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Development of Risk-Based Computer Models for Deriving Criteria on Residual Radioactivity and Recycling*

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Development of Risk-Based Computer Models for Deriving Criteria on Residual Radioactivity and Recycling[1]

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ABSTRACT

Argonne National Laboratory (ANL) is developing multimedia environmental pathway and health risk computer models to assess radiological risks to human health and to derive cleanup guidelines for environmental restoration, decommissioning, and recycling activities. These models are based on the existing RESRAD code, although each has a separate design and serves different objectives. Two such codes are RESRAD-BUILD and RESRAD-PROBABILISTIC. The RESRAD code was originally developed to implement the U.S. Department of Energy's (DOE's) residual radioactive materials guidelines for contaminated soils. RESRAD has been successfully used by DOE and its contractors to assess health risks and develop cleanup criteria for several sites selected for cleanup or restoration programs.

RESRAD-BUILD analyzes human health risks from radioactive releases during decommissioning or rehabilitation of contaminated buildings. Risks to workers are assessed for dismantling activities; risks to the public are assessed for occupancy. RESRAD-BUILD is based on a room compartmental model analyzing the effects on room air quality of contaminant emission and resuspension (as well as radon emanation), the external radiation pathway, and other exposure pathways. RESRAD-PROBABILISTIC, currently under development, is intended to perform uncertainty analysis for RESRAD by using the Monte Carlo approach based on the Latin-Hypercube sampling scheme. The codes being developed at ANL are tailored to meet a specific objective of human health risk assessment and require specific parameter definition and data gathering. The combined capabilities of these codes satisfy various risk assessment requirements in environmental restoration and remediation activities.

INTRODUCTION

Decades of nuclear fuel cycle operations associated with both civilian and military applications in the United States have left many installations contaminated with varying levels of residual radioactivity. Cleaning up these installations and returning the sites to public use have been objectives of the U.S. Department Of Energy (DOE) and regulators. Criteria for establishing acceptable cleanup levels have been aimed at protecting human health; such criteria are therefore "risk-based." For instance, the U.S. Environmental Protection Agency (EPA) has specified an acceptable human health lifetime risk level of 10^{-4} to 10^{-6} in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

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cleanup requirements. Likewise, DOE and the Nuclear Regulatory Commission (NRC) have established dose limits for developing soil guidelines (DOE 1990) and proposed decommissioning of nuclear facilities (NRC 1994). In the process of demonstrating compliance with the prescribed risk (or dose) levels, sophisticated tools are needed to accurately translate the human health risks into cleanup levels (such as radioactivity concentrations) of the environmental media. To accomplish this objective, Argonne National Laboratory (ANL) has developed several computer codes designed to assess human health risks associated with residual radioactivity and recycling. These codes are based on risk-based pathway models and are intended for use in assessing radiological health risks to humans and in deriving cleanup guidelines for environmental restoration, decommissioning, and recycling activities. Three codes have been developed for these purposes: RESRAD, RESRAD-BUILD, and RESRAD-PROBABILISTIC.

RESRAD, designed to calculate site-specific residual radioactive material guidelines to an on-site resident, was developed to implement the DOE's residual radioactive materials guidelines for contaminated soils (DOE 1990). RESRAD-BUILD analyzes human health risks from contaminants during building dismantling and occupancy through decommissioning or rehabilitation, as well as for material end-use scenarios (such as for reuse and recycle). RESRAD-PROBABILISTIC is a separate model of RESRAD currently under development. While RESRAD provides deterministic results of the analysis, RESRAD-PROBABILISTIC is intended to perform uncertainty analysis for RESRAD by using the Monte Carlo approach (Yu 1993). It is based on the Latin-Hypercube sampling scheme (Iman and Shortencarier 1984). This PROBABILISTIC code complements RESRAD in that it offers the capability of generating PROBABILISTIC distribution of resulting risks from the RESRAD pathway analysis.

