

[Decommissioning]

DEVELOPMENT OF RESRAD PROBABILISTIC COMPUTER CODES FOR NRC LICENSE TERMINATION APPLICATIONS. S.Y. Chen, C. Yu (Argonne National Laboratory, 9700 Cass Ave., Argonne, IL 60439), T. Mo and C. Trottier (U.S. Nuclear Regulatory Commission, Washington, D.C. 20555)

ABSTRACT

In 1999, the U.S. Nuclear Regulatory Commission (NRC) tasked Argonne National Laboratory to modify the existing RESRAD and RESRAD-BUILD codes to perform probabilistic, site-specific dose analysis for use with the NRC's Standard Review Plan for demonstrating compliance with the license termination rule. The RESRAD codes have been developed by Argonne to support the U.S. Department of Energy's (DOEs) cleanup efforts. Through more than a decade of application, the codes already have established a large user base in the nation and a rigorous QA support. The primary objectives of the NRC task are to: (1) extend the codes' capabilities to include probabilistic analysis, and (2) develop parameter distribution functions and perform probabilistic analysis with the codes. The new codes also contain user-friendly features specially designed with graphic-user interface. In October 2000, the revised RESRAD (version 6.0) and RESRAD-BUILD (version 3.0), together with the user's guide and relevant parameter information, have been developed and are made available to the general public via the Internet for use.

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INTRODUCTION

On July 21, 1997, the U.S. Nuclear Regulatory Commission (NRC) published the License Termination Rule (Title 10, Code of Federal Regulations, Part 20 [10 CFR 20], Subpart E), which establishes requirements for nuclear facility licensees who are terminating their licensed operations. The NRC's approach to demonstrate compliance with the license termination rule is based on a philosophy of moving from simple, prudently conservative calculations toward more realistic simulations, as necessary, using dose modeling to evaluate exposure to residual radioactivity in soil and structures. Such potential exposures are evaluated for two general scenarios from residual contamination: building occupancy for building contamination, and site residential occupancy for soil contamination.

* Work supported by the U.S. Department of Energy, Assistant Secretary for Environmental Management, under Contract W-31-109-Eng-38, and the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, under Contract Job Code Number Y6112.

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The objective of dose modeling is to assess the total effective dose equivalent (TEDE) to an average member of the *critical group** from residual contamination, including any contamination that has reached ground sources of drinking water. The assessment offers a reasonable translation of residual contamination into estimated radiation doses to the public. Compliance with the NRC-prescribed dose criteria can then be assessed by the modeling results. The assessment can be further used to obtain the derived concentration guideline levels (DCGLs) for cleanup activities.

As part of the development of site-specific implementation guidance supporting the License Termination Rule and development of a Standard Review Plan (SRP) on Decommissioning, the NRC recognized the need to perform probabilistic analysis with codes that could be used for site-specific modeling. Such modeling capabilities exist with the RESRAD (Yu et al. 1993) and RESRAD-BUILD (Yu et al. 1994) codes (Figure 1). The RESRAD and RESRAD-BUILD computer codes have been developed by Argonne under U.S. Department of Energy (DOE) sponsorship for use in evaluating radioactively contaminated sites and structures, respectively. Both are widely used in cleanup operations in the United States and abroad. These DOE codes possess the following attributes: (1) the software has been widely accepted and there is already a large user base, (2) the models in the software were designed for and have been successfully applied at sites with relatively complex physical and contamination conditions, and (3) verification and validation of the codes are well documented (Cheng et al. 1995; Gnanapragasam and Yu 1997a, 1997b; NUREG/CP-0163 [NRC] 1998c). The RESRAD codes have been used primarily to derive site-specific cleanup DCGLs based on the deterministic method.

In 1999, the U.S. Nuclear Regulatory Commission (NRC) tasked Argonne National Laboratory (Argonne) with adapting the existing RESRAD and RESRAD-BUILD codes for use in site-specific modeling in accordance with the NRC's license termination compliance process and Standard Review Plan (SRP) on Decommissioning. For use in this NRC process, the codes are being revised to be consistent with the current NRC guidance for dose modeling being developed in the SRP on Decommissioning. Thus, the primary objectives of Argonne's effort are to (1) extend the codes' capabilities to include probabilistic analysis, and (2) develop parameter distribution functions and perform probabilistic analysis with the codes. The two codes incorporate pathway analysis models designed to evaluate the potential radiological dose to an average individual of the critical group who lives or works at a site or in a structure contaminated with residual radioactive materials.

