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**U.S. NUCLEAR REGULATORY COMMISSION
DOSE MODELING WORKSHOP, NOV. 13-14, 1997,
RESRAD MODEL PRESENTATION***

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for submission to
proceedings of
U.S. Nuclear Regulatory Commission
Dose Modeling Workshop
November 13-14, 1997
Washington, D.C.

December 1997

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* Work supported by the U.S. Department of Energy, Office of Environmental Policy and Assistance, and Office of Environmental Restoration, under contract W-31-109-Eng-38.

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ABSTRACT:

RESRAD was one of the multimedia models selected by the U.S. Nuclear Regulatory Commission (NRC) to include in its workshop on radiation dose modeling and demonstration of compliance with the radiological criteria for license termination. This paper is a summary of the presentation made at the workshop and focuses on the 10 questions the NRC distributed to all participants prior to the workshop. The code selection criteria, which were solicited by the NRC, for demonstrating compliance with the license termination rule are also included. Among the RESRAD family of codes, RESRAD and RESRAD-BUILD are designed for evaluating radiological contamination in soils and in buildings. Many documents have been published to support the use of these codes. This paper focuses on these two codes. The pathways considered, the databases and parameters used, quality control and quality assurance, benchmarking, verification and validation of these codes, and capabilities as well as limitations of these codes are discussed in detail.

1 INTRODUCTION

On November 13-14, 1997, the U.S. Nuclear Regulatory Commission (NRC) conducted a workshop on radiation dose modeling and demonstration of compliance with the radiological criteria for license termination. The RESRAD model, developed at Argonne National Laboratory (ANL) for the U.S. Department of Energy (DOE), was one of the models the NRC selected to include in the workshop. The RESRAD model and code are used to derive site-specific guidelines for allowable residual concentrations of radionuclides in soil and to calculate doses, risks, and guideline values (Yu et al. 1993b). Argonne's presentation focused on the 10 questions the NRC distributed to all participants prior to the workshop. The NRC also asked participants to suggest criteria for selecting code for demonstrating compliance with the license termination rule. On the basis of its experience in developing and using computer models for decontamination and decommissioning, Argonne recommended the following criteria for selecting computer code for demonstrating compliance with the license termination rule:

- Code should have a users' manual and other supporting materials documenting its methodology and databases/parameters.

- Code should be benchmarked, verified, and undergo quality assurance (QA) and quality control (QC) procedures.
- Code should be easy to use and the results reproducible.
- Code should have a state-of-science dose conversion factors (DCFs) database and transfer factors database.
- Code should be able to evaluate both soil and building contamination.
- Code should address both volume and surface contamination with varying thicknesses and areas, with or without cover.
- Code should address time-dependent processes such as ingrowth and decay, in both the source and during transport in the environment.
- Code should address radionuclide-dependent processes such as leaching, transfer, and migration (retardation).
- Code should support estimations of both individual dose and average collective dose and risk.
- Code should include, or allow users to construct, all potential exposure scenarios.
- Code should have the capability to accommodate modification of parameters as well as selection/suppression of pathways.
- Code should be able to perform sensitivity analysis and probabilistic uncertainty analysis.
- Code should have specific models for special radionuclides (e.g., tritium, carbon-14, and radon-222 and radon-220) that behave differently in the environment and in buildings.
- Code should have a sufficient radionuclide database, and it should be easy to add radionuclides if needed (under QA/QC conditions).

2 ARGONNE'S RESPONSES TO NRC QUESTIONS

The following sections present the questions asked by the NRC regarding the RESRAD code and Argonne's responses.

2.1 Question One

1. *Please describe the history of the analytical method's development (e.g., who developed it? For what purpose was it developed? Who were the sponsors? Is there documentation on the code such as a "users' manual"?)*.

Development of the RESRAD model and code was initiated in the early 1980s. The code has evolved into its present form as a result of extensive reviews, application experience, and scientific development. The model and code were developed as integral parts of DOE guidelines for control of residual radioactive material issued as interim guidance in 1984-85; incorporated into the DOE public and environmental radiation protection directive, Order DOE 5400.5 in 1990; and proposed as part of Title 10, Part 834 of the *Code of Federal Regulations* (10 CFR 834) in 1993.

During 1983 and 1984, DOE conducted workshops to support the development of its guidelines for controlling residual radioactive material. The workshops were attended by representatives from DOE (Offices of the Secretary, Nuclear Energy, Defense Programs, Energy Research, General Counsel and Environment and Policy and DOE field offices); the national laboratories (Argonne, Los Alamos, Oak Ridge, and Pacific Northwest); industry (The Aerospace Corp.; Bechtel National, Inc.; Bendix Field Engineering; EG&G; Jacobs Engineering; and UNC Nuclear Industries); the U.S. Environmental Protection Agency (EPA); and the NRC. These workshops resulted in the development of draft interim guidelines issued for review and comment in 1984. The interim guidelines contained generic soil concentration criteria (based on models that were predecessors of RESRAD) that were to be the maximum concentration levels that could not be exceeded and that would be subjected to the ALARA (as low as reasonably achievable) process to determine how far below the criteria authorized limits for a cleanup should be set. The generic soil concentration criteria approach was generally found to be unacceptable because of its inflexibility and because it was difficult to address ALARA requirements without specifically estimating like doses to populations associated with alternative cleanup limits. Current DOE requirements and the RESRAD model and code were developed on the basis of experience associated with early effects.

DOE used input from field and program elements attempting to apply the interim guidelines to determine that a standardized dose/ALARA-based approach would be the most flexible and cost-effective way to establish protective authorized limits for the release of DOE real property. Initially, DOE guidelines simply required that authorized limits for the release of property be developed to be as low as is reasonably achievable below the 100 mrem per year

primary dose limit. Later guidance recommended the use of a dose constraint of about one quarter of the primary dose limit as the cap for the ALARA analysis to ensure that multiple sources would not result in public exposures exceeding the "all sources" primary dose limit.

The RESRAD code was developed for use in conducting dose assessments and supporting ALARA process analyses necessary to meet DOE requirements. The initial criteria used by DOE to develop the RESRAD model and code were as follows:

- The model
 - must be sufficiently flexible to handle multiple radionuclides, all significant pathways, numerous land uses, and various spatial configurations and other site-specific considerations.
 - should be based on the best peer-reviewed science available.
 - should be able to handle special radionuclides such as tritium, carbon-14, and radon.
- The code implementing the model should
 - run on computer systems readily available to DOE and DOE contractors.
 - be user friendly.
 - be validated and verified.
 - be fully documented.
 - permit sensitivity analyses for various parameters.
 - output dose estimates or soil guidelines.
 - provide graphical output as a function of time, pathway, and radionuclide.
 - default parameters should be selected so as not to underestimate potential doses should they be used for screening assessments in lieu of site-specific factors; *guidance, however, should encourage site-specific analysis and discourage the use of default parameters.*

Subsequently, the following criteria for code were added, on the basis of user input and DOE needs.

- should estimate both risks and doses.
- should be capable of uncertainty analyses, graphical output dose distributions, and deterministic values.
- should be capable of evaluating indoor building contamination in addition to outdoor soil contamination.

Several national laboratories and DOE program offices were involved in the initial development of the code. Argonne spearheaded the development effort, and DOE was the sole sponsor of the project.

RESRAD is designed for evaluating sites that contain residual radioactive material. It can be used to derive contaminated site cleanup criteria and for site screening and pre- and postremediation dose/risk assessment. It is designed with user-friendliness and flexibility in mind. Initially, the RESRAD code was developed on the IBM main frame computer and was later converted to a PC code. After several years of testing and evaluation, the first version of the RESRAD PC code was published in June 1989, along with a users' manual (Gilbert et al., 1989) that documents the methodology used in the code and the DOE guidelines for residual radioactive material. These guidelines were revised, and in 1990, they were issued as part of DOE Order 5400.5. On the basis of input from DOE and non-DOE users, including the NRC and the EPA, the code and model were updated and several supporting documents were prepared to aid in the use of the RESRAD code. These include the *RESRAD Data Collection Handbook* (Yu et al., 1993a), *Compilation of Radionuclide Transfer Factors* (Wang et al., 1993), *RESRAD Sensitivity Analysis* (Cheng et al., 1991), *RESRAD Benchmarking Against Six Radiation Exposure Pathway Models* (Faillace et al., 1994), and *Verification of RESRAD* (Halliburton, 1994). The RESRAD code is continually maintained and updated under control of a DOE-approved QA plan. An updated users' manual (Yu et al., 1993b) was published in September 1993; a new update of the manual is planned for 1998.