APPROACH

The basic framework of the RESRAD code series has four major parts: (1) source analysis, (2) environmental transport analysis, (3) dose/exposure analysis, and (4) scenario analysis. Source analysis addresses the source terms that determine the rate at which residual radioactivity is released into the environment. That rate is determined by the geometry of the contaminated region, the concentrations of radionuclides present, the ingrowth and decay rates of the radionuclides, and the removal rate by erosion, leaching, or resuspension. Environmental transport analysis addresses the areas of (1) identifying environmental pathways by which radionuclides can migrate from the source to a human exposure location and (2) determining the migration rate along these pathways. Dose/exposure analysis addresses the derivation of dose conversion factors for the radiation dose that will be incurred by exposure to ionizing radiation. The parameters that control the rate of radionuclide release into the environment and the severity and duration of human exposure at a given location are determined by patterns of human activity referred to as exposure scenarios.

The RESRAD-PROBABILISTIC code incorporates additional uncertainty analysis capability to the RESRAD code. It utilizes Monte Carlo simulation techniques to obtain a statistical distribution of the results.

RESRAD: Nine environmental pathways are modeled by RESRAD. For each exposure pathway, radionuclides can migrate from a source to a human exposure location by many environmental pathways. Major pathways used to derive site-specific soil guidelines in the RESRAD code are identified in Figure 1.

External gamma radiation from radionuclides distributed throughout the contaminated zone is the dominant external radiation pathway and the only external radiation pathway taken into account in calculating soil guidelines. The dose due to the external gamma radiation is first calculated for an individual exposed continuously to radiation from an infinite contaminated zone at a distance of 1 m from the ground surface. Correction factors are then applied for the finite area and thickness of the contaminated zone, shielding by a cover of uncontaminated soil, irregular shape, shielding by the floors and walls of a house, and less-than-continuous occupancy.

Inhalation exposure results primarily from inhalation of radon decay products and contaminated dusts. An inhalation pathway consists of two segments: (1) an exposure segment linking the source (contaminated zone) with the airborne radionuclides at an exposure location and (2) an inhalation segment linking the airborne radionuclides with the exposed individual. Modeling the airborne exposure pathway segment consists of two steps: (1) modeling the process by which radionuclides become airborne and (2) modeling the process by which the airborne radionuclides are transported to a human exposure location and diluted before inhalation. The first step gives the ratio of the airborne emission near the source before it is dispersed and diluted to the concentration in the resuspendable layer of dust; the second step gives the ratio of the airborne concentration at the point of exposure to the airborne emission at the source.

Ingestion pathways consist of food, water, and soil ingestion pathways. Four food pathway categories are considered: plant foods, meat, milk, and aquatic foods. Analysis of food pathways involves rather complex radionuclide transport in the relevant environmental media and the subsequent uptake via various food chains. Terrestrial pathways and water pathways are included. The terrestrial pathway includes the following four plant food pathways: (1) root uptake from crops grown in the contaminated zone, (2) foliar uptake from contaminated dust deposited on the foliage, (3) root uptake from contaminated irrigation water, and (4) foliar uptake from contaminated irrigation water. The water pathways include surface and well water. Both well water and surface water can be used for drinking. The fraction of well water blended with or supplemented by surface water is used to calculate the total contribution from groundwater and surface water. The ingestion pathway also includes direct ingestion of contaminated soil itself. The dose due to ingestion of soil depends on the amount of soil ingested and the radionuclide concentrations in the soil.