In meeting the NRC's objectives, the enhanced RESRAD codes are designed to comprise three major capabilities: probabilistic sampling, analytical capabilities, and

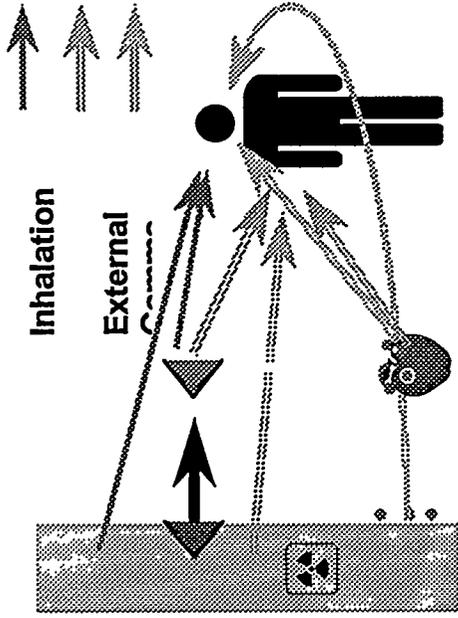
* The critical group is defined as an individual or relatively homogenous group of individuals expected to receive the highest exposure under the assumptions of the particular scenario considered (NUREG/CR-5512, Vol. 1, 1992). The average member of the critical group is an individual assumed to represent the most likely exposure situation.

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RESRAD-BUILD (Building)



RESRAD (Soil)

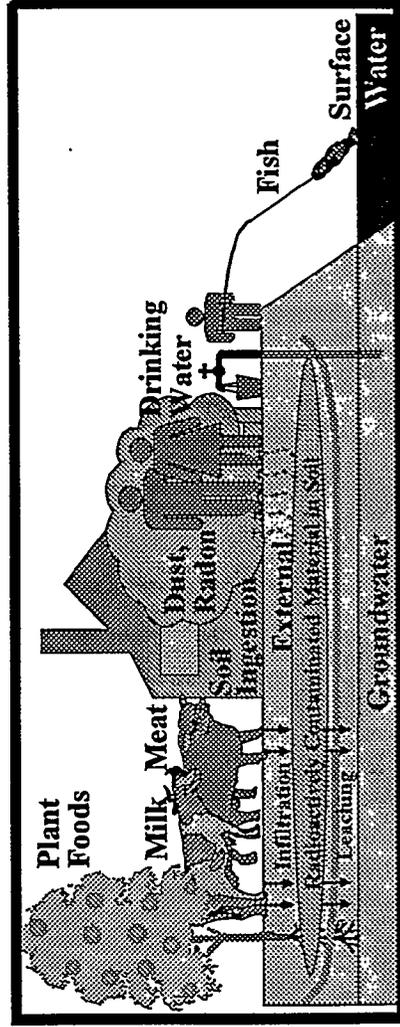


Figure 1. Schematic Illustration of RESRAD (Soil) and RESRAD-BUILD (Building) Pathway Analysis Approach

user-friendly interface. The probabilistic sampling module incorporates the Latin Hypercube (LHC) sampling method (Iman et al. 1984) to perform random sampling of input parameters. The RESRAD codes serve as the analytical core module for dose calculation. The codes are further equipped with user-friendly input and output interface features.

The code development effort is supported by a rather extensive data search and development. To this end, a total of nearly 200 combined input parameters for RESRAD and RESRAD-BUILD were screened and ranked for their relative importance to the dose analysis. About one third of the parameters were identified as important with detailed probability distribution functions developed. Such data distribution was developed using a rather extensive data search based on national variability followed by an analysis of the distribution function.

