using the default probabilistic input distributions. The results are given as the mean dose over time and the corresponding cumulative distribution functions for the estimated peak dose.

Tables 4.20 through 4.26 show the comparisons of results between the two cases (i.e., the default distributions versus the updated distributions). In these tables, the values of the parameters (for the default and updated distributions) are given as the mean or geometric mean.

1. Cs-137

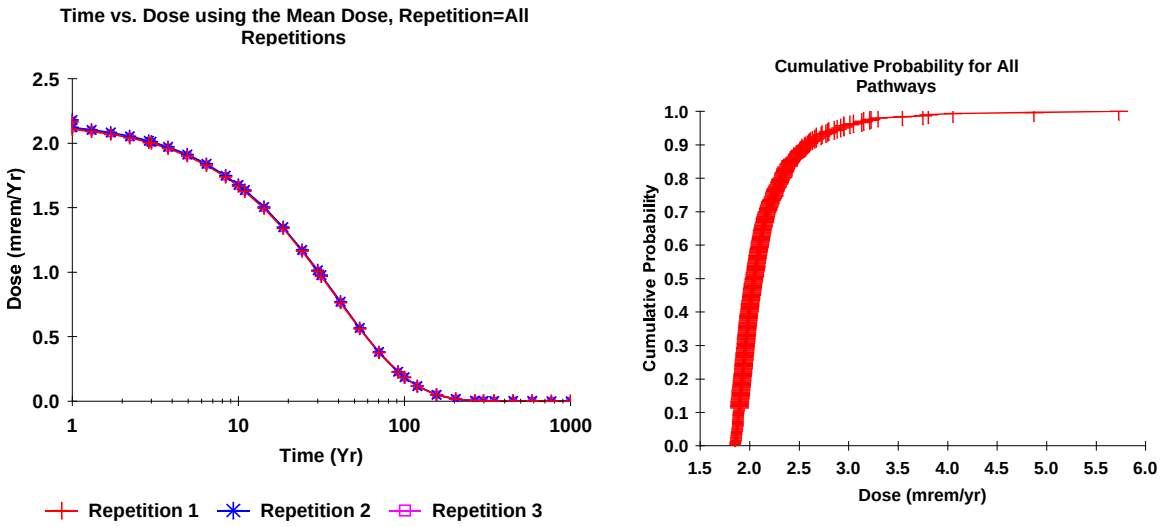

Figure 4.30 Dose over time in year and CDF of peak dose for default distributions (Cs-137)

Table 4.20 Dose results with updated information for Cs-137

Default peak TEDE: 2.17 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		9.9344	2.3268	2.17	0
Contaminated zone b parameters		2.8864	4.9	2.17	0
Precipitation (m/yr)		1	0.7827	2.18	0.0212
Saturated zone hydraulic conductivity (m/s)		9.9742	0.007572	2.18	0.0046
Saturated zone hydraulic gradient		0.006036	0.056	2.18	0.0006
Density of Unsaturated Zone (g/cm^3)		1.52	1.5383	2.18	0.3828
Density of Saturated Zone (g/cm^3)		1.52	1.5383	2.17	0
Porosity of Unsaturated Zone		0.425	0.4178	2.17	0
Porosity of Saturated Zone		0.425	0.4178	2.17	0
Consumption rate	Leafy	14	13.5	2.18	0.1290
	Fruit, vegetable, and grain	160	173.4	2.20	0.1651
	Meat and poultry	63	63.51	2.18	0.5693
Partition Coefficient Kd (ml/g)		445.86	2643.87	2.18	0.0009
Soil-to-plant transfer Factor (pCi/kg / pCi/kg)		0.04	0.052	2.28	0.1690

2. Sr-90

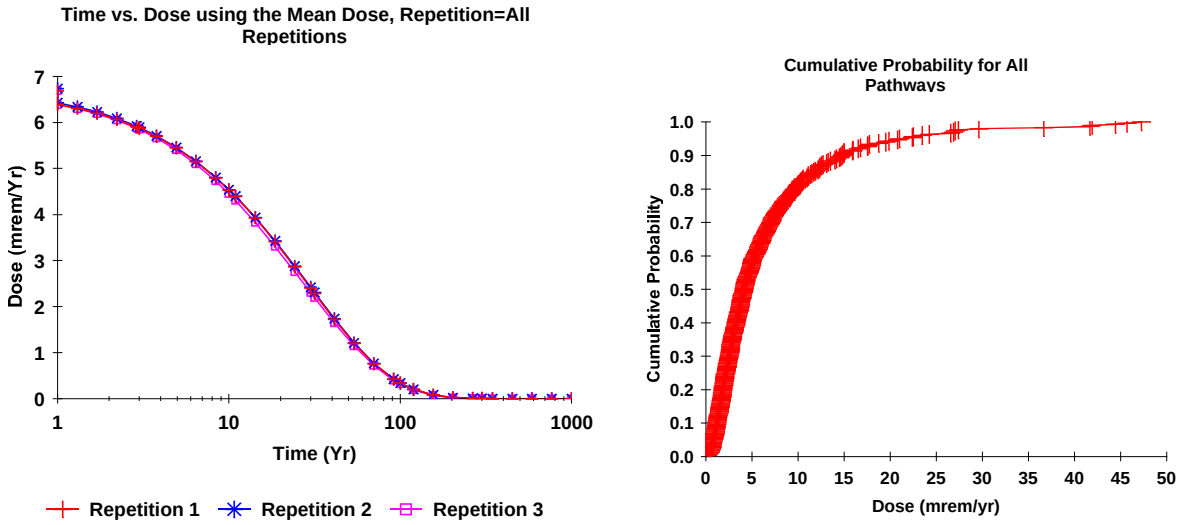

Figure 4.31 Dose over time in year and CDF of peak dose for default distributions (Sr-90)

Table 4.21 Dose results with updated information for Sr-90

Default peak TEDE: 6.71 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		9.9344	2.3268	6.71	0
Contaminated zone b parameters		2.8864	4.9	6.71	0
Precipitation (m/yr)		1	0.7827	6.75	0.0274
Saturated zone hydraulic conductivity (m/s)		9.9742	0.007572	6.70	0.0015
Saturated zone hydraulic gradient		0.006036	0.056	6.71	0
Density of Unsaturated Zone (g/cm^3)		1.52	1.5383	6.70	0.1238
Density of Saturated Zone (g/cm^3)		1.52	1.5383	6.70	0.1238
Porosity of Unsaturated Zone		0.425	0.4178	6.70	0.0880
Porosity of Saturated Zone		0.425	0.4178	6.70	0.0880
Consumption rate	Leafy	14	13.5	6.72	0.4717
	Fruit, vegetable, and grain	160	173.4	7.23	0.9235
	Meat and poultry	63	63.51	6.74	0.5523
Partition Coefficient Kd (ml/g)		31.5	23.9	6.74	0.1895
Soil-to-plant transfer Factor (pCi/kg / pCi/kg)		0.3	0.39	8.71	0.9935

3. Pu-239

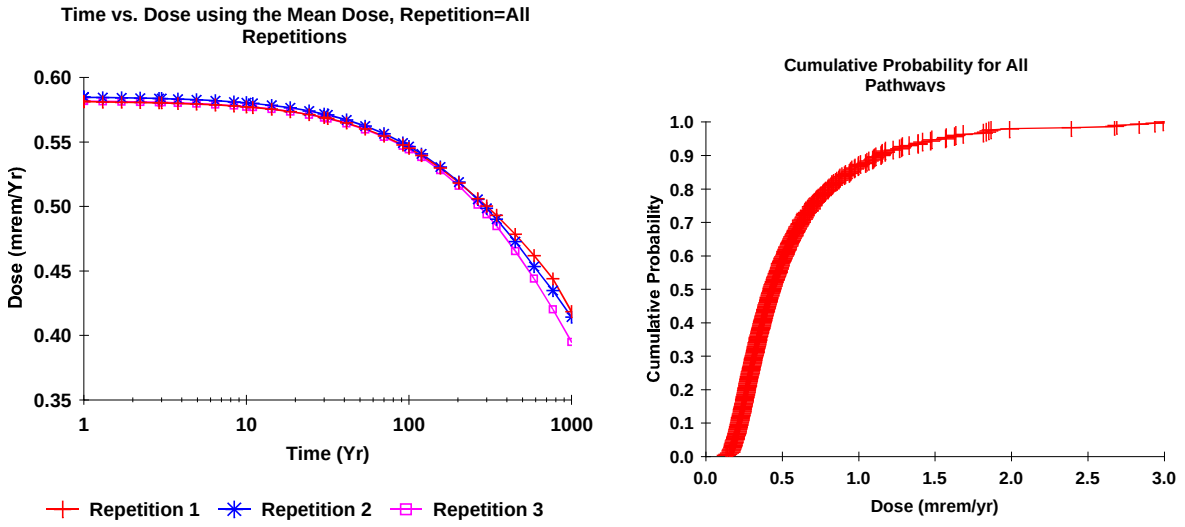

Figure 4.32 Dose over time in year and CDF of peak dose for default distributions (Pu-239)

Table 4.22 Dose results with updated information for Pu-239

Default peak TEDE: 0.589 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		9.9344	2.3268	0.591	0.0044
Contaminated zone b parameters		2.8864	4.9	0.589	0
Precipitation (m/yr)		1	0.7827	0.586	0.0234
Saturated zone hydraulic conductivity (m/s)		9.9742	0.007572	0.583	0.0102
Saturated zone hydraulic gradient		0.006036	0.056	0.593	0.0008
Density of Unsaturated Zone (g/cm^3)		1.52	1.5383	0.589	0
Density of Saturated Zone (g/cm^3)		1.52	1.5383	0.589	0
Porosity of Unsaturated Zone		0.425	0.4178	0.589	0
Porosity of Saturated Zone		0.425	0.4178	0.589	0
Consumption rate	Leafy	14	13.5	0.585	0.1902
	Fruit, vegetable, and grain	160	173.4	0.622	0.6690
	Meat and poultry	63	63.51	0.586	0.6292
Partition Coefficient Kd (ml/g)		953.37	1123.16	0.583	0.0572
Soil-to-plant transfer Factor (pCi/kg / pCi/kg)		9.98E-4	1.28E-3	0.725	0.8172