RESRAD-BUILD: The RESRAD-BUILD code (Yu et al. 1994) is based on a room compartmental model that analyzes the effects on room air quality of contaminant emission and resuspension (as well as radon emanation), the external radiation pathway, and other pathways such as air immersion and indirect ingestion. The RESRAD-BUILD computer code is a pathway analysis model that was developed to evaluate the potential radiological dose (or risk) incurred by an individual (see Figure 2). Because of the proximity of human-to-contaminant contact during building decommissioning or dismantling, RESRAD-BUILD requires more precise pathway modeling and input data than does RESRAD. For instance,

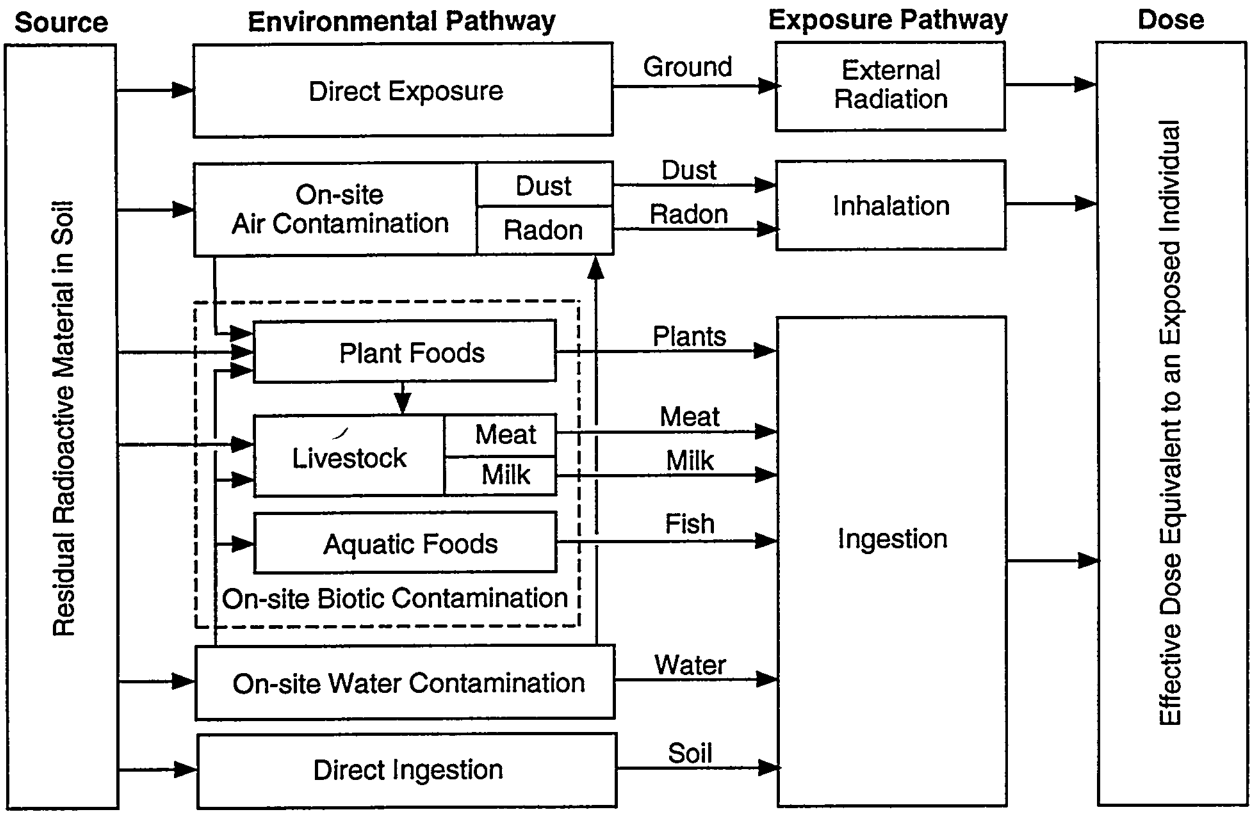

FIGURE 1. Schematic Representation of RESRAD Pathways
(Source: Yu et al. 1993)