The software was designed with a user-centered approach. It provides easy access of output through interactive tabular windows; interactive graphical windows; fixed tabular reports; and a complete, formatted database. The output results were chosen to support resultant dose distribution statistics, distributions, and correlations with the input variables. These results can be queried on the basis of environmental pathway, initial nuclide contamination, and time since contaminant placement. The calculation also identifies the peak doses over the specified time (within 1,000 years per the NRC's SRP guidance) for the purpose of demonstrating compliance.

The integrated software package leverages the user's familiarity with standard Microsoft WindowsTM tools and the family of RESRAD software tools. The probabilistic screens are tightly integrated with the previously identified default distributions for the input variables. Additionally, users also have a variety of options to enter site-specific parameters through the newly developed features. The software offers feedback to quickly identify the default and site-specific distributions. The user can also graphically preview the distribution shape. The integrated RESRAD and RESRAD-BUILD codes are designed to operate on Microsoft WindowsTM 95, 98, 2000, and NT platforms.

APPROACH

The objective of dose modeling is to assess the total effective dose equivalent (TEDE) to an average member of the critical group from residual contamination, including any contamination that has reached ground sources of drinking water. The assessment offers a reasonable translation of residual contamination into estimated radiation doses to the public. Compliance with the NRC-prescribed dose criteria can then be assessed by the modeling results.

The task of developing probabilistic RESRAD and RESRAD-BUILD codes is discussed in subsequent sections. The effort represents three major areas of development: (1) identify key parameters and develop data distribution (i.e., parameter categorization, parameter ranking, and parameter distribution), (2) develop probabilistic module (i.e., probabilistic modules), and (3) perform code testing and analysis (i.e., probabilistic

analysis and probabilistic module testing). Because of the interrelationships among these efforts, an iterative process is used to attain optimal results. For instance, preliminary code testing was frequently conducted to test the code at the various stages of development. Likewise, periodical testing of the preliminary codes also provided valuable feedback to the data distribution development.

The strategy to the approach was to fully use the capabilities of the existing RESRAD codes and provide needed enhancements for satisfying the NRC's Standard Review Plan objectives for site-specific dose analysis (Figure 2). In the process of development, consistencies were also maintained, to the extent possible, with the generic methodologies or publications described by the NRC (NRC 2000; NUREG/CR-1549, 1998; NUREG/CR-5512, Vols. 1-3, 1992, 1998, 1999).

PARAMETER AND DATA DEVELOPMENT

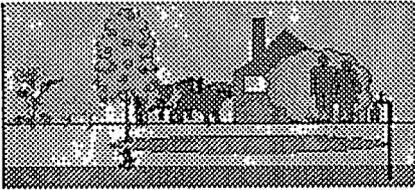
Parameter Categorization. The first step was to list and categorize the total combined input parameters (about 200) used in the RESRAD and RESRAD-BUILD codes. The parameters were first listed into three major categories: physical, behavioral, and metabolic. Parameters that would not vary with the conditions of receptors were classified as physical parameters. Examples include soil leaching factor and contamination thickness. Parameters that exhibit a relationship with the receptor's behavior and the scenario definition were classified as behavioral parameters. Examples include building occupancy factor and food ingestion rate. Parameters that represent the metabolic characteristics of the potential receptor and that would be independent of the scenario being considered were classified as metabolic parameters. Examples include dose conversion factors. Certain parameters, such as inhalation rate (both behavioral and metabolic), have been found to exhibit dual characteristics. In those instances, the parameter was assigned to the category of its dominant characteristic.

Of a total of 142 RESRAD parameters (discounting the 3 flag parameters), 107 have been identified as physical (P), 25 behavioral (B), and 10 metabolic (M). For a total of 50 parameters of RESRAD-BUILD, 33 were identified as physical, 12 behavioral, and 5 metabolic (Kamboj et al. 1999).