4. Co-60

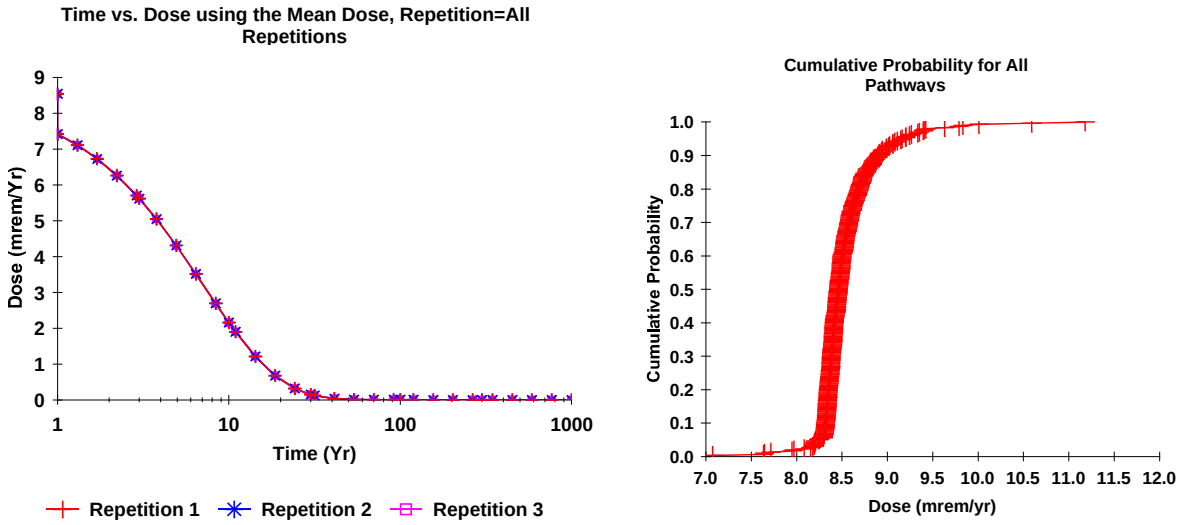

Figure 4.33 Dose over time in year and CDF of peak dose for default distributions (Co-60)

Table 4.23 Dose results with updated information for Co-60

Default peak TEDE: 8.54 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		9.9344	2.3268	8.54	0
Contaminated zone b parameters		2.8864	4.9	8.54	0
Precipitation (m/yr)		1	0.7827	8.56	0.0108
Saturated zone hydraulic conductivity (m/s)		9.9742	0.007572	8.54	0
Saturated zone hydraulic gradient		0.006036	0.056	8.54	0
Density of Unsaturated Zone (g/cm^3)		1.52	1.5383	8.54	0
Density of Saturated Zone (g/cm^3)		1.52	1.5383	8.54	0
Porosity of Unsaturated Zone		0.425	0.4178	8.54	0
Porosity of Saturated Zone		0.425	0.4178	8.54	0
Consumption rate	Leafy	14	13.5	8.55	0.0328
	Fruit, vegetable, and grain	160	173.4	8.57	0.0419
	Meat and poultry	63	63.51	8.55	0.1446
Partition Coefficient Kd (ml/g)		235.10	909.41	8.58	0.0016
Soil-to-plant transfer Factor (pCi/kg / pCi/kg)		0.0797	0.104	8.63	0.0346

5. C-14

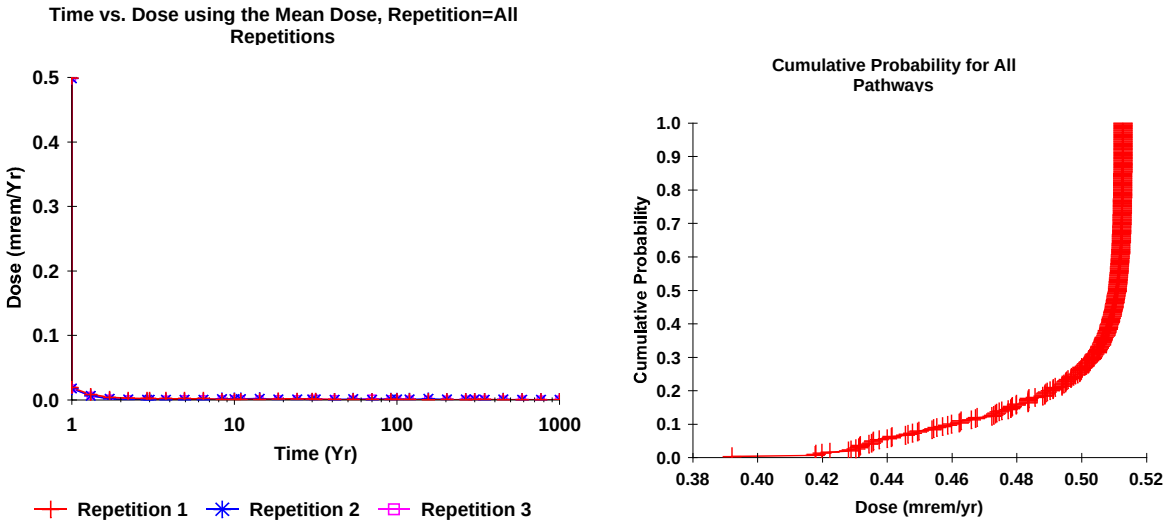

Figure 4.34 Dose over time in year and CDF of peak dose for default distributions (C-14)

Table 4.24 Dose results with updated information for C-14

Default peak TEDE: 0.499 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		9.9344	2.3268	0.499	0
Contaminated zone b parameters		2.8864	4.9	0.500	0.0029
Precipitation (m/yr)		1	0.7827	0.501	0.0184
Saturated zone hydraulic conductivity (m/s)		9.9742	0.007572	0.499	0
Saturated zone hydraulic gradient		0.006036	0.056	0.499	0
Density of Unsaturated Zone (g/cm^3)		1.52	1.5383	0.499	0
Density of Saturated Zone (g/cm^3)		1.52	1.5383	0.499	0
Porosity of Unsaturated Zone		0.425	0.4178	0.499	0
Porosity of Saturated Zone		0.425	0.4178	0.499	0
Consumption rate	Leafy	14	13.5	0.499	0
	Fruit, vegetable, and grain	160	173.4	0.536	0.8854
	Meat and poultry	63	63.51	0.500	0.2476
Partition Coefficient Kd (ml/g)		11.0	18.98	0.511	0.0331
Soil-to-plant transfer Factor (pCi/kg / pCi/kg)		0.70	0.907	0.499	0

6. Am-241

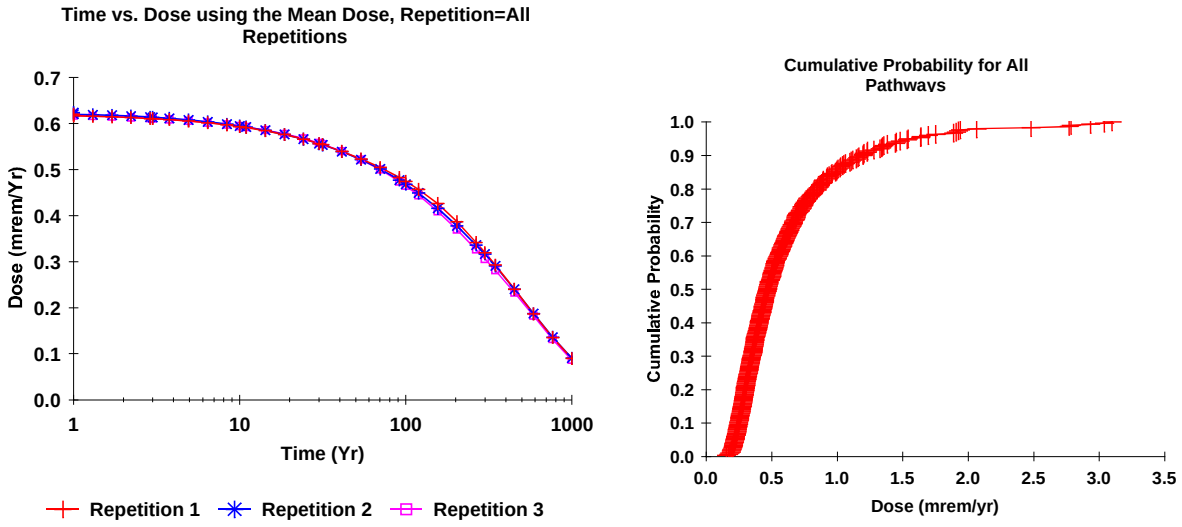

Figure 4.35 Dose over time in year and CDF of peak dose for default distributions (Am-241)

Table 4.25 Dose results with updated information for Am-241

Default peak TEDE: 0.627 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		9.9344	2.3268	0.636	0.0187
Contaminated zone b parameters		2.8864	4.9	0.627	0
Precipitation (m/yr)		1	0.7827	0.624	0.0220
Saturated zone hydraulic conductivity (m/s)		9.9742	0.007572	0.627	0
Saturated zone hydraulic gradient		0.006036	0.056	0.629	0.0004
Density of Unsaturated Zone (g/cm^3)		1.52	1.5383	0.627	0
Density of Saturated Zone (g/cm^3)		1.52	1.5383	0.627	0
Porosity of Unsaturated Zone		0.425	0.4178	0.627	0
Porosity of Saturated Zone		0.425	0.4178	0.627	0
Consumption rate	Leafy	14	13.5	0.625	0.0893
	Fruit, vegetable, and grain	160	173.4	0.663	0.6856
	Meat and poultry	63	63.51	0.626	0.1970
Partition Coefficient Kd (ml/g)		1451.0	7031.8	0.623	0.0017
Soil-to-plant transfer Factor (pCi/kg / pCi/kg)		9.978E-4	1.297E-3	0.767	0.7446

7. Ni-59

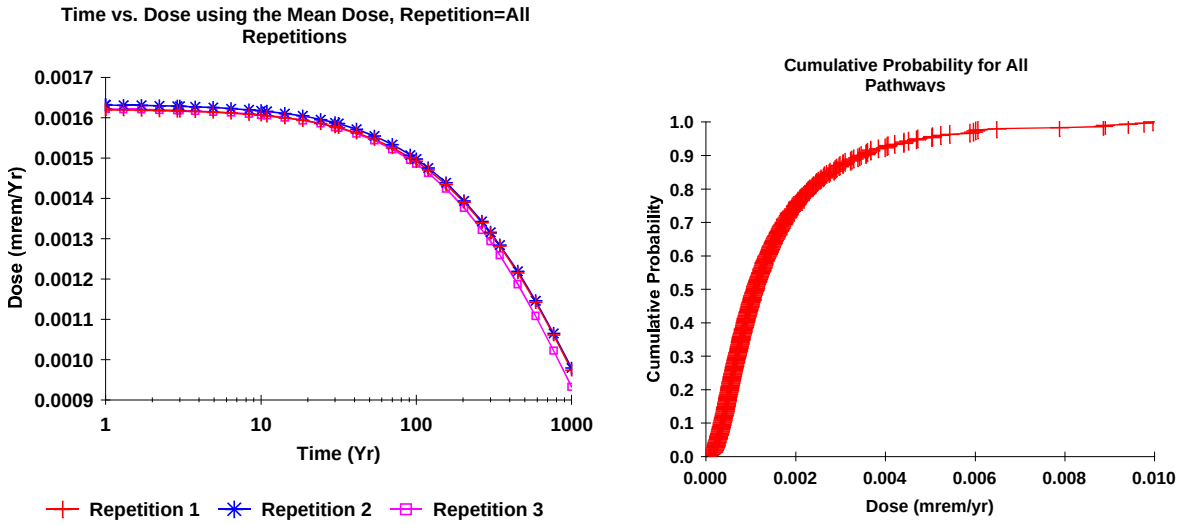

Figure 4.36 Dose over time in year and CDF of peak dose for default distributions (Ni-59)

Table 4.26 Dose results with updated information for Ni-59

Default peak TEDE: 0.00163 mrem/yr

Parameter		Default value	Updated value	TEDE with updated value (mrem/yr)	Relative importance
Thickness of unsaturated zone (m)		9.9344	2.3268	0.00163	0
Contaminated zone b parameters		2.8864	4.9	0.00163	0
Precipitation (m/yr)		1	0.7827	0.00163	0
Saturated zone hydraulic conductivity (m/s)		9.9742	0.007572	0.00163	0
Saturated zone hydraulic gradient		0.006036	0.056	0.00163	0
Density of Unsaturated Zone (g/cm^3)		1.52	1.5383	0.00163	0
Density of Saturated Zone (g/cm^3)		1.52	1.5383	0.00163	0
Porosity of Unsaturated Zone		0.425	0.4178	0.00163	0
Porosity of Saturated Zone		0.425	0.4178	0.00163	0
Consumption rate	Leafy	14	13.5	0.00163	0
	Fruit, vegetable, and grain	160	173.4	0.00174	0.8058
	Meat and Poultry	63	63.51	0.00163	0
Partition Coefficient Kd (ml/g)		424.1	335.1	0.00163	0
Soil-to-plant transfer Factor (pCi/kg / pCi/kg)		0.05	0.065	0.0021	0.9611

The relative importance of various parameters in this probabilistic analysis with RESRAD 6.0 for different radionuclides is summarized in Table 4.27. The Table only lists those parameters with the relative importance greater than a cutoff threshold, 0.20. Based on these results, only the key parameters were included for further analysis in section 4.5 and 4.6.