RESRAD is designed for evaluating soil contamination. Another code, RESRAD-BUILD is designed for evaluating indoor building contamination. The RESRAD-BUILD code was also developed by Argonne for DOE. A users' manual (Yu et al., 1994) was published in November 1994, and a draft RESRAD-BUILD Data Collection Handbook is under development.

In addition to the RESRAD and RESRAD-BUILD codes, ANL developed several codes in the RESRAD series for DOE. These codes are shown in Figure 1. RESRAD-CHEM includes special models for volatile compounds and dermal absorption pathways. RESRAD-BASELINE was developed to perform baseline risk assessments in accordance with EPA human health risk

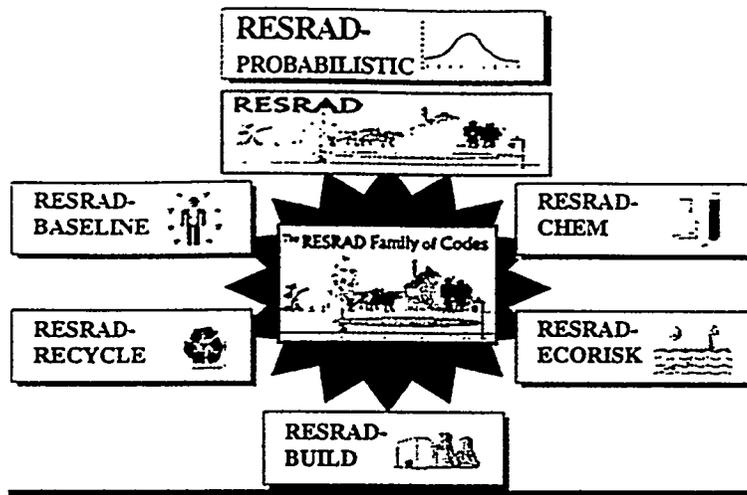


Figure 1. The RESRAD Family of Codes

assessment guidelines. The RESRAD-BASELINE database contains both radionuclides and chemicals. RESRAD-RECYCLE estimates radiation doses to various receptors resulting from the recycle and/or reuse of radioactively contaminated materials/equipment. RESRAD-ECORISK estimates the risk to ecological receptors from contaminant exposure. The RESRAD-Probabilistic code was developed to quantify uncertainties associated with predicted doses and risks. The probabilistic code has been incorporated into the RESRAD, RESRAD-BUILD, and RESRAD-RECYCLE codes.

2.2 Question 2

2. *What transport mechanisms, scenarios, and exposure pathways are considered?*

2.2.1 RESRAD

In the RESRAD code, the initial source of contamination is assumed to be radionuclides in soil; however, measured concentrations of radionuclides in a downgradient well or pond can also be entered. The code will calculate (predict) contaminant concentrations in various media and pathways.

Up to nine exposure pathways can be modeled in RESRAD: direct exposure to external radiation from contaminated soil material; internal dose from inhalation of airborne radionuclides, including radon progeny; and internal dose from ingestion of plant foods grown in the contaminated soil and irrigated with contaminated water, meat and milk from livestock fed with contaminated fodder and water, drinking water from a contaminated well or pond, fish (and other aquatic organisms) from a contaminated pond, and contaminated soil. These pathways and

the transport among environmental media are shown in Figure 2. The transport mechanisms considered in the RESRAD code are listed in Table 1.

The code may be used to analyze doses to on-site individuals under current or plausible future land uses of the site. The default land use scenario in RESRAD assumes an on-site subsistence farmer with all exposure pathways active. By suppressing selected pathways and modifying applicable intake or occupancy parameter values, the user may simulate any number of potential scenarios such as (but not limited to) recreational, industrial, and residential. Two scenarios that may be modeled in RESRAD are shown in Figures 3 and 4. Doses to off-site individuals may be modeled by following the recommendations in the users' manual. These models are being incorporated in a version of the code that will calculate off-site doses and risks directly.

In most cases, the code should be applied to chronic exposure scenarios with durations of one year or more, particularly for those scenarios with food pathways. However, the code may also be used to assess short-term exposures from external gamma, inhalation, soil, and water ingestion pathways.

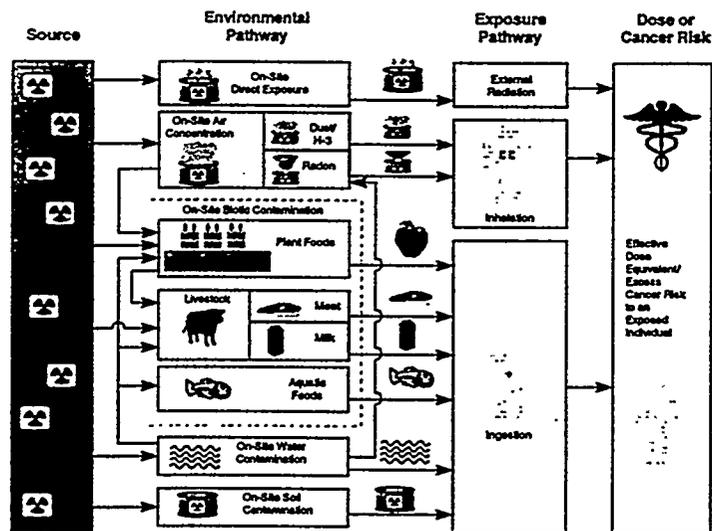


Figure 2. Graphical Representation of Pathways Considered in RESRAD

Table 1. Transport Mechanisms Considered in RESRAD

Transport Mechanism	Media	Affected Exposure Pathways
Leaching	Soil→water	All pathways
Advection	Water	Water-dependent pathways
Mixing with uncontaminated soil	Soil	Water-independent pathways
Erosion (source loss only)	Soil→water/air	All pathways
Resuspension	Soil→air	Inhalation of particulates; ingestion of plant, meat, and milk
Diffusion	Soil→air	Inhalation of radon
Off-gassing	Soil→air	C-14 pathways
Evapotranspiration	Soil→air	Tritium pathway
Bioaccumulation	Water→aquatic organisms	Ingestion of aquatic organisms
Root uptake	Soil→plant	Ingestion of plant, meat, milk
Foliar deposition	Air→plant	Ingestion of plant, meat, milk
Irrigation	Water→plant	Ingestion of plant, meat, milk
Photosynthesis	Air→plant	C-14 pathways
Electromagnetic (gamma, x-ray) and charged particle (beta) transport	Soil→human	External
inhalation	Air→human	Inhalation of particulates, radon, ¹⁴ CO ₂ , HTO
Ingestion	Soil→livestock	Meat, Milk
	Water→livestock	Meat, Milk
	Plant→livestock	Meat, milk
	water→human	Water
	Soil→human	Soil
	Plant→human	Plant
	Meat→human	Meat
	Milk→human	Milk
	Aquatic organisms→human	Aquatic organisms
Dermal Absorption	Air→human	Tritium pathway



Figure 3. Schematic Representation of Exposure Pathways in a Typical Industrial Use Scenario



Figure 4. Schematic Representation of Exposure Pathways in a Typical Subsistence Farming Scenario

2.2.2 RESRAD-BUILD

In RESRAD-BUILD, an individual may be exposed to a source through up to seven exposure pathways, as shown in Figure 5 and listed below:

- External exposure directly from the source,
- External exposure due to air submersion,
- External exposure to materials deposited on the floor,
- Inhalation of airborne radioactive particulates,
- Inhalation of aerosol indoor radon progeny (in the case of radon predecessors),

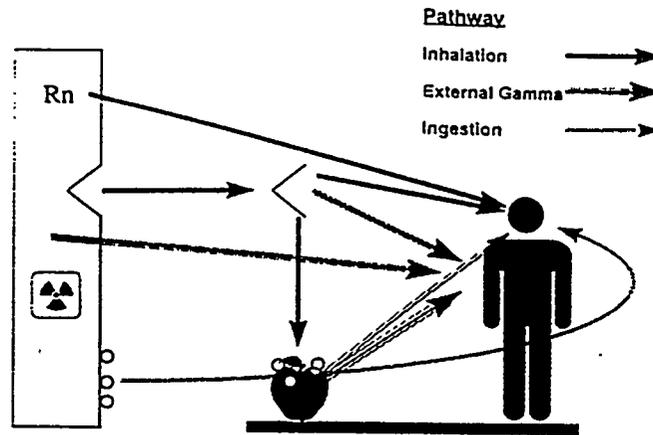


Figure 5. Graphical Representation of Pathways Considered in RESRAD-BUILD

- Inadvertent ingestion of radioactive material directly from the source, and
- Inadvertent ingestion of radioactive materials deposited on the surfaces of the building compartments.