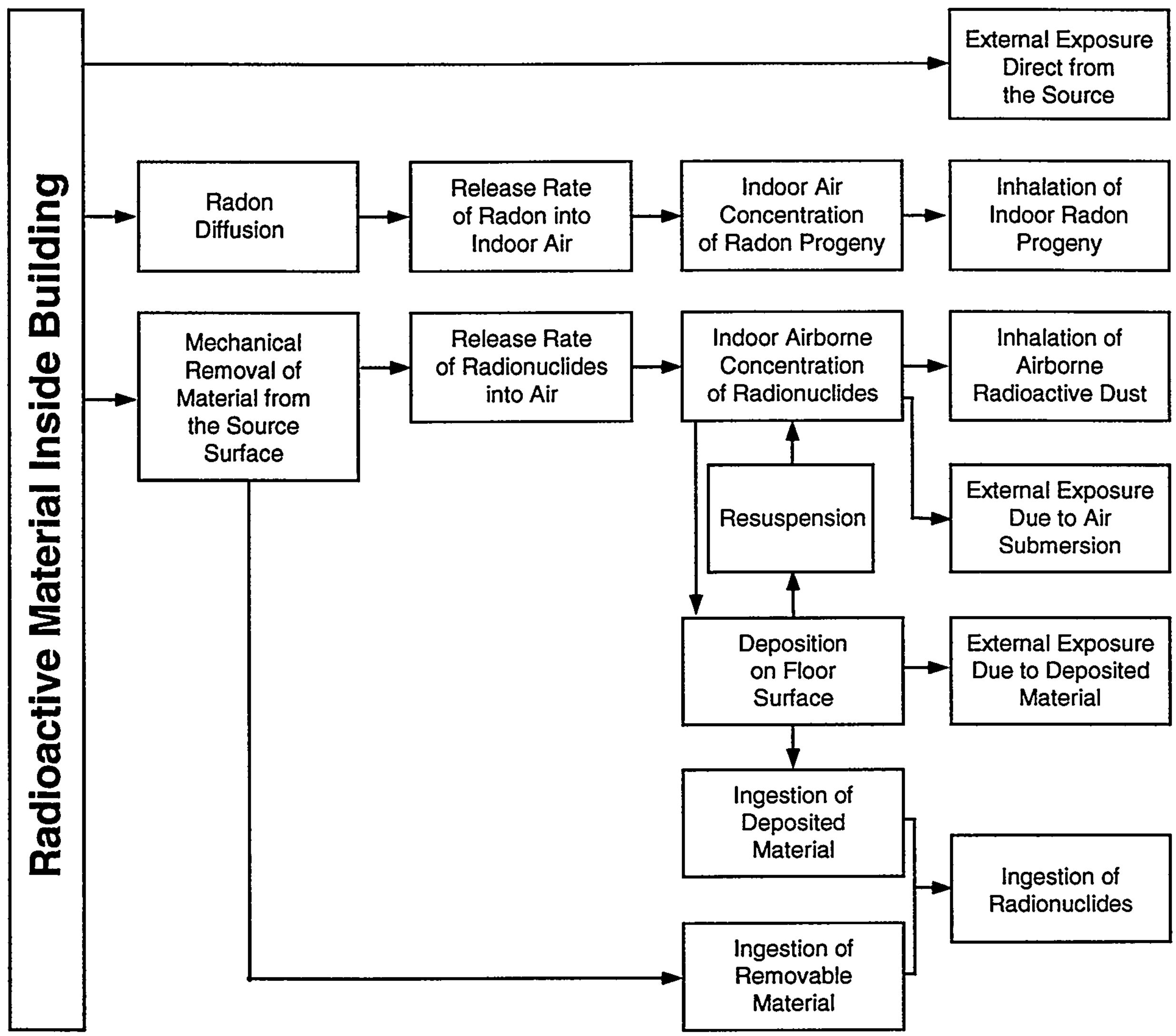

FIGURE 2. Schematic Representation of RESRAD-BUILD Pathways
(Source: Yu 1994)

a detailed description of contaminant distribution is needed to better define the source-to-receptor configuration. The same applies to the room air quality.

Several important site-specific parameters – including building structural material, air exchange, room size, and contamination thickness – are considered in assessing risk associated with building decontamination. Thus, detailed modeling of the transport of contaminants inside the building and a comprehensive exposure pathway analysis have been considered in RESRAD-BUILD evaluation of human health risks resulting from building contamination and material end-use scenarios.