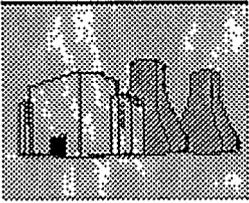
Parameter Ranking. A strategy was developed to rank the RESRAD and RESRAD-BUILD input parameters and identify parameters for detailed distribution analysis. Depending on their importance, parameter distributions were characterized as high, medium, or low priority. The parameters were ranked on the basis of four criteria: (1) relevance of the parameter in dose calculations, (2) variability of the radiation dose as a result of changes in the parameter value, (3) parameter type (physical, behavioral, or metabolic), and (4) availability of data on the parameter in the literature. A composite scoring system was developed to rank the parameters based on each criterion, with a low score assigned to parameters with a higher priority and a high score assigned to parameters with lower priority under the considered criterion. In all, parameters for

Base Deterministic Codes

RESRAD 6.0



RESRAD-BUILD 3.0



Steps to Develop Probabilistic Modules

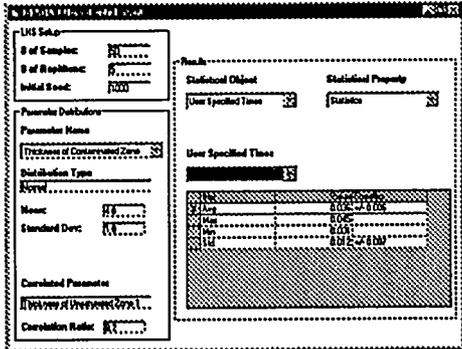
PARAMETER AND DATA DEVELOPMENT

- Parameter Categorization
- Parameter Ranking
- Developing Parameter Distributions

PROBABILISTIC CODE DEVELOPMENT

CODE TESTING AND ANALYSIS

- Probabilistic Dose Analysis
- Testing Probabilistic Modules and Integrated Codes



Cumulative Probability

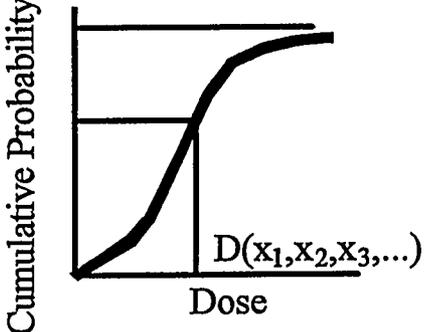


Figure 2. Approach to the Development of Probabilistic RESRAD and RESRAD-BUILD Codes

RESRAD are ranked as follows: 10 as high priority (H), 39 for medium priority (M), and 93 as low priority (L). For RESRAD-BUILD, there are 4 ranked as high priority, 20 as medium priority, and 26 as low priority (Cheng et al. 1999).

Parameter Distribution. Parameter distributions were developed for those identified as high priority and for the majority of the medium priority in the RESRAD and RESRAD-BUILD codes. A total of 67 parameters were selected for analysis. These parameters were deemed to be the ones most relevant to the NRC objective of dose analysis for demonstrating compliance with the radiological criteria stipulated in the decommissioning and license termination guidance. Development of parameters distributions entailed the following basis and assumptions: (1) use nationwide data representation, (2) use the most relevant and up-to-date data sources across the nation, (3) obtain the best fit to characterize the distribution, and (4) assume an average adult male as a receptor (constrained by current availability of dose conversion factors). Compilation of the data entailed an extensive literature search using library and Internet resources. The focus was placed on analyzing the available data and making the most plausible distribution assignments for each selected parameter (Biwer et al., 2000). In general, parameters were characterized into five distribution types: uniform/loguniform, triangular, normal, lognormal, and empirical.

In this process, it was recognized that many of the national parameters in question may not be well suited for site-specific applications, since they can vary significantly from site to site or even within the same site. Nevertheless, the users are encouraged to develop site-specific data distributions where warranted using the similar methodology for deriving the appropriate representation for a particular parameter distribution. It is also recognized that the derived distribution information contains varying quality due to the availability and quality of the original data sources. In general, data quality for RESRAD parameters tends to be better than that of RESRAD-BUILD parameters. The primary reason is attributable to the much longer history of dealing with site (i.e. soil) cleanup than that of the building decontamination and decommissioning. One example is the surface resuspension factor, which tends to dominate the estimated dose from a contaminated building surface (using RESRAD-BUILD). Existing information on this particular parameter is, however, rather scant. Continued research on such key parameters is certainly warranted and strongly recommended.

