NUREG/CR-5512, Vol. 4
SAND99-2147

Comparison of the Models and Assumptions used in the DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50 Computer Codes with Respect to the Residential Farmer and Industrial Occupant Scenarios Provided in NUREG/CR-5512

Draft Report for Comment

Sandia National Laboratories

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

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Draft Report for Comment

Manuscript Completed: August 1999
Date Published: October 1999

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Washington, DC 20555-0001
NRC Job Code W6227

UNITED STATES NUCLEAR REGULATORY COMMISSION

Abstract

This report provides a detailed comparison of the models, simplifying assumptions and default parameter values implemented by the DandD 1.0, RESRAD 5.61 and RESRAD Build 1.50 computer codes. Each of these codes is a potentially useful tool for demonstrating compliance with the license termination criteria published by the Nuclear Regulatory Commission in the Federal Register on July 21, 1997. The comparison was limited to the industrial occupant and residential farmer scenarios defined in NUREG/CR-5512 (Kennedy and Strenge, 1992). The report is intended to describe where and how the models and default parameter values in each of the codes differ for the specified scenarios. Strengths, weaknesses and limitations of the models are identified. The practical impacts of the identified differences to dose assessment results are discussed.

RESRAD 5.61 and DandD 1.0 were compared based on the residential farmer scenario. The primary differences between the two codes are due to the use of different groundwater and atmospheric transport models, default parameter values and dose rate reporting. Doses related to pathways involving the use of contaminated groundwater tend to be rather different because of fundamental differences in the groundwater models. Another major difference in dose assessments resulted from the apparently large value of default soil plant mass loading factor used in DandD 1.0. In general there were significant differences in doses modeled for scenarios involving carbon-14, tritium and radon because RESRAD 5.61 includes special flux models for simulating the transport of these isotopes from the soil to the atmosphere while DandD 1.0 does not.

RESRAD Build 1.50 and DandD 1.0 were compared based on the industrial occupant scenario. The modeling approach of the two codes is very different. RESRAD Build 1.50 uses kinetic models to assess the dose, while DandD 1.0 does not. When input parameter values are matched, the models provide similar initial dose rates. Time dependencies of the two models are rather different due to fundamental differences in the models.

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Contents

List of Figures

List of Tables

FOREWORD

This contractor report, NUREG/CR-5512, Volume 4, was prepared by Sandia National Laboratory under their DOE Interagency Work Order (JCN W6227) with Radiation Protection, Environmental Risk & Waste Management Branch, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. This report is the fourth volume to be published in the NUREG/CR-5512 series, and provides a detailed comparison of the model structure, assumptions, and parameters used in the Nuclear Regulatory Commission's DandD software code with those used in the Department of Energy's RESRAD 5.61 and RESRAD-Build 1.50 software codes.

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

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Acknowledgments

Mr. Charley Yu (Argonne National Laboratory) reviewed a preliminary draft of this report and provided helpful comments and information about the RESRAD and RESRAD Build computer codes. Ms Faith Puffer (Tech Reps, Inc.) provided invaluable technical editing support. The word processing support provided by Ms Sherry Rice, Ms Rayleen Sanchez, Ms. Jaclene Ripple, and Ms Debbie Rivard is appreciated.

1. Introduction

This report provides a comparison of the assumptions, models, and default parameters in three environmental dose assessment computer codes that have been used to assess compliance with license termination requirements promulgated by the Nuclear Regulatory Commission (NRC) (NRC, 1997). The computer codes compared were DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50. The report also includes the results of a number of simulations performed with each model and, to the degree possible, an explanation of why the results differed. The comparison was limited to the residential farmer and industrial occupant exposure scenarios given in NUREG/CR-5512. In the case of the residential farmer scenario, simulations were run for three general sub-cases:

1. Simulations having minimal changes to defaults,
2. Simulations representing a wet climate with effort to make parameters comparable, and
3. Simulations representing a dry climate with effort to make parameters comparable.