The radioactive material in the building structure can be released into the indoor air by mechanisms such as diffusion (radon gas), mechanical removal (decontamination activities), or erosion (removable surface contamination). The RESRAD-BUILD code consists of two major model components: air quality resulting from removal and transport of radioactive material inside the building, and external exposure based on various source-receptor configurations. The air quality model considers the transport of radioactive dust particulates and radon progeny due to (1) air exchange between compartments and with outdoor air, (2) deposition and resuspension of particulates, and (3) radioactive decay and ingrowth. The external exposure model is based on the SOILD model (Chen et al. 1991), which also has incorporated the latest recommendations of the EPA. The external exposure model, additionally, allows variation in source geometry, shape, and source material.

Seven pathways are considered in the RESRAD-BUILD code: (1) external exposure to penetrating radiation emitted directly from the sources, (2) external exposure to penetrating radiation emitted from radioactive particulates deposited onto the floors of the compartments, (3) external exposure to penetrating radiation due to submersion in airborne radioactive particulates, (4) inhalation of airborne radioactive particulates, (5) inhalation of aerosol indoor radon decay products, (6) direct, inadvertent ingestion of radioactive material contained in removable material, and (7) inadvertent ingestion of airborne radioactive particulates deposited onto the surfaces of the building. The first three pathways would result in external exposure, while the others would result in internal exposure due to internal contamination of the exposed individual.

In the RESRAD-BUILD model, the building is conceptualized as a structure composed of up to three compartments. It can be a one-room warehouse, a two-room office or apartment, a three-room ranch house, a three-story office building, or a two-story house with a basement. Air exchange is assumed to occur between compartments 1 and 2 and compartments 2 and 3 but not between compartments 1 and 3. All compartments can exchange air with the outdoor atmosphere.

An air quality model was developed to calculate the contaminant concentration in each compartment. A coordinate system is used in RESRAD-BUILD to define the location of the sources and receptor points inside the building. With the user specifying the locations of the sources and receptors, as well as the time each receptor spends in each compartment, the radiological dose to the receptors can be calculated for any type of building use, including residential, commercial, or industrial. The analysis of the inhalation pathway also includes consideration of the emanation of radon and concentrations of its progeny. Therefore, the building model approach used in RESRAD-BUILD is quite flexible.

The building is assumed to be contaminated with radioactive materials located at a defined number of places within the structure of the building. Each contaminated location in the building is considered a distinct source, and as many as 10 sources can be specified in a single run of RESRAD-BUILD. Depending on its geometric appearance, the source can be defined as a volume, area, line, or point source. The distinction between these types of sources is rather arbitrary and reflects the modeling objective of simplifying the overall configuration, whenever justifiable. The proper classification of each source is left to the user's best judgment.

RESRAD-PROBABILISTIC: The RESRAD-PROBABILISTIC code employs an existing Monte Carlo sampling algorithm as a driver to simulate statistic distribution of the RESRAD output results. The algorithm, based on the Latin Hypercube Sampling (LHS) method (Iman and Shortencarier 1984), has been developed by Sandia National Laboratories. Thus, RESRAD-PROBABILISTIC basically represents an integration of the LHS driver and the RESRAD code, plus a postprocessor for data compilation and treatment. Input to the LHS sampling requires parametric characteristics such as data distribution characteristics, mean values, as well as standard deviations. An effort has been initiated at ANL to compile data on parameter distributions, distribution characteristics, and correlations among parameters.

SCENARIOS AND APPLICATIONS

RESRAD: Many parameters that determine the quantity of radionuclides or radiation to which an individual is exposed are determined by exposure scenarios; that is, patterns of human activity that can affect the release of radioactivity from the contaminated zone and the amount of exposure received at the exposure location. For RESRAD, soil guidelines are based on a family farm exposure scenario. This scenario includes all environmental pathways for on-site or near-site exposure and is expected to result in the highest predicted lifetime dose. Other scenarios, such as the industrial worker and recreationist, can be taken into account by adjusting the scenario parameters in formulas for calculating the transport of radionuclides through the pathways.