Table 4.27 Relative important parameters for different radionuclides in analysis (RESRAD)

Radionuclide	Important parameter	Importance value
Cs-137	① Density of unsaturated zone	0.3828
	② Consumption rate-Meat and poultry	0.5693
Sr-90	① Consumption rate-Leafy	0.4717
	② Consumption rate-Fruit, vegetable, and grain	0.9235
	③ Consumption rate-Meat and poultry	0.5523
	④ Soil-to-plant transfer factor	0.9935
Pu-239	① Consumption rate-Fruit, vegetable, and grain	0.6690
	② Consumption rate-Meat and poultry	0.6292
	③ Soil-to-plant transfer factor	0.8172
Co-60	None	/
C-14	① Consumption rate-Fruit, vegetable, and grain	0.8854
	② Consumption rate-Meat and poultry	0.2476
Am-241	① Consumption rate-Fruit, vegetable, and grain	0.6856
	② Soil-to-plant transfer factor	0.7446
Ni-59	① Consumption rate-Fruit, vegetable, and grain	0.8058
	② Soil-to-plant transfer factor	0.9611

4.5.2 Effects of Using the Posterior Data on DCGL Calculations

A. DCGL Calculation for the Deterministic Case:

The screening dose analysis made by both DandD and RESRAD with default inputs, i.e., prior data, were deterministic. The screening analysis results were given in Table 4.2 (as peak dose and the corresponding DCGL). With the use of posterior data developed with the site-specific information, the results from the screening analysis will change. Section 4.4 described these changes for the TEDE results with the DandD code.

This section describes the effects of using the posterior data on the deterministic DCGL calculations with DandD. The results are shown in Table 4.27. Only the key parameters identified in Table 4.27 are listed in Table 4.28.

Table 4.28 Dose results and DCGL for selected parameter (DandD)

Radionuclide	Important parameter	Peak dose (mrem/yr)	DCGL (pCi/g)
Cs-137	① Thickness of unsaturated zone	16.9	1.48
	② Infiltration rate	38.2	0.65
	③ Density of unsaturated zone	26.6	0.94
Sr-90	① Consumption rate-Leafy	49.2	0.51
	② Soil-to plant transfer factor	4.25	5.88
Pu-239	① Thickness of unsaturated zone	173	0.14
	② Infiltration rate	383	0.07
	③ Density of unsaturated zone	272	0.09
Co-60	None	/	
C-14	① Thickness of unsaturated zone	4.04	6.19
	② Infiltration rate	8.27	3.02
	③ Density of unsaturated zone	6.14	4.07
	④ Partition coefficient Kd	1.77	14.12
Am-241	① Consumption rate-Grain	15.33	1.63
Ni-59	① Infiltration rate	0.00705	3546.10

B. DCGL Calculation for the Probabilistic Case:

The effects of using the posterior data on the probabilistic DCGL calculations are described in this section. Only the key parameters identified in section 4.5.1 (as listed in Table 4.28) were use for the analyses. The following example illustrates how the peak dose results calculated by the RESRAD probabilistic code are used to derive the DCGL distribution.

Example: The following is a summary of the predicted dose by RESRAD 6.0 for the 1 pCi/g of Cs-137 source term given the uncertainty of the bulk density of the unsaturated zone. All the other inputs were given default (deterministic) values.

Dose summary given by RESRAD 6.0:

RESRAD, Version 6.0 T« Limit = 0.5 year 12/14/2000 15:26 Page 3
MCSummar: Cs-137 Site Analysis File: CS137.RAD

Monte Carlo Total Dose Summary

Nuclide (j)	Peak Time	Peak Dose	t= 0.00E+00	1.00E+00	3.00E+00	1.00E+01	3.00E+01	1.00E+02	3.00E+02	1.00E+03
			DOSE(j,t), mrem/yr							
Cs-137										
Min	0.00E+00	1.85E+00	1.85E+00	1.71E+00	1.17E+00	3.11E-01	7.03E-03	1.22E-08	2.86E-17	0.00E+00
Max	0.00E+00	5.73E+00	5.73E+00	5.59E+00	5.33E+00	4.52E+00	2.81E+00	5.34E-01	4.64E-03	4.05E-10
Avg	0.00E+00	2.17E+00	2.17E+00	2.12E+00	2.01E+00	1.67E+00	1.01E+00	1.84E-01	1.57E-03	1.16E-10
Std	0.00E+00	4.26E-01	4.26E-01	4.18E-01	4.06E-01	3.76E-01	2.79E-01	6.80E-02	7.82E-04	8.08E-11
ΣALL										
Min	0.00E+00	1.85E+00	1.85E+00	1.71E+00	1.17E+00	3.11E-01	7.03E-03	1.22E-08	2.86E-17	0.00E+00
Max	0.00E+00	5.73E+00	5.73E+00	5.59E+00	5.33E+00	4.52E+00	2.81E+00	5.34E-01	4.64E-03	4.05E-10
Avg	0.00E+00	2.17E+00	2.17E+00	2.12E+00	2.01E+00	1.67E+00	1.01E+00	1.84E-01	1.57E-03	1.16E-10
Std	0.00E+00	4.26E-01	4.26E-01	4.18E-01	4.06E-01	3.76E-01	2.79E-01	6.80E-02	7.82E-04	8.08E-11

ΣALL is total dose summed for all nuclides.

The peak dose was found to occur at year 0 with the annual mean of 2.17 mrem/yr and the standard deviation of 0.426. Figure 4.37 shows the PDF and CDF of the results. Then, 1000 data points were randomly drawn from the predicted dose distribution to develop a distribution for the DCGL by using,

$$DCGL = \frac{25}{dose} \qquad (pCi/g) \tag{4.2}$$

The PDF and CDF of the predicted DCGL for this example are shown in Figure 4.38.

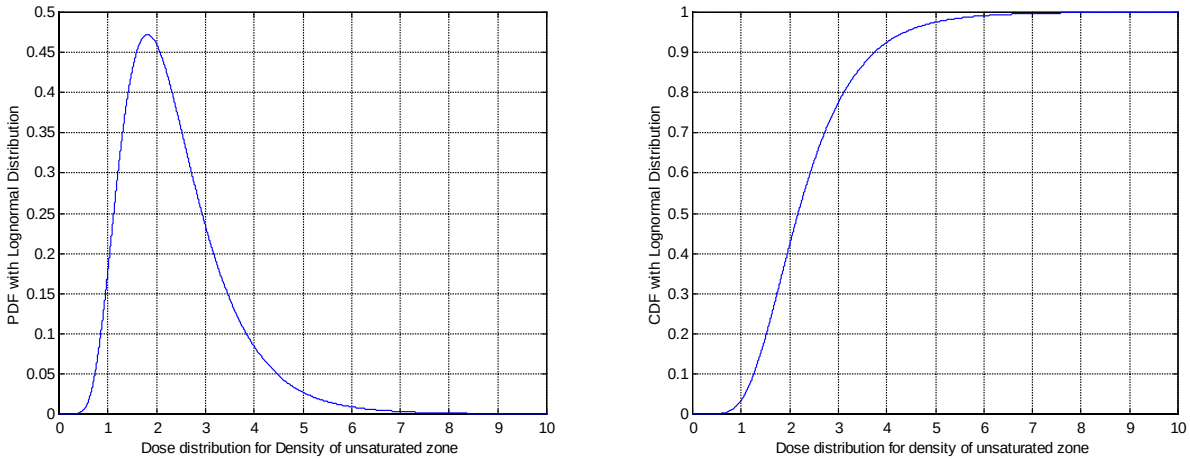

Figure 4.37 Uncertainty in dose predictions due to the uncertainty in the density of unsaturated zone

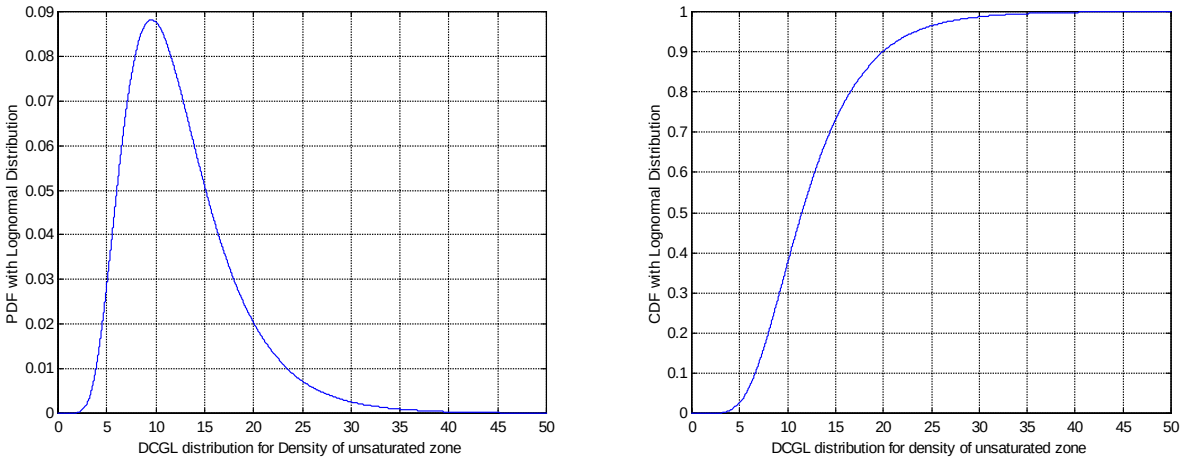

Figure 4.38 Uncertainty in the DCGL due to the uncertainty in the density of unsaturated zone

Table 4.29 lists the distribution of the predicted dose and the DCGL using the RESRAD probabilistic code by using the same approach (all results are represented by lognormal distributions).