This report does not describe every difference between DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50. However, an effort was made to identify major differences between the computer codes as well as aspects of the codes that may lead to underestimation or gross overestimation of doses for the NUREG/CR-5512 scenarios considered.

Sandia National Laboratories developed the DandD 1.0 computer code. It represents an implementation of the dose assessment screening models given in NUREG/CR-5512 (Kennedy and Strenge, 1992) as modified by Wernig, et al. (1999). DandD 1.0 provides a structured interface that allows users to apply screening models to estimate doses under four distinct exposure scenarios: industrial occupancy, renovation, residential farmer, and drinking water. Default parameters were selected based on a rigorous analysis so that defensible screening calculations can be made using information about the source.

RESRAD 5.61 (Yu et al., 1993) and RESRAD-Build 1.50 (Yu et al., 1994) were developed by Argonne National Laboratories, and are widely used by DOE and other government agencies to estimate doses from residual radioactive material. These programs are flexible modeling platforms, but they are not specifically organized for implementing the four exposure scenarios given in NUREG/CR-5512. RESRAD 5.61 is primarily useful for estimating doses arising from occupancy of land contaminated by radioactive material. RESRAD-Build 1.50 is primarily useful for estimating doses resulting from occupancy of structures that have surfaces or volumes contaminated with radioactive materials.

2. Scenarios

The comparison of the three computer codes was completed for two scenarios: a residential farmer and an industrial occupant. Both of these scenarios are described in detail in NUREG/CR-5512. The scenarios are summarized below.

2.1 Residential Farmer

The residential farmer scenario is intended to allow estimation of radiation doses that may result from radioactive contamination in soil. The contamination is assumed to be present in a 15-cm thick surface layer on property that can be used for residential and light farming activities. The following pathways are considered in the residential farmer scenario given in NUREG/CR-5512:

- External Exposure from Volume Soil Sources While Outdoors and While Gardening,
- External Exposure from Volume Soil Sources While Indoors,
- Inhalation Exposure to Resuspended Soil While Outdoors and While Gardening,
- Inhalation Exposure to Resuspended Soil While Indoors,
- Inhalation Exposure to Resuspended Surface Sources of Soil Tracked Indoors,
- Ingestion of Soil – Direct,
- Inadvertent Ingestion of Soil Tracked Indoors,
- Ingestion of Drinking Water from a Groundwater Source,
- Ingestion of Plant Products Grown in Contaminated Soil,
- Ingestion of Plant Products Grown With Contaminated Groundwater,
- Ingestion of Animal Products Grown On-Site, and
- Ingestion of Fish Grown in a Pond that is Contaminated by Groundwater.

A number of other pathways are not considered in the residential farmer scenario that is described in NUREG/CR5512. These include:

- External exposure to radioactive material tracked indoors,
- External exposure to sources due to submersion in an airborne cloud of radioactive material,
- External exposure related to contaminated surface water,
- Inhalation of radon and radon progeny,
- Ingestion of drinking water from contaminated surface water sources, and
- Dermal absorption of radionuclides.

Of the pathways not considered, inhalation of radon and radon progeny while indoors is apt to be the most significant in cases where the radioactive contaminants are Naturally Occurring Radioactive Materials (NORM) or Atomic Energy Act 11(e)2 byproduct materials[1]. However, the radon inhalation pathway was excluded from the scenario because NRC does not regulate NORM and closure of facilities contaminated by 11(e)2 byproduct material is already covered by existing regulations.

2.2 Industrial Occupant

The industrial occupancy scenario given in NUREG/CR-5512 is intended to allow estimation of the doses resulting from occupancy of a building that contains both fixed and removable surface contamination. It is assumed that the individual simply occupies a commercial facility in a passive manner without deliberately disturbing surface sources of radioactive contamination. The following pathways were considered in the industrial occupancy scenario:

- External exposure due to source,
- Inhalation of airborne radioactive material, and
- Inadvertent ingestion of radioactive material.

[1]Uranium/thorium mill tailings produced as a consequence of extraction of source material.