Soil guidelines are based on on-site exposure because on-site residents will receive a radiation dose that is at least as large as (and generally larger than) the dose to off-site residents. The external radiation dose will decrease rapidly with distance from the site, and secondary off-site sources – such as surface deposits of airborne contaminated soil or water contaminated by radionuclides leached from the soil – will have lower radionuclide concentrations. The contributions from inhalation pathways will decrease with distance from the site for the same reasons. The largest contribution from the groundwater pathway will be for drinking water from the unconfined aquifer tapped by a well at the downgradient boundary of the contaminated area. This contribution can be the same for on-site and near-site residents but will decrease for wells at greater distances from the boundary. The situation is more complicated for foodchain pathways because reconcentration can occur. However, the predominant contribution is from on-site crops and domestic animals, and this contribution will be greatest for on-site residents who raise food for their own consumption.

The assignment of appropriate values to the scenario parameters is based on existing patterns of human activity that can be expected to persist for an indefinite period. For most scenario parameters, this criterion enables a straightforward determination of parameter values on the basis of data for current conditions.

Over the years, RESRAD has undergone major improvements in terms of both added modeling capability and input database. The latest updates are described in the RESRAD Manual, Version 5.0 (Yu et al. 1993). RESRAD is a participating code in the international verification and validation (BIOMOVS) effort. The code has been used widely by DOE and its contractors and to a certain extent outside of DOE. To date, some 30 RESRAD workshops have been conducted by ANL. Several major DOE programs have successfully utilized the code in assessing human health risks and developing site cleanup criteria.

RESRAD-BUILD: The RESRAD-BUILD code is designed with flexibility and simplicity in mind so that it can evaluate diverse exposure scenarios for a contaminated building, such as office work, building cleaning and maintenance work, building decontamination, building renovation, building visits, and continuous residency. The receptors considered in the RESRAD-BUILD model include office worker, resident, industrial worker, decontamination worker, building visitor, or any other individual spending time inside the contaminated building. The exact location (coordinates) of the receptor is required to calculate external exposure. The receptor location should be the midpoint of the person. For example, if the receptor is standing on a contaminated floor, the receptor location should be 1 m above the floor. For other pathways, the code requires information only about the room in which the receptor is located because the air quality model assumes that the air concentration is homogeneously mixed in each compartment. To calculate the external dose, input parameters to the code include the receptor location and the shielding material type, density, and thickness. The orientation of the receptor to the source can also be selected, that is, rotational or facing the source (anterior-posterior). The anterior-posterior orientation will result in a higher direct external dose than the rotational orientation.

Up to 10 receptor points can be specified in the RESRAD-BUILD code. A time fraction spent at each receptor point needs to be input. The total time can exceed unity, thus allowing a single run of the RESRAD-BUILD code to evaluate total (collective) worker dose and total individual dose.

RESRAD-BUILD is currently completed as draft and has been reviewed by DOE. The code has been applied successfully for analyzing scenarios described in a separate DOE effort to assess potential release standards by calculating human health risks from radioactive scrap metal recycle and reuse (Murphie et al. 1993).

RESRAD-PROBABILISTIC: Scenarios used for RESRAD-PROBABILISTIC are similar to those used by RESRAD, except RESRAD-PROBABILISTIC accepts input as distribution functions and provides a range of output results. Figure 3 shows an example of RESRAD-PROBABILISTIC output that provides a cumulative probability distribution curve for the resulting dose.