PROBABILISTIC MODULE DEVELOPMENT

Probabilistic Modules. The RESRAD and RESRAD-BUILD computer codes have been developed by Argonne under sponsorship of the U.S. Department of Energy (DOE) for use in evaluating, by a deterministic approach, the radioactively contaminated sites and structures, respectively. Both are widely used in cleanup operations in the United States and abroad. Both codes are pathway analysis models designed to evaluate the potential radiological dose to an average individual of the critical group who lives or works at a site or in a structure contaminated with residual radioactive materials.

As part of the ongoing effort to meet NRC's objectives, external modules equipped with probabilistic sampling and analytical capabilities were developed for RESRAD and RESRAD-BUILD. To this end, the major aspects of the software system design include: (1) development and integration of the existing deterministic RESRAD codes with the external Latin Hypercube (LHC) sampling software (Iman et al. 1984), (2) incorporation of parameter distribution data previously discussed, (3) development of input and output interfaces of the integrated system, (4) development of testing methods, and (5) incorporation of software quality assurance (QA) methods (LePoire et al. 2000). Design of the integrated software system is shown in Figure 3.

The modules are further equipped with user-friendly input and output interface features to accommodate numerous parameter distribution functions and result display requirements. The integrated system, consisting of the codes and the interface modules, is designed to operate on Microsoft Windows™ 95, 98, and NT platforms.

CODE TESTING AND ANALYSIS

Probabilistic Module Testing. The testing effort was performed periodically to satisfy the project QA requirements and to ensure consistency of development throughout the process. Testing consists of four major components:

- Testing of the probabilistic inputs sampling program. This effort is to ensure the compatibility and functionality of the externally acquired Latin Hypercube program prior to its adaptation to the system.
- Calculation integration testing. The probabilistic modules were tested during the development mode for their proper execution and for the reasonableness of the results. Testing was conducted on radionuclides, pathways, input correlations, and comparison with deterministic results.
- Output interface testing. Testing focused on the output interface that is relevant to the accuracy of the results. This includes a comparison of percentile and statistics of interactive tables and reports. Results reported in the tables and the corresponding graphic outputs were also compared for consistency. Results on peak dose were also examined.
- Integrated testing. The calculation, interface, and distribution aspects of the fully integrated system were tested. A scenario case was used and the results from the software are interpreted. The interface was reviewed with modern user interface heuristics as a guide. The distribution process was checked for completeness, compatibility, and security from viruses over a range of operating systems. Testing was also conducted independently by the NRC staff as well as the industry. Feedback was incorporated into the final code development.