A number of other pathways are not considered in the industrial occupancy scenario described in NUREG/CR-5512. These include:

- External exposure to sources due to submersion in an airborne cloud of radioactive material,
- Inhalation of radon and radon progeny,
- Dermal absorption of radionuclides.

The pathways not considered in the industrial occupancy scenario are unlikely to be important in most cases, with the possible exception of inhalation of radon and radon progeny, as discussed in section 2.1.

3. Model Comparisons

3.1 DandD 1.0 and RESRAD 5.61

The most fundamental difference between the two codes is that RESRAD 5.61 is a general purpose environmental dose assessment model while DandD 1.0 is specifically designed to model the scenarios given in NUREG/CR-5512.

The pathways considered in DandD 1.0 and RESRAD 5.61 are provided in Table 1.

The major pathway differences can be summarized as follows:

- DandD 1.0 treats inhalation exposure to soil that has been tracked indoors and become airborne as a discrete pathway, while RESRAD 5.61 does not.
- RESRAD 5.61 has a radon diffusion model and treats inhalation of radon and radon progeny as a separate pathway, while DandD 1.0 does not.
- DandD 1.0 treats inadvertent ingestion of soil tracked indoors as a discrete pathway, while RESRAD 5.61 does not.

In addition, there are numerous significant differences between the two models. These are summarized below.

- DandD 1.0 reports doses accrued over a year of exposure, while RESRAD 5.61 reports instantaneous dose rates. Although both of the codes report dose rates in units of mrem/y, they are distinctly different quantities that cannot always be directly compared.
- DandD 1.0 has a larger library of isotopes than RESRAD 5.61. The DandD 1.0 isotope library includes many primary isotopes with half-lives between 10 minutes and 30 days that are not considered by RESRAD 5.61.
- DandD 1.0 and RESRAD 5.61 observe different formalisms concerning treatment of decay chains. These differences are not likely to give rise to significant differences in simulation results, however.
- DandD 1.0 considers ingestion of eggs and poultry, while RESRAD 5.61 does not.
- DandD 1.0 subdivides plant foods consumed by humans into four groups, while RESRAD 5.61 subdivides plant foods into two groups.

Table 1. Residential farmer scenario pathways considered by DandD 1.0 and RESRAD 5.61

Pathway	DandD 1.0	RESRAD 5.61
External Exposure from Volume Soil Sources While Outdoors	yes	yes
External Exposure from Volume Soil Sources While Indoors	yes	yes
Inhalation Exposure to Resuspended Soil While Outdoors	yes	yes
Inhalation Exposure to Resuspended Soil While Indoors	yes	yes
Inhalation Exposure to Resuspended Surface Sources of Soil Tracked Indoors	yes	no
Inhalation – Radon Progeny	no*	yes
Ingestion of soil – Direct	yes	yes
Inadvertent Ingestion of Soil Tracked Indoors	yes	no
Ingestion of Drinking Water from a Groundwater Source	yes	yes
Ingestion of Plant Products Grown in Contaminated Soil	yes	yes
Ingestion of Plant Products Grown With Contaminated Groundwater	yes	yes
Ingestion of Animal Products Grown On-Site	yes	yes
Ingestion of Fish	yes	yes

*Radon-222 is released from radium-226. Radium-226 in uranium mill tailings is regulated through section 11(e) 2 of the Atomic Energy Act as byproduct material. Cleanup requirements for such radium residues are promulgated through the Uranium Mill Tailings Radiation Control Act. Radium-226 in a form other than source material or byproduct material is largely regulated by the states.

- RESRAD 5.61 considers consumption of shellfish and fish, while DandD 1.0 only considers consumption of fish.

- RESRAD 5.61 food consumption rates are based on national averages, while DandD 1.0 food consumption rates are based on consumption rates of home grown foods.

- As a default, RESRAD 5.61 calculates the contamination fraction of foods as a function of the surface area of contamination. DandD 1.0 does not.

- RESRAD 5.61 has a non-dispersion groundwater model (default) and a mass balance groundwater model; DandD 1.0 has a groundwater model that resembles RESRAD 5.61's mass balance groundwater model in some respects.