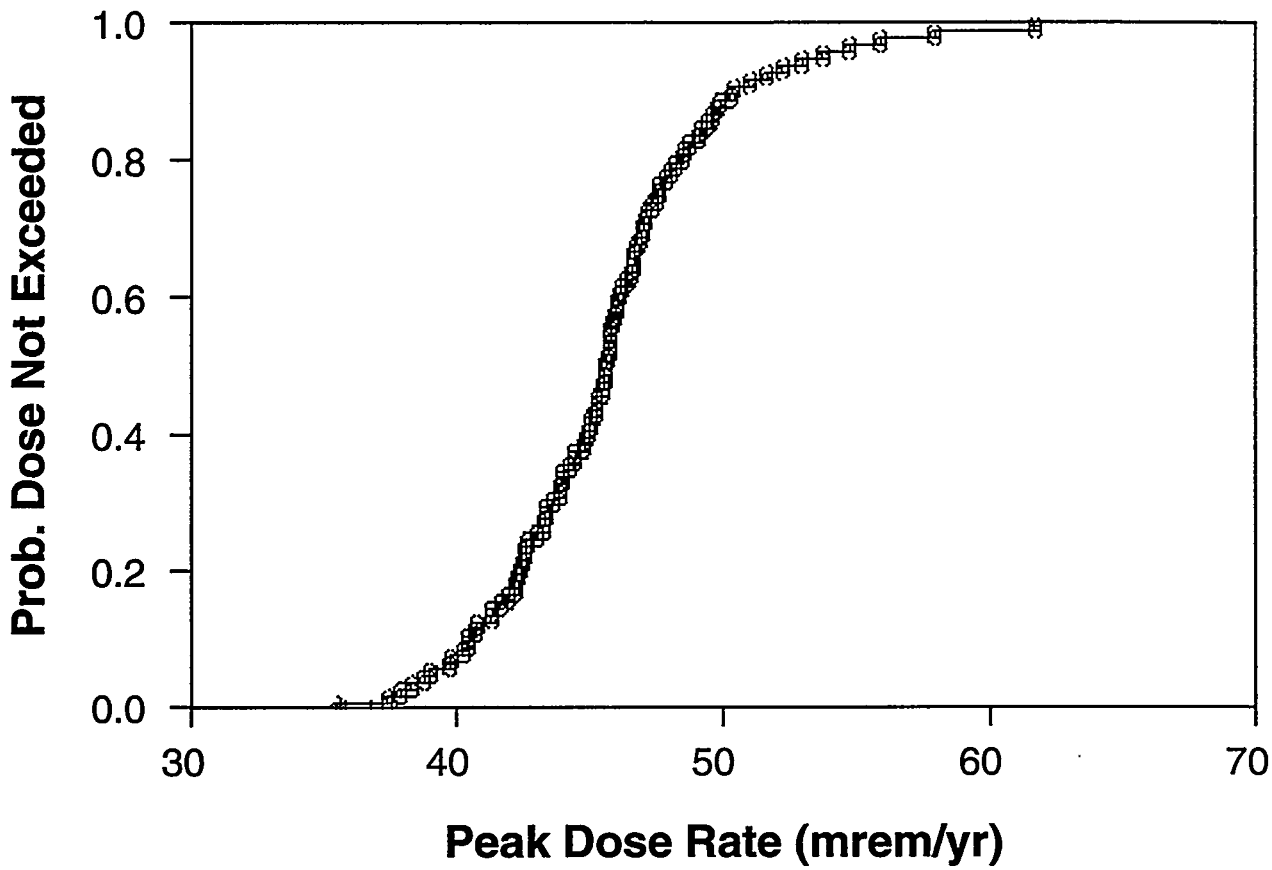

FIGURE 3. Sample of Cumulative Probability Distribution Calculated by RESRAD-PROBABILISTIC

SUMMARY AND CONCLUSIONS

A RESRAD code series is under development at ANL. These codes are designed to perform human health risk analysis based on multimedia environmental pathway models. Each code is tailored to meet a specific objective of human health risk assessment, requiring specific parameter definition and data gathering. Through continued improvement and incorporation of state-of-art methodology and data information, the combined capabilities of these codes serve to satisfy various risk assessment requirements in environmental restoration and remediation activities.

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