Table 4.29 Dose results and DCGL for selected parameter (RESRAD)

Radionuclide	Important parameter	Dose parameters		DCGL parameters	
		Geo. Mean (mrem/yr)	Geo. Std*/ Log(Geo.Std)	Geo. Mean (pCi/g)	Geo. Std
Cs-137	① Density of unsaturated zone	2.17	0.426	11.4833	1.5405
	② Consumption rate-Meat and poultry	2.18	0.486	11.2407	1.5991
Sr-90	① Consumption rate-Leafy	6.72	7.88	3.8649	8.9912
	② Consumption rate-Fruit, vegetable, and grain	7.23	8.48	3.7061	9.0337
	③ Consumption rate-Meat and poultry	6.74	7.9	3.8390	7.6665
	④ Soil-to-plant transfer factor	8.71	9.88	2.5938	9.4091
Pu-239	① Consumption rate-Fruit, vegetable, and grain	0.622	0.528	40.0695	1.6769
	② Consumption rate-Meat and poultry	0.586	0.49	44.4118	1.6599
	③ Soil-to-plant transfer factor	0.725	0.616	35.2186	1.8156

Table 4.29 (Continued)

Co-60	None	/	/	/	/
C-14	① Consumption rate-Fruit, vegetable, and grain	0.536	0.0252	46.6808	1.0261
	② Consumption rate-Meat and poultry	0.500	0.0231	49.9936	1.0236
Am-241	① Consumption rate-Fruit, vegetable, and grain	0.663	0.542	38.9968	1.7467
	③ Soil-to-plant transfer factor	0.767	0.63	32.8628	1.8938
Ni-59	① Consumption rate-Fruit, vegetable, and grain	0.00174	0.00181	14368.0	1.0018
	② Soil-to-plant transfer factor	0.0021	0.00213	11904.0	1.0021

* If the value is greater than 1.

4.6 Value of Information Analysis for the Plant Site

Within the decision framework for the decommissioning of nuclear power plant, assessing the benefit of obtaining new information through site-specific investigations for various parameters in dose assessment is very important. Use of the value of information (VOI) analysis for this purpose was proposed in this thesis. Details of the theory were discussed in section 2.4. In this section, application of the VOI analysis to an actual decommissioning plant site is described.

The basic decision involved in the given problem is to compare the residual contamination levels (concentration) and the target clean up levels (DCGL) and determine if the residual contamination should be accepted or not. This decision needs to be made under the uncertainty in both the residual contamination levels and the target DCGL. Therefore, the analysis needs to be performed by taking into account the uncertainty in both the contamination level and the DCGL.

4.6.1 Utility Function for the Problem

For the VOI analysis of the problem, the utility functions are defined in a simplistic way as following:

$$u_1(R) = \begin{cases} c_1 & if \quad Concentration < DCGL \\ 0 & if \quad Concentration > DCGL \end{cases} \tag{4.3}$$

$$u_2(R) = \begin{cases} 0 & if \quad Concentration < DCGL \\ c_2 & if \quad Concentration > DCGL \end{cases} \tag{4.4}$$

where u_1 is the utility function for "Accept the current system" and u_2 is the utility function for "Reject the current system". c_1 is a threshold set by decision maker, which represents the level of reliability that decision maker will accept and c_2 is a threshold set by decision maker, which represents the level of reliability that decision maker will reject. In practice, if the probability that concentration level > DCGL is less than 5%, the system is acceptable. On the other hand, if the probability that concentration level > DCGL is greater than 5%, the system needs to be rejected.

By this definition, the decision only involves the testing on regulatory compliance and does not examine the cost and/or benefits of other related efforts.

According to this, we can set $c_1 = 0.05$ and $c_2 = 0.95$ for the problem because they represent the confidence or relative value of accepting the system while the residual contamination will prove to be less than the DCGL.

Now we define function F(R) to be the cumulative function of the prior $f'(R)$ for system R and use symbol $'$ and $''$ to represent the prior and posterior information. For prior information, let

$$\bar{u_1}' = c_1[1 - F'(R < R_0)] = c_1[1 - F'(Concentration > DCGL')] \tag{4.5}$$

$$\bar{u_2}' = c_2 F'(R < R_0) = c_2 F'(Concentration > DCGL') \tag{4.6}$$

where R_0 is the reliability "equilibrium" value, which in dose assessment could mean DCGL. This can be assumed to be a deterministic quantity for simplicity. If Concentration > DCGL, the utility of "Accept" for prior information is not zero, has a value of $\bar{u_1}'$, and the utility of "Reject" for prior information has a value of $\bar{u_2}'$. Similarly, for posterior information, define

$$\bar{u_1}'' = c_1[1 - F''(R < R_0)] = c_1[1 - F''(Concentration > DCGL'')] \tag{4.7}$$

$$\bar{u}_2'' = c_2 F''(R < R_0) = c_2 F''(Concentration > DCGL'') \quad (4.8)$$

where the DCGL" is a distributed//uncertain quantity (not deterministic).

4.6.2 Optimum Action based on Prior and Posterior Information

The optimum action a* for the decision problem can be defined based on the comparison of concentration and DCGL.

For prior information,

$$a'^* = \begin{cases} a_1 & if \quad F'(Concentration > DCGL') < \dfrac{c_1}{c_1 + c_2} = 0.05 \\ a_2 & if \quad F'(Concentration > DCGL') \geq \dfrac{c_1}{c_1 + c_2} = 0.05 \end{cases} \quad (4.9)$$

which means, if the probability that concentration level > DCGL is less than 5% $\Rightarrow$ Accept the system.

For posterior information,

$$a''^* = \begin{cases} a_1 & if \quad F''(Concentration > DCGL'') < \dfrac{c_1}{c_1 + c_2} = 0.05 \\ a_2 & if \quad F''(Concentration > DCGL'') \geq \dfrac{c_1}{c_1 + c_2} = 0.05 \end{cases} \quad (4.10)$$

4.6.3 Results of VOI for the Problem

In this section, the results of VOI performed for the selected parameters and radionuclides both with DandD and RESRAD are presented.

(1). For prior information:

A. DandD

Based on the contamination level indicated in Table 4.4 and the DCGL calculated with the deterministic DandD code in Table 4.2, the utility was calculated and the optimum action/decision were determined. . The results for prior analysis are listed in Table 4.30. In this analysis, the probability $F'(Concentration > DCGL')$ was first

calculated based on the random sampling from the concentration distributions. With this probability, $\bar{u}_1$' and $\bar{u}_2$' were calculated and the optimum decisions were determined based on the discussions in section 4.6.2.

Table 4.30 Utility analysis for prior information (DandD)

Radionuclide	*F'*(*Concentration* > *DCGL'*)	$\bar{u}_1$'	$\bar{u}_2$'	Action a'*
Cs-137	0.1124	0.0444	0.1068	a_2 (Reject)
Sr-90	0.0013	0.0499	0.0012	a_1 (Accept)
Pu-239	0.8869	0.0057	0.8426	a_2 (Reject)
Co-60	0.00081	0.05	0.0008	a_1 (Accept)
C-14	0	0.05	0	a_1 (Accept)
Am-241	0.0274	0.0486	0.0260	a_1 (Accept)
Ni-59	0	0.05	0	a_1 (Accept)

B. RESRAD

Using a similar approach with the DandD code, prior analysis with RESRAD was made. The results are listed in Table 4.31.

Table 4.31 Utility analysis for prior information (RESRAD)

Radionuclide	*F'*(*Concentration* > *DCGL'*)	$\bar{u}_1$'	$\bar{u}_2$'	Action a'*
Cs-137	0.00014	0.05	0.0001	a_1 (Accept)
Sr-90	0	0.05	0	a_1 (Accept)
Pu-239	0	0.05	0	a_1 (Accept)
Co-60	0.0019	0.0499	0.0018	a_1 (Accept)
C-14	0	0.05	0	a_1 (Accept)
Am-241	0.0485	0.0476	0.0461	a_1 (Accept)
Ni-59	0	0.05	0	a_1 (Accept)

(2). For posterior information:

A. DandD

Using the concentration levels in Table 4.4 and the DCGL levels in Table 4.28, the analyses were performed. The results are shown in Table 4.32.

Table 4.32 Utility analysis for posterior information (DandD)

Radionuclide	Parameter of interest	$F''(Con > DCGL')$	$\bar{u}_1''$	$\bar{u}_2''$	Action a"*
Cs-137	① Thickness of unsaturated zone	0.0462	0.0477	0.0439	a_1 (Accept)
	② Infiltration rate	0.1737	0.0413	0.1650	a_2 (Reject)
	③ Density of unsaturated zone	0.1012	0.0449	0.0961	a_2 (Reject)
Sr-90	① Consumption rate-Leafy	0.00068	0.05	0.0006	a_1 (Accept)
	② Soil-to-plant transfer factor	0	0.0500	0	a_1 (Accept)
Pu-239	① Thickness of unsaturated zone	0.7648	0.0118	0.7266	a_2 (Reject)
	② Infiltration rate	0.9215	0.0039	0.8754	a_2 (Reject)
	③ Density of unsaturated zone	0.8788	0.0061	0.8349	a_2 (Reject)
Co-60	None	/	/	/	/
C-14	① Thickness of unsaturated zone	0	0.05	0	a_1 (Accept)
	② Infiltration rate	0	0.05	0	a_1 (Accept)
	③ Density of unsaturated zone	0	0.05	0	a_1 (Accept)
	④ Partition coefficient Kd	0	0.05	0	a_1 (Accept)
Am-241	① Consumption rate-Grain	0.035	0.0483	0.0333	a_1 (Accept)
Ni-59	① Infiltration rate	0	0.05	0	a_1 (Accept)

B. RESRAD

A similar approach was used for RESRAD. However, two differences need to be pointed out: (1) both the DCGL and concentration are uncertain quantities represented by

certain types of probability distribution functions. To calculate the probability, $F"(Con. > DCGL")$, both the Concentration and DCGL were treated as random variables and Monte Carlo sampling was used for the probability estimation; (2) only the parameter listed in Table 4.29 for which the posterior probabilistic information is available need to be analyzed in the VOI analysis. The results are given in Table 4.33.

Table 4.33 Utility analysis for posterior information (RESRAD)

Radionuclide	Parameter of interest	$F"(Con > DCGL")$	$\bar{u}_1"$	$\bar{u}_2"$	Action a"*
Cs-137	① Density of unsaturated zone	0.00052	0.05	0.0005	a_1 (Accept)
	② Consumption rate-Meat and poultry	0.00072	0.05	0.0007	a_1 (Accept)
Sr-90	① Consumption rate-Leafy	0.012	0.0494	0.0114	a_1 (Accept)
	② Consumption rate-Fruit, vegetable, and grain	0.0117	0.0494	0.0111	a_1 (Accept)
	③ Consumption rate-Meat and poultry	0.0078	0.0496	0.0074	a_1 (Accept)
	④ Soil-to-plant transfer factor	0.0189	0.0491	0.018	a_1 (Accept)
Pu-239	① Consumption rate-Fruit, vegetable, and grain	0	0.05	0	a_1 (Accept)
	② Consumption rate-Meat and poultry	0	0.05	0	a_1 (Accept)
	③ Soil-to-plant transfer factor	0	0.05	0	a_1 (Accept)
Co-60	None	/	/	/	/
C-14	① Consumption rate-Fruit, vegetable, and grain	0	0.05	0	a_1 (Accept)
	② Consumption rate-Meat and poultry	0	0.05	0	a_1 (Accept)

Table 4.33 (Continued)

Am-241	① Consumption rate-Fruit, vegetable, and grain	0	0.05	0	a_1 (Accept)
	② Soil-to-plant transfer factor	0	0.05	0	a_1 (Accept)
Ni-59	① Consumption rate-Fruit, vegetable, and grain	0	0.05	0	a_1 (Accept)
	② Soil-to-plant transfer factor	0	0.05	0	a_1 (Accept)

4.6.4 Conditional Value of Sample Information (CVSI) Analysis

The CVSI can be calculated according to the equation 2.27. Table 4.34 and 4.35 give the final results of CVSI for DandD and RESRAD.