Contaminants may move from the source to the receptor by the various transport mechanisms outlined in Table 2.

RESRAD-BUILD may be used to assess a number of different exposure scenarios related to building activities. The code may be used as a scoping tool in preparation for decontamination activities and estimates both individual and collective doses to cleanup workers. It can be used to derive cleanup criteria under occupancy or renovation scenarios. Finally, it can be used as a tool for ALARA, by assessing the dose impact of the no-action alternative versus different remedial activities.

2.3 Question 3

3. *How are parameter values determined for input? (Can uncertainties be incorporated into parameter distributions and the subsequent dose calculations?)*

Table 2. Transport Mechanisms Considered in RESRAD-BUILD

Transport Mechanism	Media	Affected Exposure Pathways
Erosion/air release fraction (volume source only)	Source→air	All pathways
Removable fraction/ lifetime/air release fraction (all other source types)	Source→air	All pathways
Diffusion (volume source only)	Source→air	Inhalation of radon, tritium
Radon release fraction (all other source types)	Source→air	Inhalation of radon
Plate-out	Free state →surfaces	Inhalation of radon
Attachment	Free state→particulates	Inhalation of radon
Decay with recoil	Surfaces→free state Particulates→free state	Inhalation of radon
Electromagnetic (gamma, x-ray) and charged particle (beta) transport	Source→human Surface→human	External External
Ventilation	Air	All air-dependent pathways
Deposition	Air→surfaces	All air-dependent pathways
Resuspension	Surfaces→air	All air-dependent pathways
Inhalation	Air→human	Inhalation of particulates, tritiated water vapor, and radon
Ingestion	Source→human Surfaces→human	Direct ingestion Indirect ingestion
Dermal absorption	Air→human	Tritium

2.3.1 RESRAD

The database included in the RESRAD code consists of two categories of parameters: contaminant-specific and site- or scenario-specific.

The first category includes parameters that are not modified frequently, but may be changed and saved in a user-specific data file. These data include decay and ingrowth functions, DCFs, cancer risk slope factors, and biological transfer factors (plant/soil, meat/fodder, milk/fodder, fish/water, other aquatic organisms/water). The defaults for these parameters are conservative and are derived from federal guidance reports (Eckerman, et. al., 1988; Eckerman and Ryman, 1993; EPA, 1994) or literature searches (Wang et al., 1993). Figure 6 shows a typical RESRAD screen for these parameters. Data are available for 84 radionuclides with half-lives greater than or equal to one month.¹ Some radionuclides were added at the request of the NRC.

¹ The user may select from two sets of radionuclide databases based on a half-life cutoff. The default database is for 67 radionuclides with half-lives greater than six months.

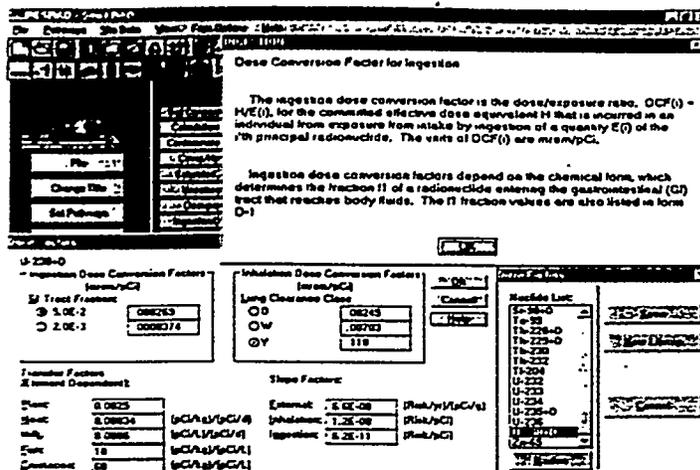


Figure 6. Typical RESRAD Dose Factor Library Screen

For those radionuclides with short-lived decay products, the latter are assumed to be in secular equilibrium with their parent and are accounted for implicitly in the dose or slope factors of the parent.

For the second category of parameters, RESRAD provides a default set of more than 150 parameters representative of national averages or reasonable maximum values for a subsistence farming scenario. Any of these parameters may be modified to reflect site-specific conditions and are grouped as follows (examples are shown in parentheses):

- Physical parameters (size, depth, density, porosity, diffusion coefficient)
- Hydrological parameters (hydraulic conductivity, gradient, soil b parameter, water table depth)
- Geochemical parameters (distribution coefficient, leach rate, solubility)
- Meteorological parameters (precipitation, evapotranspiration, erosion, runoff, mass loading)
- Usage and consumption parameters (inhalation, irrigation, ingestion, occupancy)

The *Data Collection Handbook* (Yu et al., 1993a) and the *Compilation of Parameter Distribution* (Yu et al., 1997) provide guidance on selecting site- and scenario-specific input values. RESRAD reduces the amount of parameter data input required from the user by only allowing access to those parameters used to calculate doses from a particular pathway. For

example, if the food ingestion pathways are suppressed, the consumption rates for plants, meat, milk, or fish are rendered inaccessible (see Figure 7).

Two tools are provided to account for variability and uncertainty in parameter values. Both the sensitivity analysis and uncertainty analysis tools may be used by the licensee to establish priorities for gathering input data; they may also be used by the regulator to determine the parameters that should receive attention.

RESRAD uses graphic output to illustrate the effects of variability in a single parameter on the response (e.g., dose as a function of time). The sensitivity analysis feature allows the user to enter a factor that will be used to multiply and divide the base parameter value (Figure 8). Sensitivity analysis can be performed on almost all input parameters, with up to five parameters per run. The code then graphically calculates the sensitivity of the result due to the variation of each parameter's values and holds all other parameters at their base value (Figure 9).

The uncertainty analysis feature (Figure 10) allows the user to assign one of five distribution types (normal, lognormal, uniform, loguniform, and triangular), along with the associated statistical parameters for the distribution (e.g., mean, standard deviation, minimum, maximum), to two or more parameters. The user may also correlate two or more dependent parameters. The code then samples these distributions and performs a user-selected number of runs. The results (dose/risk as a function of time) are presented both statistically (minimum, maximum, average, standard deviations) and graphically in Figures 11 and 12.