- DandD 1.0 recycles irrigation water back through the unsaturated zone to the aquifer, while RESRAD 5.61 does not.

- RESRAD 5.61 allows the user to specify whether irrigation water comes from surface water or from groundwater. DandD 1.0 assumes that irrigation water comes from groundwater.

- RESRAD 5.61 allows different water sources to be used for irrigation and watering of livestock. DandD 1.0 does not.

- RESRAD 5.61 considers sorption in the saturated zone, while DandD 1.0 does not.

- Travel times of contaminants to the well are very different for the two models due to different default values for distribution coefficients, and different groundwater model assumptions. This results in different time dependence and dose rates for pathways related to surface water or groundwater usage.

- DandD 1.0 uses the same distribution coefficients for surface soils and the unsaturated zone, while RESRAD 5.61 allows for different distribution coefficients.

- DandD 1.0 assumes that carbon-14 and tritium only become airborne as a component of airborne dust; RESRAD 5.61 contains flux models for these isotopes and it takes into account inhalation of gaseous forms of these isotopes. RESRAD 5.61 also takes into account inhalation of particulate forms of carbon-14.

- DandD 1.0 assumes that conventional soil-to-plant transfer coefficients can be used to model uptake of carbon-14 by plants. RESRAD 5.61 has a carbon-14 model based on the assumption that assimilation of carbon by plants occurs through leaf surfaces and through the root system.

- RESRAD 5.61 models direct gamma doses from soil as a function of thickness and areal extent of contamination, while DandD 1.0 considers only a 6" thick infinite slab of contaminated soil.

- RESRAD 5.61 takes the surface area of contamination into account, while DandD 1.0 does not; this allows RESRAD 5.61 to model doses from "hot spots" of radioactive contamination.

- RESRAD 5.61 allows for the presence of a cover of clean fill over the contaminated area. DandD 1.0 does not.

- RESRAD 5.61 allows the user to select an erosion rate that applies to the cover and contaminated area, while DandD 1.0 does not take erosion into account.

- RESRAD 5.61 uses a conservative correction factor for contamination fraction of dust present in outdoor air that depends on areal extent of contamination, while DandD 1.0 assumes that all dust present in outdoor air is resuspended contaminated soil.

- RESRAD 5.61 models the amount of soil present in plants as the result of a dynamic process involving deposition and removal through weathering. DandD 1.0 addresses this through use of an empirical mass loading factor. The current mass loading factors used by DandD 1.0 appear to be rather high; it is recommended that they be reconsidered.

- RESRAD 5.61 uses a single human respiration rate. DandD 1.0 uses different respiration rates for indoors, gardening, and "other outdoor activities."

- RESRAD 5.61 has a single outdoor air mass loading for inhalation, while DandD 1.0 has separate values of mass loading for gardening and "other outdoor activities."

- DandD 1.0 distinguishes between indoor airborne dust concentrations resulting from infiltration of outdoor air and from resuspension of soil tracked indoors. RESRAD 5.61 does not.

- Throughout the model, RESRAD 5.61 and DandD 1.0 tend to use different values for default parameters.

- DandD 1.0 assumes overhead irrigation, RESRAD 5.61 will model either overhead or ditch irrigation.

3.1.1 Dose Rate Reporting Basis

DandD 1.0 computes average doses that occur over a one-year period of time and reports the value as the maximum annual dose for the time interval of interest. RESRAD 5.61 computes and reports instantaneous dose rates for the times specified by the user as well as the maximal instantaneous dose rate projected during the interval of interest. These are fundamentally different approaches. Both approaches should provide essentially the same annualized dose rate for scenarios involving nuclides having a half-life of a few years or longer and nuclides moving slowly out of the contaminated zone.

The maximal instantaneous dose rate reporting basis of RESRAD 5.61 presents a complication in the interpretation of results for certain isotopes. Cleanup standards in 10 CFR 20, Subpart E, "Radiological Criteria for License Termination," are based on limiting the annual dose to a prescribed value (25 mrem) and not a limitation of the instantaneous dose rate. Substantial differences will result from the dose rate reporting basis alone for isotopes having a half-life between one month and six months and for tritium and carbon-14 because of their rapid movement out of surface soils.