Table 4.34 Conditional value of information results (DandD)

Radionuclide	Parameter of interest	$\bar{u}_1' > \bar{u}_2'$	$\bar{u}_1'' > \bar{u}_2''$	CVSI
Cs-137	① Thickness of unsaturated zone	No	Yes	0.0038
	② Infiltration rate	No	No	0
	③ Density of unsaturated zone	No	No	0
Sr-90	① Consumption rate-Leafy	Yes	Yes	0
	② Soil-to-plant transfer factor	Yes	Yes	0
Pu-239	① Thickness of unsaturated zone	No	No	0
	② Infiltration rate	No	No	0
	③ Density of unsaturated zone	No	No	0
Co-60	None	/	/	/
C-14	① Thickness of unsaturated zone	Yes	Yes	0
	② Infiltration rate	Yes	Yes	0
	③ Density of unsaturated zone	Yes	Yes	0
	④ Partition coefficient Kd	Yes	Yes	0
Am-241	① Consumption rate-Grain	Yes	Yes	0
Ni-59	① Infiltration rate	Yes	Yes	0

Table 4.35 Conditional value of information results (RESRAD)

Radionuclide	Parameter of interest	$\bar{u}_1' > \bar{u}_2'$	$\bar{u}_1'' > \bar{u}_2''$	CVSI
Cs-137	① Density of unsaturated zone	Yes	Yes	0
	② Consumption rate-Meat and poultry	Yes	Yes	0
Sr-90	① Consumption rate-Leafy	Yes	Yes	0
	② Consumption rate-Fruit, vegetable, and grain	Yes	Yes	0
	③ Consumption rate-Meat and poultry	Yes	Yes	0
	④ Soil-to-plant transfer factor	Yes	Yes	0
Pu-239	① Consumption rate-Fruit, vegetable, and grain	Yes	Yes	0
	② Consumption rate-Meat and poultry	Yes	Yes	0
	③ Soil-to-plant transfer factor	Yes	Yes	0
Co-60	None	/	/	/
C-14	① Consumption rate-Fruit, vegetable, and grain	Yes	Yes	0
	② Consumption rate-Meat and poultry	Yes	Yes	0
Am-241	① Consumption rate-Fruit, vegetable, and grain	Yes	Yes	0
	② Soil-to-plant transfer factor	Yes	Yes	0
Ni-59	① Consumption rate-Fruit, vegetable, and grain	Yes	Yes	0
	② Soil-to-plant transfer factor	Yes	Yes	0

The final results indicated that the value of site-specific information is very low. Only one site-specific parameter, i.e., the thickness of unsaturated zone, resulted in a nontrivial CVSI for Cs-137 with DandD code.

As for the RESRAD results, none of the site-specific information was found to have any value according to the VOI analysis. The results mean that site-specific information was mostly not necessary for the demonstration of regulatory compliance.

4.7 Further Explorations on the Likelihood Function in Bayesian Updating

As stated in section 4.3.4, a major issue in the use of Bayesian updating was the definition of likelihood function. The analyses performed in sections 4.5 and 4.6 were based on the assumption that the likelihood of observing the new information given the prior national data is represented by the probability distributions of the parameters developed from site-specific investigations. In this section, use of a more conservative approach to develop the likelihood function was examined and the impacts of using different likelihood functions on the overall results of the VOI analysis were noted. The new conservative approach was based on the assumption that the likelihood function behaves as Gaussian distribution as described in section 2.2.2. To produce a conservative likelihood function, the errors in the likelihood function were amplified.

The analyses were made for only the most important/relevant parameters from the previous VOI analysis. Based on the results in section 4.6, those parameters that resulted in the ***acceptance of the site*** both in the prior analysis and posterior analysis through the use of site-specific information were excluded. This was because, regardless of the use of new analysis, no benefit would be added to the problem. This indicates that only the parameters of the DandD code for Cs-137 and Pu-239 are relevant for further Bayesian analysis (see Table 4.30 to 4.33). Therefore, the analyses were focused on only three parameters, i.e., the thickness of unsaturated zone, infiltration rate, and the density of unsaturated zone.

As discussed in section 2.2.2, if several independent observations are considered, then the likelihood function represents the likelihood of observing all of the observations simultaneously.

It can be shown that the product of *m* normal density functions with respective means μ_i and standard deviations σ_i is also a normal density function with mean and variance

$$\mu^* = \frac{\sum_{i=1}^{m} \mu_i / \sigma_i^2}{\sum_{i=1}^{m} 1/\sigma_i^2} \quad and \quad (\sigma^*)^2 = \frac{1}{\sum_{i=1}^{m} 1/\sigma_i^2}$$

For the samples obtained from the same site-specific distribution, they have the same standard deviation. Thus,

$$\mu^* = \bar{x} \quad and \quad (\sigma^*)^2 = \frac{\sigma^2}{S} \tag{4.11}$$

where $\bar{x}$ is the sample mean. Since the samples are randomly picked from the distribution for site-specific information, the mean of the distribution can be used as the sample mean $\bar{x}$. The number of samples is S. This approach is demonstrated by using the density of the unsaturated zone, as an example.

The given prior distribution for the density of the unsaturated zone was a normal distribution with a mean of 1.52 g/cm^3 and standard deviation of 0.23. The given site-specific distribution was normally distributed with a mean of 1.56 g/cm^3 and standard deviation of 0.25. If the number of samples were 5, the likelihood function was also normally distributed with a mean of 1.56 g/cm^3 and standard deviation of 0.11. The posterior distribution after the Bayesian updating is shown in Figure 4.39. The mean value of the posterior distribution was 1.5524 g/cm^3.

If the number of samples were set to be 1, the result would become equivalent to the Bayesian updating with the conjugate pair. This is because, when S=1, the parameters of the likelihood function are the same as the site-specific distribution, which can be analyzed using the conjugate pairs. Each additional sample taken will lead to narrowing

the shape of the posterior distribution of the data. Figure 4.40 shows the changes in the posterior information as the sample numbers used for updating increases.

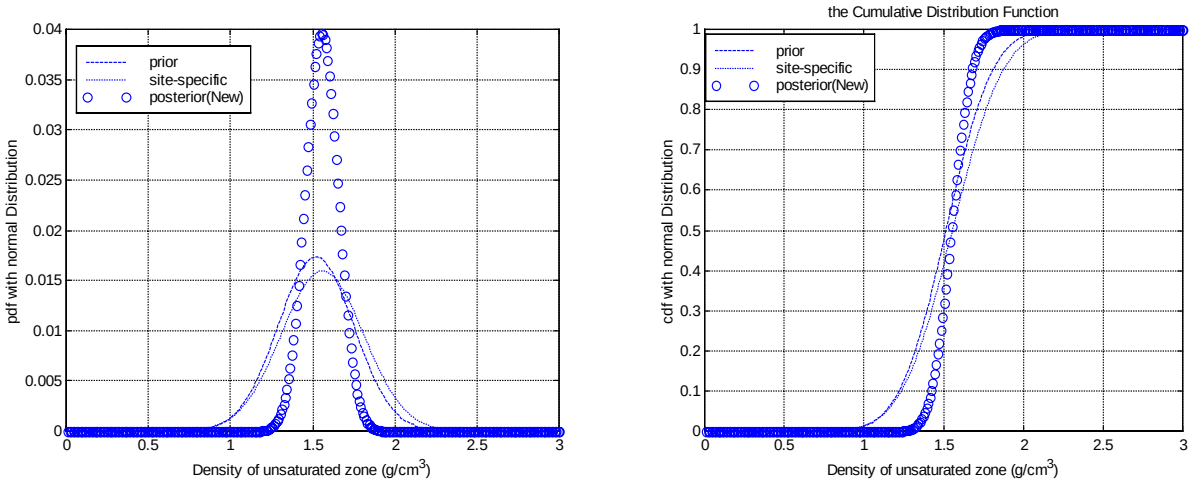

Figure 4.39 Updated posterior function with new likelihood function -density of unsaturated zone

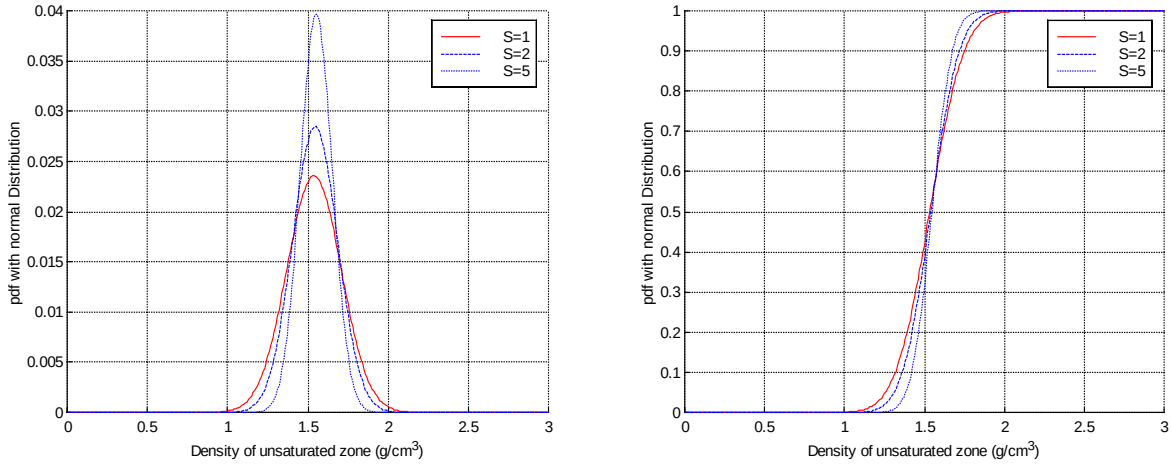

Figure 4.40 Comparison among different number of samples

For example, the mean estimate of the density for a single sample (S=1) was 1.538 g/cm^3; 1.545 g/cm^3 from two samples (S=2); 1.5524 g/cm^3 from five samples (S=5). The

trend is approaching the site-specific value of 1.56 g/cm^3 as the sampling number increases. This agrees with an argument that if more site-specific information becomes available, the prior information will have less influence on the posterior result.