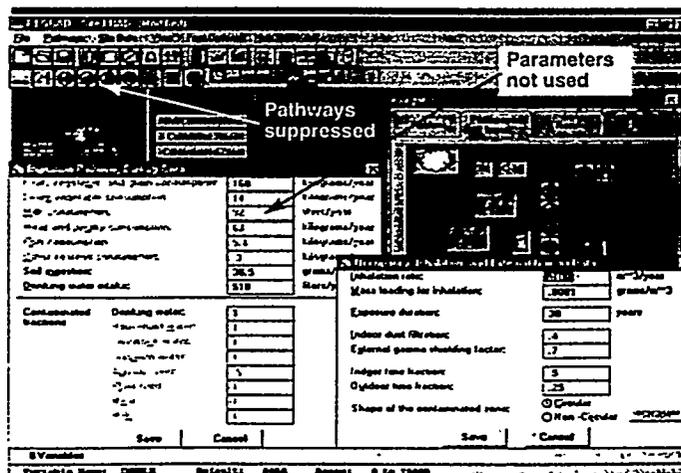


Figure 7. Typical RESRAD Site-Specific Parameter Input Screen

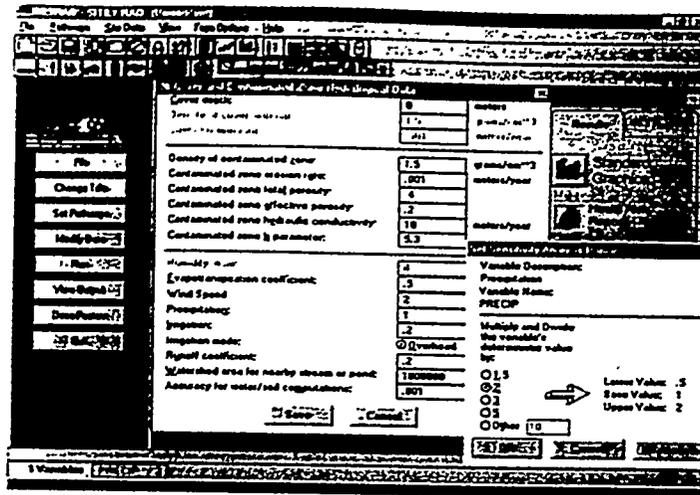


Figure 8. Typical RESRAD Sensitivity Analysis Input Screen

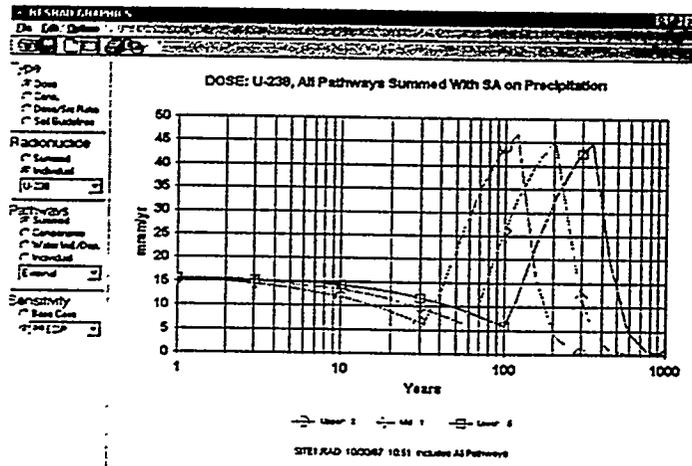


Figure 9. Typical RESRAD Sensitivity Analysis Graphical Output Screen

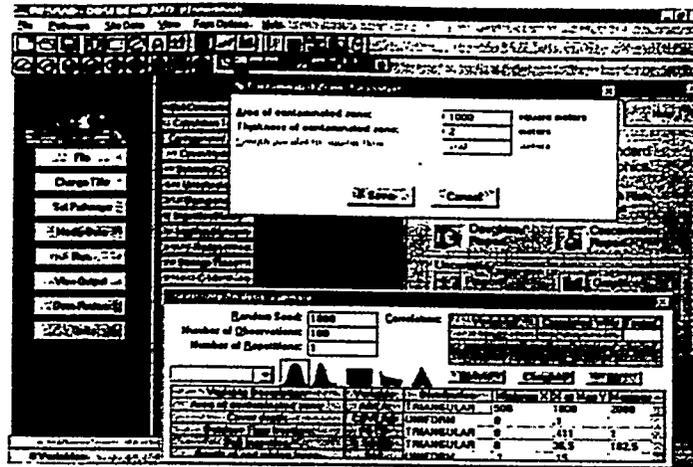


Figure 10. Typical RESRAD Uncertainty Analysis Input Screen

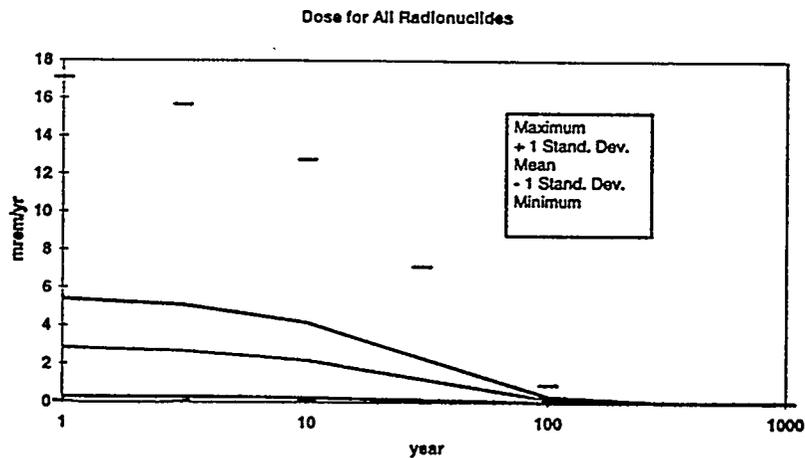


Figure 11. Typical RESRAD Uncertainty Analysis Graphical Output Screen — Statistical Distribution of Results

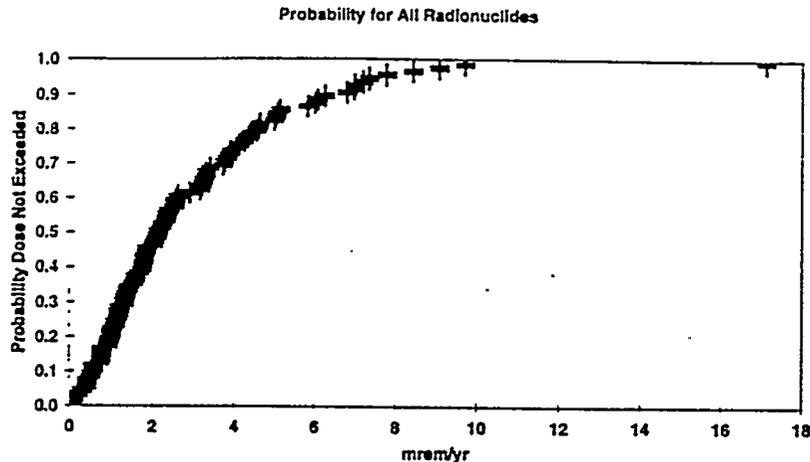


Figure 12. Typical RESRAD Uncertainty Analysis Graphical Output Screen — Cumulative Probability Distribution of Results

2.3.2 RESRAD-BUILD

The contaminant-specific database for RESRAD-BUILD is consistent with the RESRAD database, with the exception of the transfer factor library, which is not required in performing dose assessments for building scenarios.

Over 40 site- and scenario-specific parameters are used in RESRAD-BUILD. These can be grouped as follows (with examples in parentheses):

- Temporal parameters (total time, indoor fraction, receptor time fraction),
- Spatial parameters (source and receptor coordinates, number of rooms),
- Air flow parameters (air exchange rates, room dimensions, deposition velocity, resuspension rate),
- Shielding parameters (thickness, density, material, orientation),
- Source characteristics (radionuclide concentration, source type, dimensions, direction, removal rate, air release fraction, radon parameters, and tritium parameters), and
- Receptor characteristics (inhalation and ingestion rates).

The defaults included in RESRAD-BUILD are based on a generic occupancy scenario. Because of high variability in building properties, sources, receptors, and scenarios that can be modeled, most default values should be replaced with site- and scenario-specific values. A data collection handbook is being prepared to assist users in gathering the required input data. RESRAD-BUILD does not have a sensitivity analysis feature; it does, however, have the same uncertainty analysis feature as the RESRAD code.

Figure 13 shows a typical parameter input screen from the RESRAD-BUILD code.

2.4 Question 4

4. *What radionuclides and chemicals which can affect radionuclide transport are considered? (Is decay and in-growth considered? To what extent?)*

2.4.1 RESRAD

The RESRAD database includes 84 principal radionuclides and 52 associated radionuclides in the decay chains (i.e., a total of 136 radionuclides). RESRAD does not perform dose or risk calculations for hazardous chemicals. This task is performed by other codes in the RESRAD family, that is the RESRAD-CHEM and RESRAD-BASELINE codes. The RESRAD-CHEM code performs transport and exposure calculations consistent with those performed by the RESRAD code (see response to Question 1). A total of 151 inorganic and organic compounds are included in the RESRAD-CHEM and RESRAD-BASELINE codes.