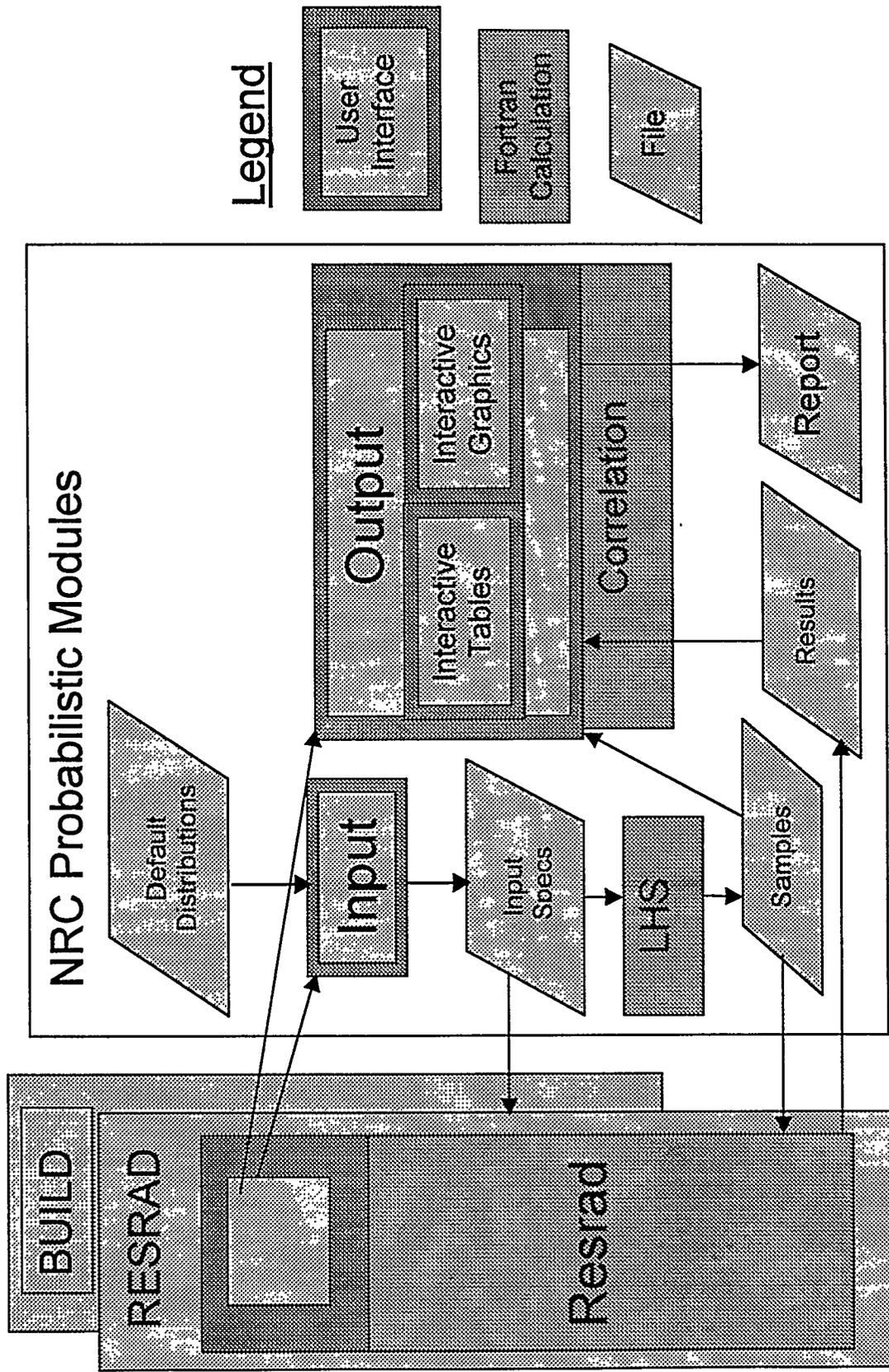


Figure 3. Design of an Integrated Software System for the Probabilistic RESRAD Codes

Testing procedure and results of the software development were documented by LePaire et al. (June 2000) and were found to satisfy the QA requirements. As is the case with any newly released codes, further testing can be realized as the codes are being released for use by the industry as well as the interested public.

Probabilistic Dose Analysis. The effects of parameter distribution on the estimated doses, taking into account parameter correlations, for the residential scenario in RESRAD and for the building occupancy scenario in RESRAD-BUILD were assessed. The analysis took into account long-term transport of residual radionuclides in the environmental media and associated exposure pathways. For RESRAD, the peak dose within a 1,000-year time frame was captured, and for RESRAD-BUILD, the initial dose (i.e., at time 0) was calculated and used as the peak dose. The probabilistic analysis was performed by using the stratified sampling of the Latin hypercube sampling method for a collection of input parameter distributions. Figure 4 shows an example of the analysis using RESRAD on a residential scenario. The results illustrate the variability of the output dose results with contamination setting for a few given radionuclides. Given a specific regulatory interpretation in terms of cumulative probability in dose, the results render a clear method for demonstrating compliance. The probabilistic analysis has demonstrated the process of using the integrated RESRAD and RESRAD-BUILD codes and the probabilistic modules, together with the parameter distributions, for dose assessment at a relatively complex site (Kamboj et al. 2000).