The remaining analysis was made using the number of samples as 5 for all parameters considered and by increasing the standard deviation of the sample data by a factor of ten to represent a conservative case.

Since there has no prior distribution for the precipitation rate, it is assumed lognormal distributed based on the RESRAD default value with geometric mean 1 m/yr and geometric standard deviation 2.7, so the log-transformed prior distribution is 0 ± 1.0. With the site-specific distribution, -0.25 ± 0.25, and the number of samples to be 5, the mean of newly updated precipitation rate is 0.79 m/yr. Figure 4.41 shows the PDF and CDF for this updating.

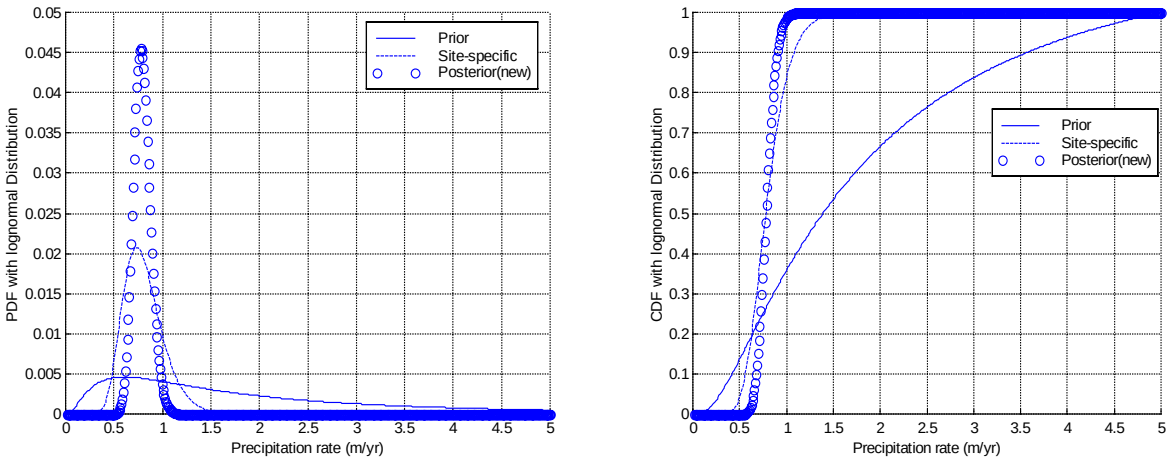

Figure 4.41 Updated posterior function with new likelihood function -precipitation rate

With the newly value of precipitation rate, the infiltration can be calculated as 0.3356 m/yr with equation $I = (1 - C_e)[(1 - C_r)P_r + I_{rr}]$.

For parameter, thickness of unsaturated zone, the mean value after analysis is 2.1311 m. Figure 4.42 shows the distributions for this updating.

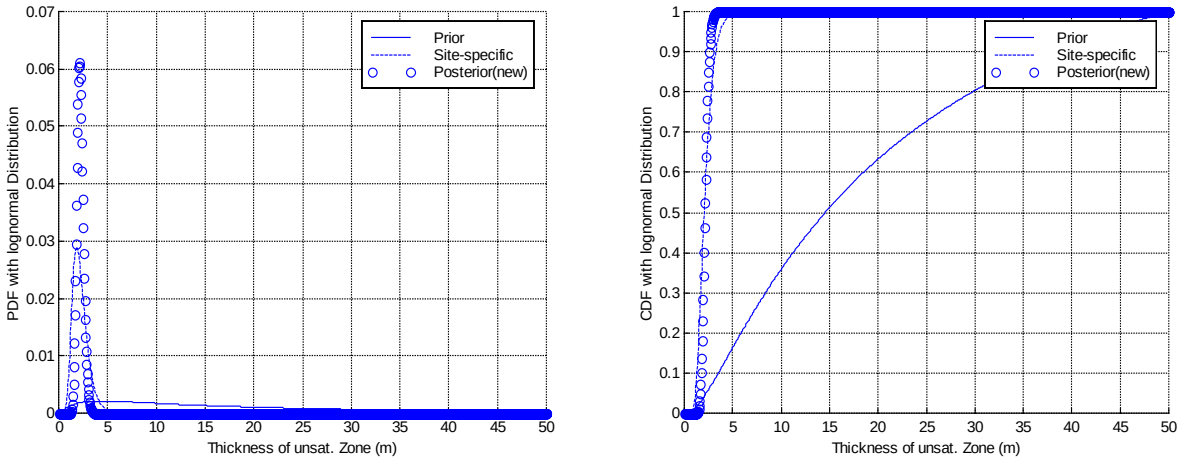

Figure 4.42 Updated posterior function with new likelihood function –thickness of unsaturated zone

The discussion in this section is made for a special situation where the site-specific data is assumed to have a fixed distribution and the sampling is from this fixed distribution. However, in a real situation, increasing the number of samples will affect the distribution of the data, which was not implemented in this study.

Table 4.36 shows the results of these analyses using the new likelihood function approach. The results are very similar to those in Table 4.32, 4.34 and indicate that using different likelihood functions has a very minor effect on the overall VOI analysis.

Table 4.36 The value of sample information analysis for newly updated parameter

Radionuclide	Parameter of interest	Peak Dose (mrem/yr)	DCGL″ (pCi/g)	$F''(Con > DCGL'')$	$\bar{u}_1' > \bar{u}_2'$	$\bar{u}_1'' > \bar{u}_2''$	Action (a*)	CVSI
Cs-137	① Thickness of unsaturated zone	17.5	1.4286	0.0496	No	Yes	Accept	0.0004
	② Infiltration rate	37.4	0.6684	0.1682	No	No	Reject	0
	③ Density of unsaturated zone	26.4	0.9470	0.1003	No	No	Reject	0
Pu-239	① Thickness of unsaturated zone	179	0.1471	0.7510	No	No	Reject	0
	② Infiltration rate	376	0.0665	0.9309	No	No	Reject	0
	③ Density of unsaturated zone	270	0.0926	0.8756	No	No	Reject	0

4.8 Discussion of the Results

There are hundreds of input parameters used in dose assessment. Collecting the site-specific information for all of these parameters will be very difficult and costly. The VOI analysis can provide useful insights to the efforts of collecting site-specific information for various parameters. This study demonstrated the application of VOI analysis for a small group of important radionuclides in nuclear power plant decommissioning.

The results in section 4.6 and 4.7 showed that the Conditional Value of Sample Information (CVSI) is zero or nearly zero for all of the parameters considered. These parameters are a small subset of key parameters in dose assessment. This indicates that using site-specific information does not add much benefit to the decisions on the regulatory compliance at the given site. And this observation was held for both of the computer codes used and regardless of the likelihood function approach used in Bayesian updating.

However, this particular observation was mainly due to the very low overall contamination levels at the plant site. The same observation may not hold for other sites with different levels of contamination. Even for the site analyzed in this study, the resulting findings may change if the methodology is applied to the regions of elevated contamination levels. Application of the methodology to the regions of elevated contamination levels is deemed desirable in the future work.

The study finds that the contamination level at a site is very important for the determination of the value of site-specific information.

Although the VOI analysis did not encourage the use of site-specific information based on the consideration of the decision on the acceptance/rejection of residual contamination at the given site, using the site-specific information was very effective and useful for the reduction of the predicted dose to humans. This was particularly true with the DandD code. With DandD, the predicted dose was found to be sensitive to many of the physical parameters warranting the benefits of using site-specific data. With RESRAD, using site-specific data for parameters such as the soil-to-plant transfer factors also had a major effect on the dose prediction.

Through the use of computer codes in this work, the differences between the DandD and RESRAD code were also noted. The observed difference in the predicted dose and the list of important parameters were due to the differences in the conceptual basis of the code, modeling approaches to the treatment of various physical processes, and the default input data.

Developing site-specific data depends not only on actual field investigations but also on the information available in the existing literature. This study relied on both but more on the literature information due to the lack of actual field data. In using the literature information, however, limitations and/or applicability of certain set of data were not always clearly described. The issue of using literature information for site-specific applications needs to be further examined in the future.

The analyses performed in this study are based on the characterization of uncertainty and variability of various parameters. Although the present conclusions of the study will not change much for the given site with the variations in the characterized uncertainty, more careful examination of the uncertainty and variability of parameters should be exercised in the future applications of the methodology.

5. Conclusions and Suggestions for Future Work

5.1 Summary and Conclusions

Developing site-specific data and using them in site-specific dose assessment can be very important in nuclear power plant decommissioning. By using an actual nuclear power plant site under decommissioning as example, this study presented the methodologies of site-specific dose assessment towards the goal of license termination using two widely-used dose assessment code, i.e., DandD and RESRAD. The focus in this study was on the use of data in site-specific analysis using the given computer models.

By identifying key radionuclides and parameters of importance in dose assessment for the site conceptual model, available data on these parameters was identified (as prior information) from the existing default input data from the computer codes or the national database.

Then, the site-specific data were developed using the results of field investigations at the site, historical records at the site, regional database, and the relevant information from the literature. This new data were compared to the prior information with respect to their impacts on both deterministic and probabilistic dose assessment.

The methodology of Value of Information Analysis was also implemented to examine the usefulness of site-specific data for each parameter within a simple decision framework. The two sets of information (i.e., site-specific data and the prior national data) were combined by using the method of conjugate-pair for Bayesian updating. Effect of using different method for Bayesian updating was also examined.

The results of VOI analysis indicated that the value of site-specific information was very low regarding the decision on site release. This observation was held for both of the computer code used. This was mainly due to the very low levels of contamination at the plant site. However, if a site has higher levels of contamination, the results could be different. The residual contamination level at a site is very important for the determination of the value of site-specific information and careful characterization of the

source term at a site is a prerequisite for the consideration of a site-specific dose assessment.

Although the value of new information was very low with regards to the decisions on site release, it was also found that the use of site-specific information is very important for the reduction in the predicted dose. This would be particularly true with the DandD code.

5.2 Recommendations for Future Work

Some suggestions are made here for further studies on the subject in the future. These are:

- For the VOI analysis, this study only looked at the overall contamination levels of a site. In actual decommissioning exercises, presence of hot spots (regions of elevated contamination levels) and their impacts on dose assessment are very important. The methodology presented in this study needs to be expanded to the hot spot areas.
- The analyses performed in this study required the characterization of uncertainty and variability of various parameters. Careful examinations of the uncertainty and variability of parameters should be exercised in the future application of the methodology.
- Developing site-specific data depends not only on actual field investigations but also on the information available in the existing literature. Limitations and/or applicability of existing literature information needs to be carefully examined for site-specific applications
- Given the importance of source term characterization in decommissioning dose modeling, a systematic and efficient way to better characterize the source term (its magnitude, distribution and variability) with given limited field data is desirable.
- For the future applications of Bayesian value of information analysis, the uncertainties in the posterior information with the use of different methods for

Bayesian updating or the construction of likelihood functions need to be further explored.

- The methodology of value of information analysis presented in this study can be further explored for its use in the overall risk management decision-making

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APPENDIX

Appendix A. Dose Model Comparisons between DandD and RESRAD

Since our interest is to determine the dose levels or risks after the license termination of nuclear power plant, the residential scenario is the actual situation we want to performance dose/risk analysis. Therefore, all of the following discussions are based on residential farmer scenario.