A pair of simulations provided in Appendix A illustrate how rapidly the RESRAD 5.61 instantaneous dose rates change in the case of tritium (Table A.1). In this example, the instantaneous dose rate declines during the first year from an initial (and maximal) value of 5 mrem/y to a final value of 2E-5 mrem/y. Using maximal instantaneous dose rates could be appropriate for screening purposes.

The maximal instantaneous dose rate approach is conservative in most cases. However, it would be desirable to modify RESRAD 5.61 to calculate the dose accrued over a year so that direct comparison with regulatory limits is possible.

3.1.2 Isotopes and Decay Chains

RESRAD 5.61 will operate with either of two isotope libraries. As the default condition, RESRAD 5.61 uses a library of 67 primary isotopes with a half-life of six months or longer. In the default mode it considers any progeny with a half-life shorter than six months to be in equilibrium with the parent isotope. As an option, users can choose to run RESRAD 5.61 with a library of 84 primary isotopes having a half-life of 30 days or longer.

The DandD 1.0 library includes 249 primary isotopes. The half-lives of all primary isotopes in the library are 10 minutes or longer. DandD 1.0 always assumes a short-lived decay product to be in equilibrium with its parent when *both* of the following conditions are met: the decay product has a half-life less than nine hours, *and* the decay product half-life is less than one tenth of the parent.

3.1.3 Human Diet

DandD 1.0 and RESRAD 5.61 subdivide the human diet differently. A comparison of the two is provided in Table 2. DandD 1.0 and RESRAD 5.61 use transfer coefficients assumed to be dependent only on radionuclide for entire classes of foods.

DandD 1.0 subdivides the "plant" foods into four categories while RESRAD 5.61 subdivides "plant" foods into two categories. The higher number of plant subdivisions could make it easier for users of DandD 1.0 to identify suitable alternate soil-to-plant transfer factors from the scientific literature. In practice, taking advantage of the greater flexibility may be difficult. It is noted that default soil-to-plant transfer factor values for many of the isotopes in the DandD 1.0 database have the same value for roots, fruits, and grains.

DandD 1.0 distinguishes between intakes of poultry, eggs, and beef, while RESRAD 5.61 only considers intakes of beef. It is desirable to distinguish between intakes of poultry, eggs, and beef, because:

- cattle and birds are different physiologically,

- foraging birds tend to ingest more soil than do cattle, and

- birds and cattle have different plant-to-animal product transfer factors.

In theory, RESRAD 5.61 users could compensate for the aggregation of intakes of animal products by adjusting the plant-to-animal transfer factors to represent a weighted average of the factors for poultry, eggs, and beef.

Table 3 provides default animal intake rates for fodder, water and soil.

Table 2. How DandD 1.0 and RESRAD 5.61 divide the human diet into food classes

Dietary Component	DandD 1.0	RESRAD 5.61
Beef and Poultry combined	no	yes
Beef	yes	no
Poultry	yes	no
Milk	yes	yes
Eggs	yes	yes
Fish	yes	yes
Mollusks and crustaceans	no	yes
Fruits, non-leafy vegetables, and grains as a group	no	yes
Leafy vegetables	yes	yes
Roots	yes	no
Fruit	yes	no
Grain	yes	no