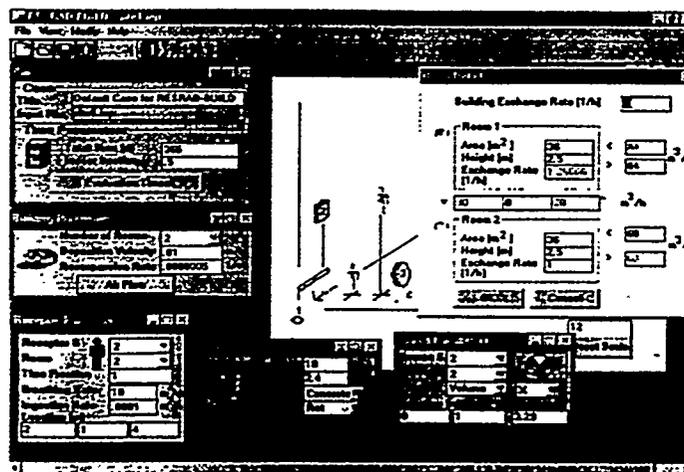


Figure 13. Typical RESRAD-BUILD Site-Specific Parameter Input Screen

The chemical form of the radionuclide is considered in the DCFs for radionuclides taken up internally. For ingestion, the user may select the DCF for one or more gastrointestinal (GI) tract fractions; for inhalation, the user may select the DCF for one or more inhalation classes. RESRAD defaults are for the most conservative DCFs, where more than one GI fraction or inhalation class is available. Short-lived radionuclides (i.e., those with half-lives less than one month or six months, depending on the user-selected cutoff) are considered to be in secular equilibrium with their parents. Thus, their DCFs and slope factors are added to the DCF and slope factor of the parent. An exception to this are radon isotopes and their short-lived progeny, for which ingrowth is tracked explicitly.

Special methodologies have been developed that take into account the different chemical forms and transport of tritium (as tritiated water and water vapor) and carbon-14 (as organic carbon and carbon dioxide) in the environment (Figure 14).

Longer-lived progeny for all radionuclides are tracked separately from their parents. This is particularly important in groundwater transport where different distribution coefficients may be assigned to the decay products. This allows the user to account for the different chemistries of the decay products during transport from the contaminated zone through the unsaturated zone and into the saturated zone. The distribution coefficient (K_d) for each long-lived radionuclide within each zone may be different and will depend on the chemical form of the radionuclide and the soil properties. These K_d s may be entered directly by the user, or the code may be used to estimate these values using four separate methodologies (Figure 15): (1) input of radionuclide concentrations in a downgradient well and time since material placement, (2) direct input of the leach rate from the contaminated zone, (3) input of a solubility limit, and (4) correlation with the soil/plant transfer factor. It is quite possible, with the above methodology, to simulate the more rapid transport of a soluble decay product, which may arrive at the exposure point ahead of its slower moving insoluble parent.

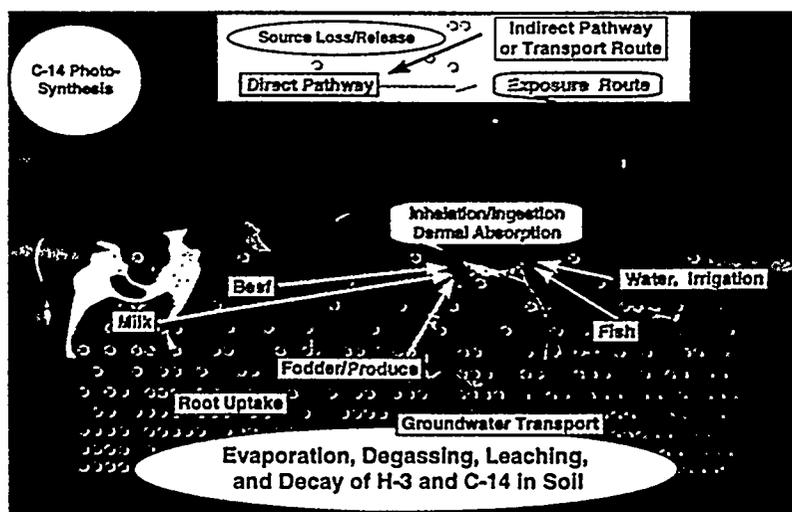


Figure 14. Special Models for Tritium and Carbon-14 in RESRAD

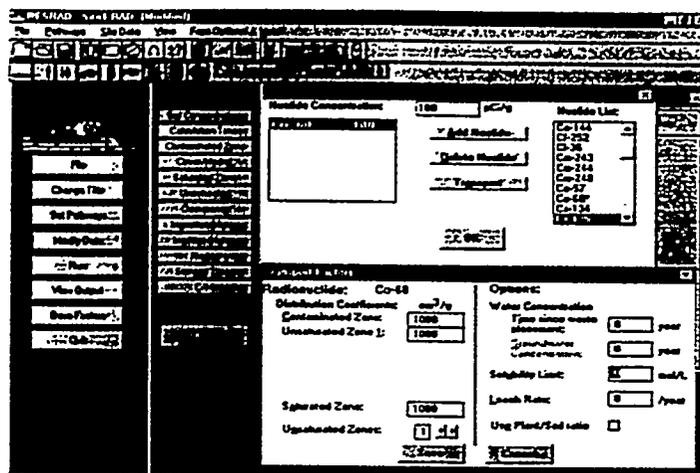


Figure 15. Typical RESRAD Distribution Coefficient Parameter Input Screen

The user may also account for the chemical form of the radionuclides by adjusting the biological transfer factors. These factors are used to estimate the transport of radionuclides from soil to plants, fodder to meat or milk, and water to aquatic organisms.

2.4.2 RESRAD-BUILD

As with RESRAD, RESRAD-BUILD applies only to radionuclide and not chemical contaminants. There is no biological transport of radionuclides. The chemical form of the radionuclide is accounted for implicitly in the DCFs used, as well by using special models for the diffusion of radon and tritium. Radionuclide decay is considered for all radionuclides, and ingrowth is accounted for explicitly when decay products have half-lives greater than the cutoff.

2.5 Question 5

5. *What are the time and spatial geometry limitations inherent in the analytical method?*

2.5.1 RESRAD

RESRAD calculates annual doses, soil guidelines, radionuclide concentrations, and lifetimes risks as a function of time. The user may enter up to nine times (time zero is always calculated). Any time horizon up to 100,000 years may be selected (the default is 1,000 years), but the uncertainty in the results will increase with increasing time. The code will also estimate

the time at which the peak dose occurs for each radionuclide and for all radionuclides summed. With few exceptions, RESRAD should be applied to chronic exposure scenarios (i.e., over one or more years of exposure) rather than short-term exposure conditions. For exposure durations greater than one year, RESRAD performs a time-integration of excess cancer risks that takes into account changes in the radionuclide concentrations in all media as a function of time.

RESRAD has few spatial constraints. The methodology requires the input of homogeneous layers (one optional cover layer, one contaminated zone, one to five optional unsaturated zones, and one optional saturated zone). The code provides graphical feedback on the thickness of the layers entered by the user (Figure 16). Nonhomogeneous (or multiple) contaminated layers may be simulated in separate runs, each with a distinct homogeneous contaminated layer, and the resulting doses may be summed. The code can also be used to perform hot spot analysis to assess doses from small subareas of contamination. No constraints are placed on the area or thickness of any layer.

In most cases, the receptor is assumed to be on-site (outdoors and/or indoors, one meter above the soil surface) and may obtain water from a well or pond located in the middle of the site (mass-balance model) or at the downgradient edge of the site (nondispersion model). For the external gamma pathway, the default source area is conservatively assumed to be circular, with the individual located above the center. However, the user may select a noncircular area, with the receptor located anywhere, including off-site locations (Figure 17). The manual contains the methodology, implemented in a version of the code currently undergoing testing and evaluation, to estimate doses to off-site receptors from airborne and groundwater transport.