A.1 Dose Rate Reporting Basis

DandD computes average doses that occur over a period of time (usually a year) and reports the value as an annual dose. RESRAD computes and reports instantaneous dose rate. Theses are fundamentally different approaches. Both approaches should provide essentially the same annualized dose rate for scenarios involving radionuclides having a half-life of a few years or longer, and radionuclides moving slowly out of the contaminated zone.

The instantaneous dose rate reporting basis of RESRAD presents a difficulty. Cleanup standards in 10 CFR 20, Subpart E “Radiological Criteria for License Termination” are based on limiting the annual dose to a prescribed value (25 mrem), and not a limitation of the instantaneous dose rate. Substantial differences will result from the dose rate reporting basis alone for isotopes having a half-life between one month and six months, and for tritium and carbon-14 because of their rapid movement out of surface soils.

A.2 Isotopes and Decay Chains

RESRAD will operate with either of two isotope libraries. As the default condition, RESRAD only considers primary isotopes with a half-life of six months or longer. In the Default mode it considers any progeny with a half-life shorter than six months to be in equilibrium with the parent isotope. Second option, users can choose to run RESRAD

with a larger library that includes isotopes having a half-life of 30 days or longer. The RESRAD libraries include 67 and 83 isotopes respectively.

The DandD library includes 249 primary isotopes. The half-life of all primary isotopes in the library appear to be 10 minutes or longer. DandD always assumes a short-lived decay product to be in equilibrium with its parent when both of the following conditions are met: the decay product has a half-life less than 9 hours, and the decay product half-life is less than one tenth of the parent.

A.3 Human Diet

Default values of intake rates for various food groups by humans are determined. DandD subdivides the human diet further than does RESRAD. The way that the human diet is subdivided is important because DandD and RESRAD use transfer coefficients for entire classes of foods that are assumed to be dependent only on radionuclide.

DandD distinguishes between intakes of poultry and beef while RESRAD does not. DandD's use of separate transfer factors for beef and poultry is desirable since cattle and poultry differ physiologically and in dietary intake. RESRAD distinguishes between intakes of shellfish and fish, while DandD only considers intakes of fish. Shellfish bio-concentration factors used in RESRAD tend to be significantly higher than the corresponding fish-bio-concentration factors.

A.4. Soil-to-Plant Transfer Factors

DandD subdivides plant-based foods into four categories (leafy vegetables, roots, fruits and grain). RESRAD subdivides plant-based food into two categories (a. leafy vegetables and b. fruits, non-leafy vegetables, and grain).

DandD and RESRAD make use of soil-to-plant transfer factors. Using generic soil-to-plant transfer coefficients involves the following assumptions:

- Transfer coefficients are independent of the chemical form of the radioactive material
- Transfer coefficients are independent of the soil composition

- All food plant can be grouped into a small number of classes and a representative transfer factor can be assigned for each radionuclide and food class

A.5 Plant-to-Animal Product Transfer Factors

DandD and RESRAD use transfer factors to model the relationship between activity per mass of the animal product and daily intake rate of a radionuclide. These transfer factors have been studied in the most detail for the plant – milk pathway. Transfer factors relating the activity per mass of beef, eggs, and poultry to daily intake of a radionuclide have also been published. Both DandD and RESRAD use plant-to animal product transfer factors to describe incorporation into animal products of radionuclides contained in ingested soils and water.

A.6 Ground Water Model

The ground water models in DandD and RESRAD are similar in some respects and different in others. The DandD ground water model is a sequence of unsteady well-mixed linear reservoirs, which are referred to as boxes. This is a linear model in which the input concentrations are well throughout the reservoir volume and the output concentrations are equal to the concentration in the reservoir. The models are linear because the concentrations in the boxes are proportional to the initial condition in the box and any additional contaminants that are input. The unsaturated zone is usually represented as one well-mixed linear reservoir. However, it can be represented with as many as ten reservoirs. These reservoirs all have the same thickness, porosity, moisture saturation, and retardation. The intent of the additional reservoirs is to remove some the numerical dispersion that is inherent in this type of model.

A.7 Surface Water Model

Neither DandD nor RESRAD model run-off or transport of contaminated sediment to the surface water. DandD's surface water pond model is based on an infinitely fast mass transfer of radionuclides between the aquifer and an aquifer/pond combination. This

model restricts compare the maximum pond concentration to that of the aquifer if the pond volume is small compared to the aquifer volume and prevents the creation of mass if the pond volume is large compared to the aquifer volume.

The surface water concentration is calculated in the similar manner as the groundwater concentration in RESRAD. The breakthrough and rise times have the same values as those in the groundwater model. The dilution factor is based on the ration of the contaminated area to the pond watershed area.

A.8 Ground Water and Surface Water Model Parameters

Some parameters are common to both DandD and RESRAD. Many are not. In some cases, parameters that are input to DandD are calculated in RESRAD from other parameters. One example is infiltration rate. Some parameters that appear similar between DandD and RESRAD are actually different in some respects. DandD has a restriction that the distribution coefficients are the same in both the soil layer and the unsaturated zone. RESRAD does not have this restriction. DandD does not permit retardation of radionuclides in the saturated zone and RESRAD does. RESRAD uses a total porosity for retardation coefficient calculations and an effective porosity for velocity calculations. DandD does not make this porosity distinction. It uses the same porosity for both the retardation coefficient and the box-to-box transfer coefficient calculation.

A.9 Tritium Models

DandD assumes that tritium only becomes airborne as titivated water vapor. Setting the absolute humidity to zero results in zero inhalation dose.

RESRAD assumes that tritium escapes from the soil, enters the atmosphere and mixes with the ambient air to a height of the “mixing height” (2 m for people, 1 m for vegetation and animals). The average tritium concentration in air above a contaminated site is assumed to decrease as the wind speed increases.

In conclusion, DandD ignores inhalation of tritiated water vapor while RESRAD ignores inhalation of tritium associated with airborne dust. DandD is apt to underestimate

the inhalation dose due to tritium in many situations, because inhalation of tritiated water vapor can be more significant means of exposure.

A.10 Carbon-14 Models

DandD assumes that carbon-14 only becomes airborne as a constituent of airborne dust. Setting the dust loading values to zero results in zero inhalation dose in instances where carbon-14 is the only airborne constituent.

In effect, RESRAD assumes that all carbon-14 released to the atmosphere is in the form of carbon-14 dioxide. RESRAD models flux and airborne concentrations of carbon-14 using the came basic model it uses for tritium. However, the carbon-14 reference evasion depth is adjustable by the user in RESRAD.

A.11 External Exposure from Volume Soil Source while Outdoors

DandD assumes an infinite slab of contamination six inches thick. The external exposure model in RESRAD was updated with version 5.50. A description of the new model was not available.

A.12 External Exposure from Volume Soil Source while Indoors

Both DandD and RESRAD include a dose from indoor exposure to volume soil contamination. Both models provide default attenuation factors that are assumed to be independent of gamma energy.

A.13 Inhalation Exposure to Re-suspended Soil while Outdoors

DandD assumes that a certain airborne dust concentration is present due to re-suspension of contaminated dust, and that the airborne dust concentration is independent of the size of the contaminated area.

RESRAD assumes that the contaminated fraction of airborne dust is related to the size of the contaminated area; the contaminated fraction is modeled by an empirical formula.

A.14 Inhalation Exposure to Re-suspended Soil while Indoors, and to Re-suspended Surface sources of Soil Tracked Indoors

DandD and RESRAD model the inhalation exposure to dust occurring indoors. RESRAD models indoor inhalation exposure taking into consideration only the outdoor air mass loading and a scale factor. DandD requires three inputs: the floor dust loading factor, a re-suspension factor, and indoor airborne dust loading from processes other than re-suspension of dust tracked into the structure.

A.15 Plant and Animal Product -Human Pathways

DandD assumes that plant foods are held briefly upon harvest, and then consumed over a period of time. RESRAD does not take into account that plant foods may be consumed over a period of time. DandD also calculates an average dose received over a year while RESRAD calculates an instantaneous dose rate.

Appendix B. Raw Data of Soil Concentration for Cs-137 and Co-60 at Different Location in Protected Area 5AI and 8AI

Table B.1 5AI(1) Shallow Sample Identification

By survey unit, grid, x & y coordinate	Cs-137 uCi/g	Co-60 uCi/g
5AI(1)228(3.4)(2.4)	<MDA	<MDA
5AI(1)228(3.4)(5.9)	<MDA	<MDA
5AI(1)228(3.4)(9.4)	<MDA	<MDA
5AI(1)228(6.9)(2.4)	5.97E-06	6.03E-07
5AI(1)228(6.9)(5.9)	<MDA	<MDA
5AI(1)228(6.9)(9.4)	<MDA	<MDA
5AI(1)229(0.4)(2.4)	2.14E-06	1.41E-07
5AI(1)229(0.4)(5.9)	1.74E-07	<MDA
5AI(1)229(0.5)(9.5)	<MDA	<MDA
5AI(1)229(4.5)(9.6)	<MDA	<MDA
5AI(1)229(7.4)(2.4)	<MDA	<MDA
5AI(1)229(7.4)(6.4)	1.70E-07	<MDA
5AI(1)230(0.9)(2.4)	1.16E-07	<MDA
5AI(1)230(4.4)(2.4)	<MDA	<MDA
5AI(1)230(7.9)(2.4)	<MDA	<MDA
5AI(1)247(3.4)(1.9)	<MDA	<MDA
5AI(1)247(3.4)(5.4)	<MDA	<MDA
5AI(1)247(3.4)(8.9)	<MDA	<MDA
5AI(1)247(6.9)(5.4)	9.71E-07	1.45E-07
5AI(1)247(6.9)(8.9)	1.61E-06	2.19E-07
5AI(1)247(7.0)(1.9)	1.84E-06	<MDA
5AI(1)248(0.0)(1.9)	<MDA	<MDA
5AI(1)248(0.0)(5.4)	2.09E-07	<MDA
5AI(1)248(0.4)(8.9)	8.67E-06	4.79E-07
5AI(1)248(3.9)(8.9)	<MDA	<MDA
5AI(1)248(7.4)(8.9)	<MDA	<MDA
5AI(1)249(0.9)(8.9)	<MDA	<MDA
5AI(1)249(4.4)(8.9)	<MDA	<MDA
5AI(1)249(7.9)(5.5)	<MDA	<MDA
5AI(1)249(7.9)(8.9)	<MDA	<MDA
5AI(1)249(9.0)(5.5)	3.31E-07	<MDA
5AI(1)266(3.4)(5.0)	<MDA	<MDA
5AI(1)266(3.4)(8.4)	<MDA	<MDA
5AI(1)266(6.9)(5.0)	<MDA	<MDA
5AI(1)266(6.9)(8.5)	<MDA	<MDA
5AI(1)267(0.0)(5.0)	<MDA	<MDA
5AI(1)267(0.0)(8.4)	<MDA	<MDA

Table B.2 Samples below were collected to Identify the Depth of Activity found in shallow samples above