SUMMARY AND CONCLUSIONS

The advanced versions of RESRAD (version 6.0) and RESRAD-BUILD (version 3.0) have been developed out of the existing deterministic versions to support NRC's Standard Review Plan for its license termination activities. The new codes are equipped with probabilistic analytical capabilities for radiological dose analysis in site-specific analysis. The development took advantage of the codes' wide circulation and popular use in environmental cleanup activities throughout the nation. An external module containing the advanced Latin Hypercube sampling technique was incorporated into the codes. To support the analysis, a database containing parameter distribution was also developed. This was accomplished by identifying key parameters from a total of nearly 200 parameters combined for both codes. Best available data were compiled for those key parameters, taking into account the national variability, and fitted into the most representative statistical representation. The codes were equipped with input/output features designed to offer users a high degree of user friendliness. Outputs are presented in tabular as graphic forms by radionuclide or pathway. Peak doses over time are identified and compiled for use in compliance purposes. Extensive testing has been conducted according to the project QA plan prior to the release of the codes. The integrated RESRAD and RESRAD-BUILD codes are designed to operate on Microsoft Windows™ 95, 98, 2000, and NT platforms. The codes and the user's guide are currently available for download at the NRC's website.

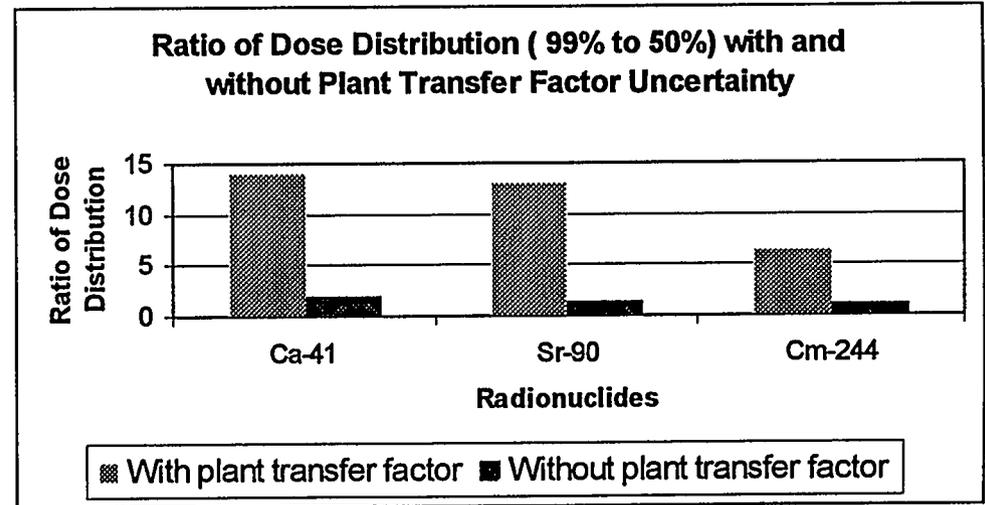
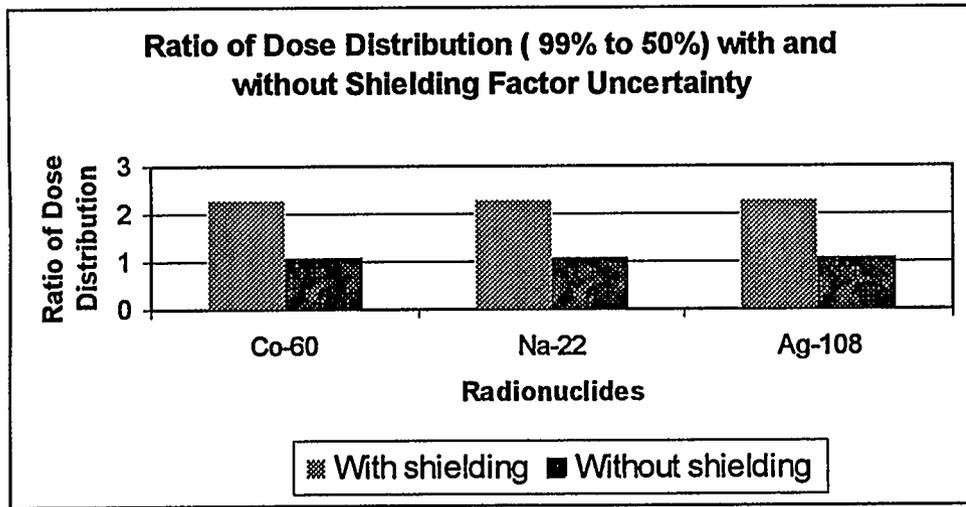
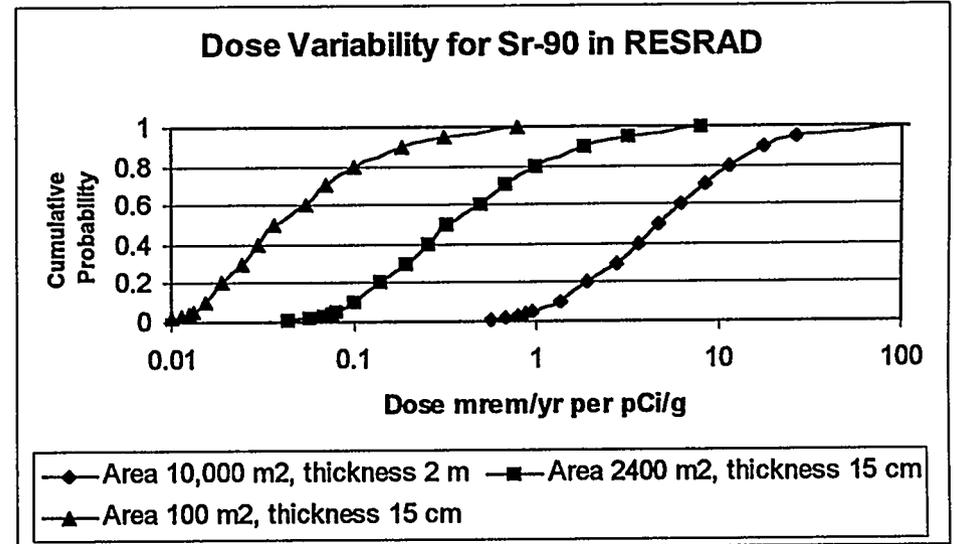
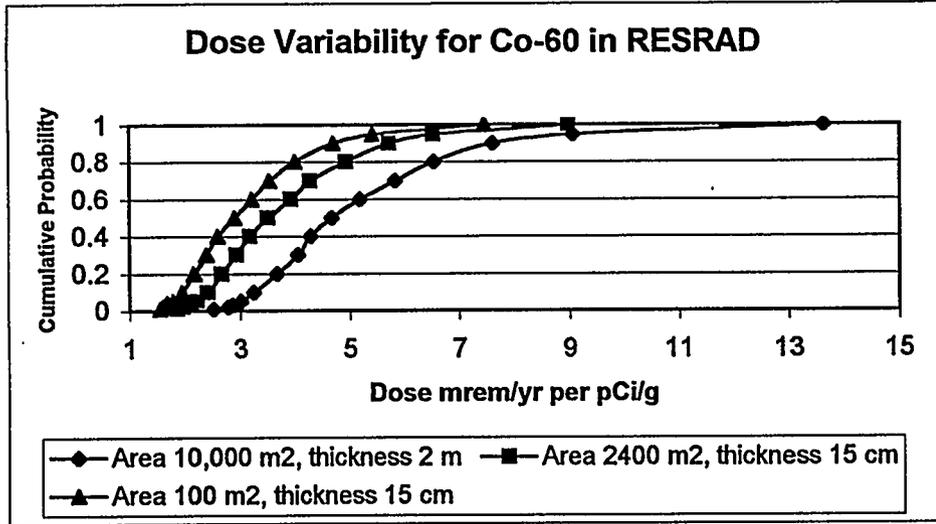


Figure 4. An Example of Dose Analysis Using the Probabilistic RESRAD Code for Residential Scenario

The development of the codes also provides future research opportunities. These potentials areas may include (1) a full-scale sensitivity analysis for analyzing the parameters to identify areas of research, (2) performing case studies to verify the application of the probabilistic method (as opposed to the deterministic approach), (3) extending the approach to other areas of analysis regarding pathway dose and risk analysis, and (4) establishing an interagency effort in maintaining consistencies in model development.

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