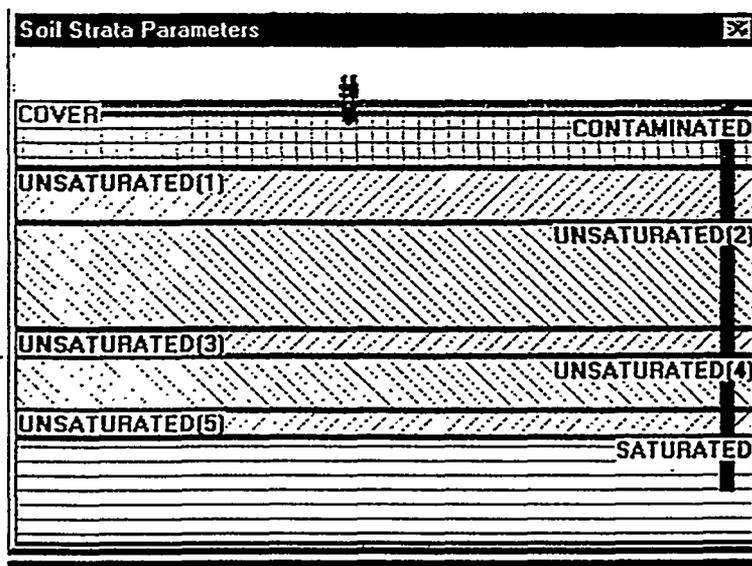


Figure 16. Typical RESRAD Soil Strata Parameter Screen

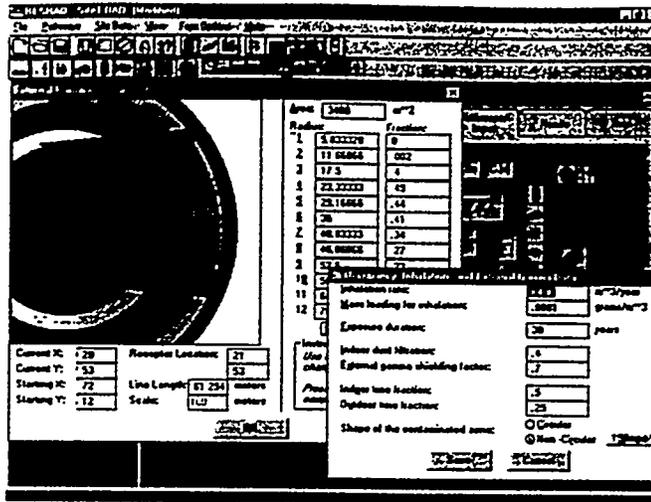


Figure 17. Typical RESRAD Shape Factor Parameter Input Screen

2.5.2 RESRAD-BUILD

Similar to RESRAD, RESRAD-BUILD calculates doses as a function of time; the user can input up to nine times. There is no limitation on the maximum time, but as a practical matter, the user should limit the calculations to the anticipated maximum lifetime of the building. By allowing future times to be investigated, it is possible to investigate the effects of source removal processes coupled with radionuclide decay and ingrowth.

The RESRAD-BUILD code is very flexible regarding spatial definitions of problems. By entering source and receptor locations in a Cartesian coordinate system, the user may place up to 10 sources and 10 receptors at any point within this coordinate system. However, receptors may not be co-located with sources or placed at locations that intersect source planes or axes. For the external gamma model, a shield of varying thickness, density, and material type may be specified for each source-receptor location pair (up to 100 shields). For the air pathways, one, two, or up to three rooms may be defined, each with unique dimensions and air exchange properties (Figure 18). Rooms must be adjacent to one another. Air is allowed to flow between adjacent rooms and may be exchanged with outside air; direct air flow between nonadjacent rooms, however, is not allowed. In a two- or three-room scenario, rooms may be configured horizontally or vertically (or mixed), with or without a basement. Receptors and sources may be placed anywhere within a room, or even outside the building, if only the external gamma pathway is of concern.

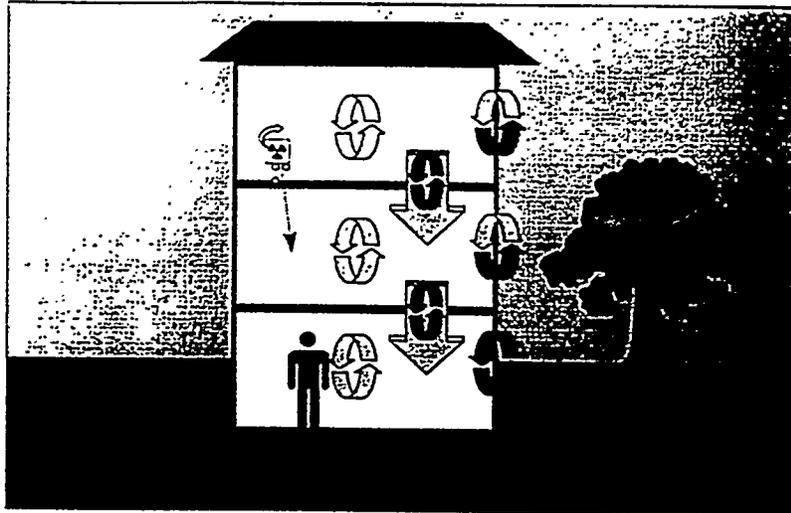


Figure 18. Schematic Representation of the RESRAD-BUILD Three-Room Model

Four source types may be specified, each with their own spatial definitions (Figure 19). A point source is simply defined by its coordinate location. A line source is defined by its length, its coordinate location at the center of the line, and a direction parallel to one of the three coordinate axes. A surface source is modeled as a disk and is defined by its area, its coordinate location at the center of the area, and a direction that is normal to the surface and parallel to one of the three coordinate axes. A volume source is modeled as a cylinder with up to five layers, one of which contains the contamination. Each layer can be defined with a unique thickness, density, erosion rate, porosity, and radon transport properties. The other dimensional definitions are the same as for a surface source. Two or more sources may be co-located. For example, a wall that is both volumetrically and superficially contaminated may be simulated by placing a volume source and a surface source at the same location; a hot spot may be simulated by placing a point source anywhere along the surface or inside the volume.

Receptors may be defined as points that represent the location at which the dose rate is measured. By entering different locations and time fractions at each location, a scenario may be set up to calculate collective doses to more than one individual, the total dose to a single individual at multiple locations, or any combination. Two receptor-source orientations, rotational and anterior-posterior, may be simulated. The latter is used when the receptor faces the source and results in slightly higher direct gamma doses than the former.

2.6 Question 6

6. *To what extent can alternative remedial actions be assessed and compared (e.g., comparison of concentrations, doses, and costs)?*

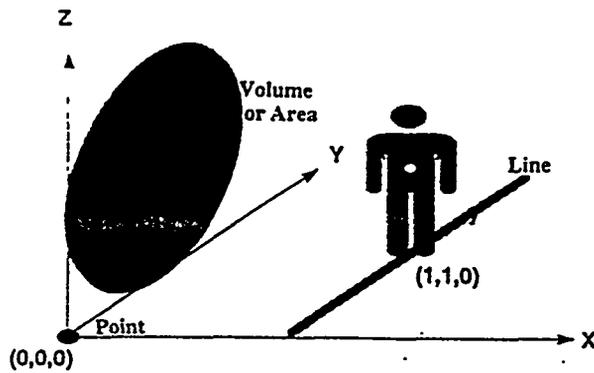


Figure 19. RESRAD-BUILD Source Types and Geometry Definitions

2.6.1 RESRAD

The RESRAD code provides output in the form of doses, risks, cleanup guidelines, and contaminant concentrations. Multiple runs of the code, as well as the sensitivity and uncertainty analysis tools discussed in the response to Question 3 may be used to assess the effects of alternative remedial actions. An example may be a sensitivity analysis performed to assess the effect on the dose of adding covers of varying thickness (Figure 20). The results are displayed both in text reports or graphically and may be used as input to cost-benefit analysis models. Sensitivity and uncertainty analyses can also be applied to assess the effects on time-dependent concentrations in various media. The results may then be used in performing ALARA analyses, as discussed in the response to Question 8, or in developing monitoring strategies, as discussed in the response to Question 10.

2.6.2 RESRAD-BUILD

With the exception of the sensitivity analysis feature and graphical output (not currently available in RESRAD-BUILD), the same applies to RESRAD-BUILD.

2.7 Question 7

7. *To what extent has the dose model been tested and included in benchmarking studies?*

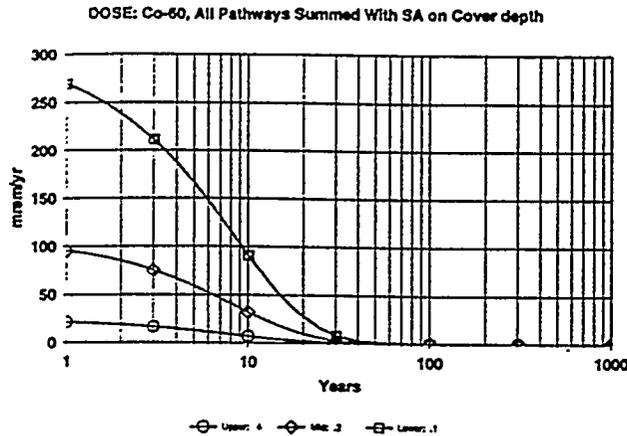


Figure 20. Example Sensitivity Analysis Graphical Output — Dose vs. Cover Thickness

2.7.1 RESRAD

The RESRAD code is subject to strict configuration control under ANL's RESRAD Software QA Plan. Under this plan, changes to RESRAD must be approved by the Project Leader and Program Manager. A modification must be reviewed by:

- An independent scientist or programmer,
- the Project Systems Analyst,
- the Project Leader, and
- the Program Manager.