5AI(1)228(6.9)(2.4) 6-12 inches	9.74E-08	<MDA
5AI(1)229(0.4)(2.4) 6-12 inches	1.32E-07	<MDA
5AI(1)229(0.4)(2.4) 1-2 feet	7.95E-07	1.75E-07
5AI(1)229(0.4)(2.4) 2-3 feet	7.90E-08	<MDA
5AI(1)229(0.4)(2.4) 3-4 feet	3.40E-08	<MDA
5AI(1)229(0.4)(5.9) 6-12 inches	<MDA	<MDA
5AI(1)229(7.4)(6.4) 6-12 inches	<MDA	<MDA
5AI(1)230(0.9)(2.4) 6-12 inches	<MDA	9.21E-08
5AI(1)230(0.9)(2.4) 1-2 feet	9.57E-08	<MDA
5AI(1)247(6.9)(5.4) 6-12 inches	1.76E-07	<MDA
5AI(1)247(6.9)(8.9) 6-12 inches	8.62E-08	<MDA
5AI(1)247(7.0)(1.9) 6-12 inches	5.50E-07	<MDA
5AI(1)247(7.0)(1.9) 1-2 feet	2.40E-07	<MDA
		<MDA
5AI(1)248(0.0)(5.4) 6-12 inches	1.20E-05	3.91E-07
5AI(1)248(0.0)(5.4) 1-2 feet	2.41E-06	1.60E-07
5AI(1)248(0.0)(5.4) 2-3 feet	1.99E-06	1.07E-07
5AI(1)248(0.0)(5.4) 3-4 feet	8.11E-07	7.00E-08
5AI(1)248(0.0)(5.4) 4-5 feet	3.37E-07	<MDA
5AI(1)248(0.0)(5.4) 5-6 feet	1.58E-06	2.02E-07
5AI(1)248(0.0)(5.4) 6-7 feet	5.79E-08	<MDA
5AI(1)248(0.4)(8.9) 6-12 inches	7.32E-07	<MDA
5AI(1)248(0.4)(8.9) 1-2 feet	1.39E-06	2.18E-07
5AI(1)248(0.4)(8.9) 2-3 feet	7.53E-07	9.49E-08
5AI(1)248(0.4)(8.9) 3-4 feet	3.09E-07	9.33E-08
5AI(1)249(7.9)(5.5)1-2 feet	<MDA	<MDA
5AI(1)249(7.9)(5.5)2-3 feet	<MDA	<MDA

Table B.3 5AI(2) Shallow Sample Identification

By survey unit, grid, x & y coordinate	Cs-137 uCi/g	Co-60 uCi/g
5AI(2)266(4.2)(0.2)	<MDA	<MDA
5AI(2)266(9.2)(0.2)	1.23E-06	3.25E-07
5AI(2)304(4.2)(0.2)	<MDA	<MDA
5AI(2)304(4.2)(5.2)	<MDA	<MDA
5AI(2)304(9.2)(0.2)	5.71E-08	1.14E-07
5AI(2)304(9.2)(5.2)	3.27E-07	1.19E-07
5AI(2)305(9.2)(0.2)	1.89E-07	7.86E-08
5AI(2)316(4.2)(0.2)	<MDA	<MDA
5AI(2)316(4.2)(5.2)	1.05E-07	<MDA
5AI(2)316(9.2)(0.2)	1.01E-07	<MDA
5AI(2)316(9.2)(5.2)	5.00E-08	2.87E-08
5AI(2)317(4.2)(0.2)	1.95E-07	<MDA
5AI(2)317(4.2)(5.5)	1.44E-07	<MDA
5AI(2)317(9.0)(0.2)	<MDA	<MDA
5AI(2)317(9.2)(5.2)	2.19E-07	1.36E-07
5AI(2)328(4.2)(0.2)	<MDA	<MDA
5AI(2)328(4.2)(5.2)	<MDA	<MDA
5AI(2)328(9.2)(0.2)	<MDA	<MDA
5AI(2)328(9.2)(5.2)	<MDA	<MDA
5AI(2)329(5.2)(0.2)	<MDA	<MDA
5AI(2)329(9.2)(0.2)	9.05E-08	<MDA
5AI(2)329(9.2)(5.2)	<MDA	<MDA
5AI(2)330(4.2)(0.2)	<MDA	<MDA
5AI(2)330(4.2)(5.2)	<MDA	<MDA
5AI(2)330(9.2)(0.2)	<MDA	<MDA
5AI(2)330(9.2)(5.2)	<MDA	<MDA

Table B.4 Samples below were collected to Identify the Depth of Activity found in shallow samples above

5AI(2)266(9.2)(0.2) 6-12 inches	3.42E-07	1.56E-07
5AI(2)266(9.2)(0.2) 1-2 feet	2.09E-07	<MDA
5AI(2)266(9.2)(0.2) 2-3 feet	<MDA	<MDA
5AI(2)266(9.9)(4.6) 0-1 feet	1.64E-05	5.96E-06
5AI(2)266(9.9)(4.6) 1-2 feet	8.88E-07	1.48E-07
5AI(2)266(9.9)(4.6) 2-3 feet	4.12E-07	1.06E-07
5AI(2)266(9.9)(4.6) 3-4 feet	1.10E-07	<MDA
5AI(2)266(9.9)(4.6) 4-5 feet	6.30E-08	<MDA
5AI(2)266(9.9)(4.6) 5-6 feet	3.55E-08	<MDA
5AI(2)304(9.2)(0.2) 6-12 inches	1.14E-06	7.12E-08
5AI(2)304(9.2)(0.2) 1-2 feet	1.14E-06	2.17E-07
5AI(2)304(9.2)(0.2) @ 2 feet	2.39E-06	6.46E-07
5AI(2)304(9.2)(5.2) 6-12 inches	5.96E-07	1.88E-07
5AI(2)304(9.2)(5.2) 1-2 feet	2.50E-07	8.89E-08
5AI(2)304(9.2)(5.2) 2-3 feet	2.25E-07	9.33E-08
5AI(2)304(9.9)(4.6) 1-2 feet	1.14E-06	<MDA
5AI(2)304(9.9)(4.6) 2-3 feet	7.24E-07	<MDA
5AI(2)304(9.9)(5.0) 2-3 feet	1.30E-07	4.59E-08
5AI(2)304(9.9)(5.0) 3-4 feet	6.63E-08	<MDA
5AI(2)304(9.9)(5.0) 4-5 feet	9.52E-08	6.85E-08
5AI(2)304(9.9)(5.0) 5-6 feet	4.56E-08	<MDA
5AI(2)304(9.9)(5.0) 6-7 feet	<MDA	<MDA
5AI(2)305(4.0)(2.0) 0-1 foot	6.74E-07	1.45E-06
5AI(2)305(4.0)(2.0) 1-2 feet	1.47E-07	3.33E-07
5AI(2)305(4.0)(2.0) 2-3 feet	<MDA	<MDA
5AI(2)305(4.0)(3.0) 2-3 feet	<MDA	<MDA
5AI(2)305(4.0)(3.0) 3-4 feet	<MDA	<MDA
5AI(2)305(4.0)(3.0) 4-5 feet	<MDA	<MDA
5AI(2)305(4.0)(3.0) 5-6 feet	<MDA	<MDA
5AI(2)305(8.0)(0.0) 1-2 feet	<MDA	<MDA
5AI(2)305(8.0)(0.0) 2-3 feet	<MDA	<MDA
5AI(2)305(8.0)(1.0) 1-2 feet	3.25E-07	2.02E-07
5AI(2)305(8.0)(1.0) 2-3 feet	1.14E-07	<MDA

Table B.4 (Continued)

5AI(2)305(9.0)(0.0) 0-1 feet	4.12E-07	1.79E-07
5AI(2)305(9.0)(0.0) 1-2 feet	<MDA	<MDA
5AI(2)305(9.0)(0.0) 2-3 feet	<MDA	<MDA
5AI(2)305(9.0)(1.0) 1-2 feet	<MDA	<MDA
5AI(2)316(9.2)(5.2) 6-12 inches	1.56E-07	<MDA
5AI(2)316(9.2)(5.2) 1-2 feet	5.40E-07	1.92E-07
5AI(2)316(9.2)(5.2) @ 2 feet	2.14E-07	<MDA
5AI(2)317(8.0)(2.0) 1.5-2 feet	<MDA	<MDA
5AI(2)317(8.0)(2.0) 2-3 feet	<MDA	<MDA
5AI(2)317(8.0)(2.0) 3-4 feet	<MDA	<MDA
5AI(2)317(8.0)(2.0) 4-5 feet	<MDA	<MDA
5AI(2)317(8.0)(2.0) 5-6 feet	<MDA	<MDA
5AI(2)317(8.0)(2.0) 6-7 feet	<MDA	<MDA
5AI(2)328(9.0)(0.0) 1-2 feet	<MDA	<MDA
5AI(2)328(9.0)(0.0) 2-3 feet	1.14E-07	<MDA
5AI(2)328(9.0)(2.0) 0-6 inches	1.50E-07	<MDA
5AI(2)328(9.0)(2.0) 2-3 feet	1.05E-07	<MDA

Table B.5 8AI Sample Locations beneath Turbine Building Floor

Survey unit, grid number, depth	Cs-137 uCi/g	Co-60 uCi/g
8AI(307)Near Turbine Sump 0-1 ft	9.44E-08	2.82E-07
8AI(307)Near Turbine Sump 1-2 ft	8.43E-08	4.07E-07
8AI(307)Near Turbine Sump 2-3 ft	7.10E-08	6.63E-07
8AI(270)East near enc.dirty line 0-1 ft	5.57E-06	1.62E-04
8AI(270)East near enc.dirty line 1-2 ft	6.82E-07	1.71E-05
8AI(270)East near enc.dirty line 2-3 ft	3.40E-07	9.09E-06
8AI(269)West near enc.clean line 0-1 ft	<mda	8.15E-08
8AI(269)West near enc.clean line 1-2 ft	<mda	1.29E-07
8AI(269)West near enc.clean line 2-3 ft	<mda	7.46E-08
8AI Main Pipeway SE 0-6 inches deep	9.72E-08	1.25E-06
8AI Main Pipeway SE 1-2 feet deep	<mda	7.69E-07
8AI Main Pipeway West 0-6 inches deep	<mda	5.50E-07
8AI Main Pipeway West 1-2 feet deep	<mda	2.05E-07
8AI Main Pipeway NE 0-6 inches deep	<mda	3.39E-07
8AI Main Pipeway NE 1-2 feet deep	<mda	2.47E-07
8AI South of Condenser 0-6 inches deep	<mda	3.98E-07
8AI South of Condenser 1-2 feet deep	<mda	<mda
8AI 3 ft hole over North Circ.Water Pipe 0-6 inches	<mda	9.29E-07
8AI 3 ft hole over North Circ.Water Pipe 1-2 feet deep	<mda	8.70E-08
8AI North of Condenser 0-6 inches deep	<mda	2.99E-07
8AI North of Condenser 1-2 feet deep	<mda	1.80E-07
8AI Near SW Pedestal(East) 0-1 foot deep	1.26E-05	2.07E-06
8AI Near SW Pedestal(North) 0-1 foot deep	9.04E-07	5.77E-07