All modifications are reviewed prior to a new code release by all programmers to ensure that there are no internal conflicts. Modifications to the code are made to maintain a state-of-the-art methodology, as well as implement suggestions made by users and sponsoring agencies.

The code has been verified and validated since 1989. An independent verification was performed by a competitively selected contractor who was entirely independent of the development of RESRAD in June 1994 (Halliburton NUS, 1994). RESRAD has been included in international code validation studies, including the Biospheric Model Validation Study: Phase II (BIOMOVS II) (Gnanapragasam and Yu, 1997a) and the Validation of Model Predictions (VAMP) study (Yu and Gnanapragasam, 1995; Gnanapragasam and Yu, 1997b) sponsored by the International Atomic Energy Agency (IAEA, 1996). These studies used actual monitoring data obtained in Europe from the Chernobyl accident and actual uranium mill tailing data. In

these “blind” studies, real-world data were provided to the participants who used their models to evaluate the data and provide an estimate of radiation dose. RESRAD has provided results that compare favorably with the “official” answers, which are only furnished after the estimates of each code developer are submitted.

RESRAD has been benchmarked against a number of other pathway analysis codes and methodologies, including GENII, GENII-S, DECOM, PRESTO, PATRHRAE, NUREG/CR-5512 (Faillace et al., 1994) and MEPAS and MMSOILS (Cheng et al., 1995; Mills et al., 1997). The latter was sponsored by the EPA (Laniak et al., 1997). These benchmarking studies have provided valuable information on how each code addresses a similar set of input parameters and exposure scenarios. These comparisons are useful in assessing the limitations of each code. In some cases, this has led to uncovering errors or initiating modification in a few of the codes that were benchmarked. RESRAD has performed satisfactorily in both benchmarking studies.

Independent of Argonne and DOE, the NRC has evaluated RESRAD prior to approving it for use by its staff and licensees. Technical suggestions furnished by the NRC staff were incorporated into the code and additional radionuclides were added. Similarly, the EPA’s Science Advisory Board reviewed RESRAD as part of its review of the development of generally applicable standards for residual radiation at sites after cleanup (Wolbarst et al., 1996).

RESRAD also has benefited from more than a decade of field applications at over 300 sites in the United States and overseas. It is used as a teaching tool at a dozen universities, including Oregon State University, Ohio State University, Rensselaer Polytechnic Institute, and the University of Tennessee.

More than 60 RESRAD training workshops have been conducted at various locations in the United States upon request of several federal (including DOE, NRC, and EPA) and state environmental, health, and safety agencies (e.g., New York, Louisiana, Connecticut, among others). Over 1,000 people have been trained at these workshops.

A computerized user database is maintained to inform users when a major revision of the code has been issued. Users may also visit the RESRAD Family of Codes web page at “www.ead.anl.gov/resrad.html” for code status and updates, an on-line version of the *Data Collection Handbook*, upcoming training workshops, and other information. Surveys and questionnaires are issued periodically to obtain feedback. Users may also contact ANL directly through e-mail at “RESRAD@anl.gov” or by phone to obtain technical assistance. Feedback obtained from users through technical assistance, training workshops, and surveys is incorporated into code revisions.

2.7.2 RESRAD-BUILD

RESRAD-BUILD is under the same software QA plan as RESRAD. Code modification and verification have been documented since 1994. The external gamma calculations performed by the code have been successfully benchmarked against MICROSIELD (a point-kernel code) and MCNP (a Monte Carlo code). Over 10 RESRAD-BUILD training workshops have been conducted since 1996; approximately 200 people have been trained at these workshops.

2.8 Question 8

8. *To what extent can the analytical method handle complex: (a) source term characterization; (b) multiple source terms; (c) hydrologic and hydrogeological conditions; (d) exposure pathway combinations; (e) remedial methods linked to cost and monitoring programs; and (f) ALARA considerations?*

2.8.1 RESRAD

(a) The RESRAD source term is entered as average soil concentrations of initially present radionuclides. The user may also enter groundwater concentrations to estimate the radionuclide K_{ds} . Short-lived radionuclides are assumed to be in secular equilibrium with their parents. Ingrowth, decay, leaching, off-gassing (C-14), and evapotranspiration (tritium) are all used to estimate the change in source concentrations as a function of time; the erosion rate is used to estimate changes in the cover and/or source thickness as a function of time (Figure 21).

(b) Multiple source terms, as well as hot spots, may be modeled by adding the results from separate runs. Features in the text and graphic output reports allow users to export data to spreadsheet programs for ease of analysis.

(c) Precipitation, irrigation, runoff, and evapotranspiration are all considered in estimating the infiltration rate. The RESRAD model assumes homogeneous hydrogeological soil properties within each horizontal layer. Up to five unsaturated layers, each with unique properties, may be modeled. These soil layers are illustrated in Figure 16. Two one-dimensional groundwater models, the mass-balance model and the nondispersion model (shown in Figure 22), may be selected for the calculations of on-site doses. For off-site groundwater transport, a three-dimensional dispersion/one-dimensional advection model is being tested and evaluated. Potentially contaminated water for drinking, household uses, livestock, and irrigation may be modeled as originating from a well and/or pond.

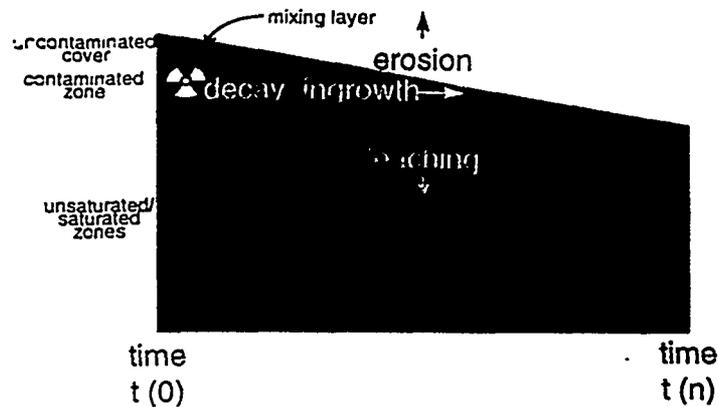


Figure 21. RESRAD Time-Dependent Source Evolution

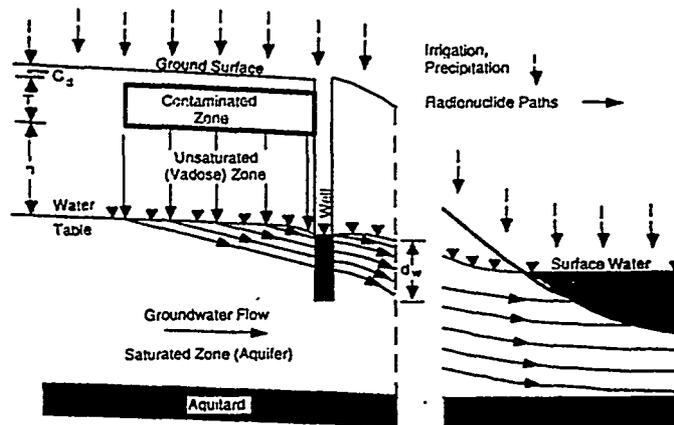


Figure 22. RESRAD Non-Dispersion Groundwater Model

(d) One or more pathway combinations, up to a total of all nine exposure pathways, may be simulated in a single run (the radon pathway can only be evaluated when a radon precursor is part of a source). It is easy to turn pathways on or off in RESRAD. Once a pathway is turned off, parameters that are unique to the pathways are suppressed, and users do not need to provide data for those parameters.

(e) RESRAD may be used as a tool to evaluate various remedial methods. The scenarios and input parameters can be easily modified, and multiple runs can be performed for each alternative. Also, the sensitivity and uncertainty analysis features of the code discussed in the responses to questions 3 and 6 may be applied to parameters related to alternative remedial methods (e.g., cover thickness or thickness of the contaminated zone) to assess their impact when the resulting doses or concentrations are entered in a cost-benefit model or are used to establish monitoring programs.

(f) Sensitivity and uncertainty analysis features, as well as multiple runs, may also be applied as a modeling tool when conducting the ALARA analysis. The output provided by RESRAD for a number of different scenarios or parameter variations can be used as input in a cost-benefit model. RESRAD has been used as an ALARA tool at a number of DOE sites, including Hanford and Fernald. The DOE draft ALARA standard (DOE 1997) provides additional information on using RESRAD for ALARA analysis and includes case studies for sites (Colonie, Elza Gate, Maywood, Ventron, and Weldon Springs) where RESRAD has been used as an ALARA tool.

2.8.2 RESRAD-BUILD

RESRAD-BUILD can be used to simulate four types of sources and up to 10 sources per run. For more details on parts (a) and (b) of this question, see the response to Question 5. Because the RESRAD-BUILD code does not assess the dose from groundwater contamination, part (c) of this question does not apply. In response to part (d), the user may assess doses from any combination of the seven pathways available (the radon pathway can only be evaluated when a radon precursor is part of a source). The response to parts (e) and (f) for RESRAD also applies to RESRAD-BUILD.

2.9 Question 9

9. *Does the dose model include software graphical output for portraying dose vs. time for various exposure pathways and specified radionuclides and total effective dose equivalents, including uncertainties?*

2.9.1 RESRAD

The graphical software package allows the user to view not just dose versus time, but also soil guidelines and concentrations as a function of time. The user may view the total effective dose equivalents or the contribution of individual radionuclides (including decay products) (see the example in Figure 23), as well as the dose from all pathways or the contribution of individual pathways (see the example in Figure 24). The user may also view the sensitivity of dose/guidelines as a function of time for each parameter selected for sensitivity (see Figures 9 and 20). A separate graphics package included with the uncertainty analysis allows the user to view the results of multiple iterations of the code; the cumulative distribution of total dose; and statistical plots showing minimum, maximum, average, and standard deviations of the total dose as a function of time (see Figures 11 and 12). Different plotting options (logarithmic vs. linear plots, color vs. black and white, solid lines vs. dashed lines) are available to the user. The data from the plots may be exported to a spreadsheet or copied to the clipboard for incorporation into documents.

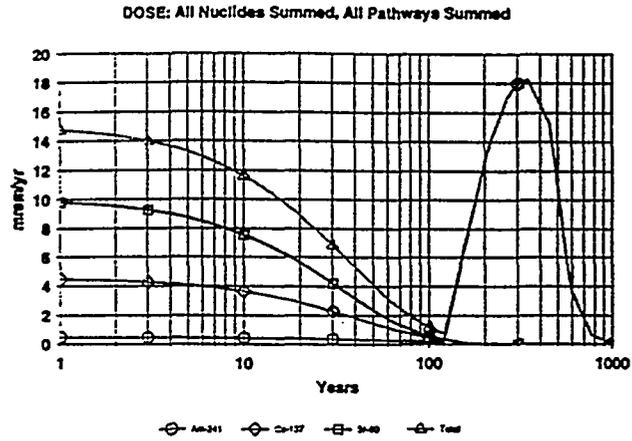


Figure 23. RESRAD Graphical Output — Dose Contributions by Radionuclide

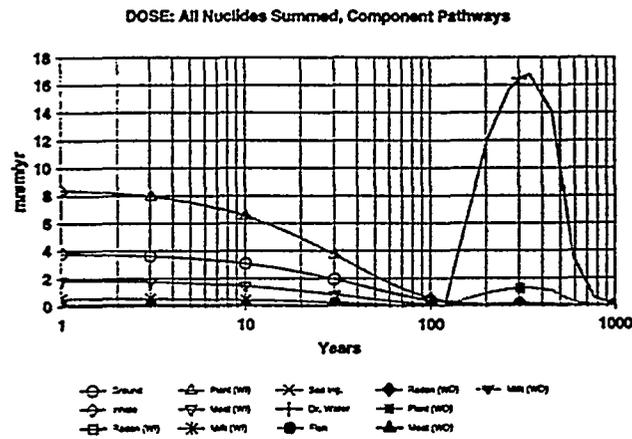


Figure 24. RESRAD Graphical Output — Dose Contributions by Pathway

2.9.2 RESRAD-BUILD

The current version of RESRAD-BUILD does not have a graphical output package. However, RESRAD-BUILD provides graphical visual feedback of the source types/direction, number of sources and receptors, and their locations relative to each other.

2.10 Question 10

10. *Can the analytical method consider various restrictions on land use and site boundaries in calculating concentrations and/or doses and in determining monitoring strategies?*

2.10.1 RESRAD

The RESRAD model can be used to assess most land uses, whether restricted or unrestricted, by simply altering the scenarios as indicated in the response to question 2. In addition, the cleanup criteria can be formulated to take into account a period of institutional control prior to the unrestricted release of the property. Soil cleanup criteria are calculated automatically by the code for each radionuclide entered, on the basis of a user-specified annual dose limit. By estimating the times at which the peak doses from water-independent pathways and water-dependent pathways occur (Figure 25), the code can be used to prioritize the

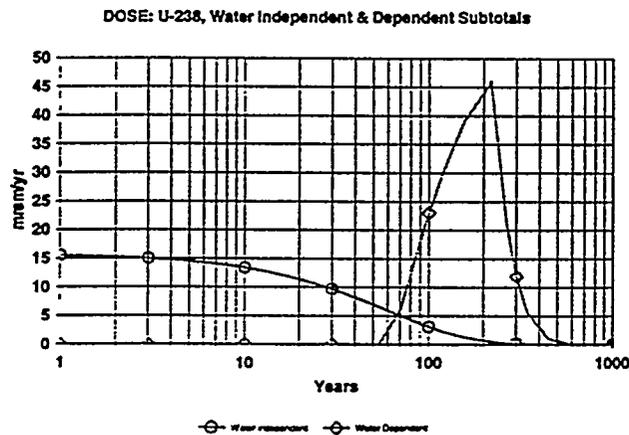


Figure 25. RESRAD Graphical Output —
Water Independent and Dependent Subtotals

monitoring strategies for various media such as soil, air, water, and food products. The code also predicts time-dependent radionuclide concentrations in various media (see the example in Figure 26), which can be used to determine monitoring strategies and data quality objectives. The off-site receptor airborne dispersion and groundwater transport methodology described in the users' manual can be used to evaluate conditions at or beyond the site boundary.

2.10.2 RESRAD-BUILD

As indicated in the response to Question 5, RESRAD-BUILD does not have significant spatial limitations and can be used to assess very site-specific building contamination problems. However, with the exception of the external gamma pathway, assessments are limited to locations inside a building. The code can assess the dose to single or multiple receptors from contamination in a number of sources in single or multiple rooms of a building. The effect of building-use restrictions may be easily assessed by modifying the parameter values (typically receptor locations, occupancy factors, consumption rates, and/or release factors) to accommodate the desired usage scenario. The results can also be used as input for monitoring strategies, particularly for external gamma dose rates and airborne contaminant levels. The code is particularly useful in estimating changes in concentrations over time as a function of decay, ingrowth, or physical removal rates.

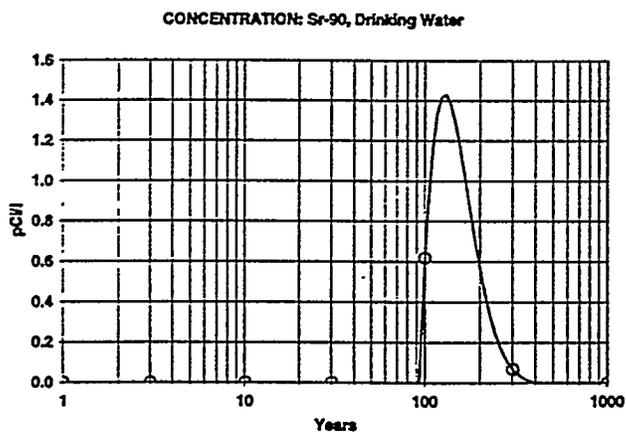


Figure 26. RESRAD Graphical Output —
Radionuclide Concentration in Drinking
Water

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