Table 3. Default animal intake rates for food, water, and soil

Animal Intake Rates	Units	DandD 1.0 Default Value	RESRAD 5.61	Remarks
Beef Forage	kg/day	8.13	NA	
Poultry Forage	kg/day	0.0562	NA	
Milk Cow Forage	kg/day	35.2	NA	
Layer Hen Forage	kg/day	.0755	NA	
Beef Grain	kg/day	2.42	NA	
Poultry Grain	kg/day	0.0630	NA	
Milk Cow Grain	kg/day	1.95	NA	
Layer Hen Grain	kg/day	0.0610	NA	
Beef Hay	kg/day	16.3	NA	
Fodder intake for meat	kg/day	NA	68.0	
Poultry Hay	kg/day	0.00	NA	
Milk Cow Hay	kg/day	26.1	NA	
Milk Cow Fodder	kg/day	NA	55.0	
Layer Hen Hay	kg/day	0.00	NA	
Beef Water	L/day	50.0	NA	
Livestock Water intake for meat	L/day	NA	50	Presumably this is the same as intake for beef.
Poultry Water	L/day	0.30	NA	
Milk Cow Water	L/day	60.0	160	RESRAD 5.61's 160 L/day water intake rate for dairy cattle seems high.
Layer Hen Water	L/day	0.30	NA	

Table 3. Default animal intake rates for food, water, and soil (continued)

Animal Intake Rates	Units	DandD 1.0 Default Value	RESRAD 5.61	Remarks
Beef Period	days	365	NA	
Poultry Period	days	365	NA	
Milk Cow Period	days	365	NA	
Layer Hen Period	days	365	NA	
Beef Soil Ingestion Fraction	None	0.020	NA	
Poultry Soil Ingestion Fraction	None	0.10	NA	
Milk Cow Soil Ingestion Fraction	None	0.020	NA	
Layer Hen Soil Ingestion Fraction	None	0.10	NA	
Livestock soil intake	kg/day	NA	0.05	

RESRAD 5.61 distinguishes between intakes of shellfish and fish, while DandD 1.0 only considers intakes of fish. The higher number of aquatic food subdivisions provides RESRAD 5.61 with additional flexibility in modeling dose from intakes of aquatic foods. This added flexibility of RESRAD 5.61 increases its usefulness as a general environmental dose assessment tool. The shellfish intake pathway is not a component of the residential farmer scenario given in NUREG/CR-5512, so this feature is not directly applicable to the scenarios considered.

An important distinction should be made between DandD 1.0 and RESRAD 5.61 concerning default ingestion rates. The default ingestion rates given in DandD 1.0 are intended to represent the ingestion rates of homegrown foods. These values are intended to be used for screening purposes with a default "DIET" fraction of 1.0. The DIET fraction used in DandD 1.0 could be set to a value of less than 1.0 if only a uniform fraction of the homegrown foods can be grown in the contaminated area (Beyeler, et al., 1998).

The ingestion rate parameters in RESRAD 5.61 represent the total consumption rates for the different food groups based on national averages (Yu, et al., 1993). The default ingestion rate of contaminated foods in RESRAD 5.61 is the product of the total consumption rate and the contamination fraction. The contamination fraction can be set by the user, but by default RESRAD 5.61 calculates a contamination fraction based on the extent of the contamination area. The default method used by RESRAD 5.61 to calculate contamination fraction is given in Table 4. Table 4 provides default ingestion rates for contaminated foods in DandD 1.0 and RESRAD 5.61.

Comparison of the DandD 1.0 values for consumption rates of homegrown foods with RESRAD 5.61 national average consumption rates (see the first page of Table 4) suggests that people may tend to consume what foods are readily available to them or that they tend to raise foods that they prefer to eat.

3.1.4 Fish and Shellfish Bio-Concentration Factors

Table 5 provides default bio-accumulation factors for RESRAD 5.61 and DandD 1.0. Shellfish bio-concentration factors (FWR) used in RESRAD 5.61 tend to be significantly higher than the corresponding fish FWR. In summary, in RESRAD 5.61 the shellfish FWR compare to the fish FWR as follows (noble gases and nitrogen excluded):

shellfish FWR $\leq$ 0.1 $\times$ fish FWR: 4 elements

shellfish FWR $<$ fish FWR: 23 elements

shellfish FWR $=$ fish FWR: 4 elements

shellfish FWR $>$ fish FWR: 45 elements

shellfish FWR $\geq$ 10 $\times$ fish FWR: 34 elements.

The fish bio-accumulation factors used by DandD 1.0 may require modification when the model is applied to scenarios where consumption of shellfish is an exposure pathway.

Table 4. Comparison of the basic residential farmer scenario default parameters of DandD 1.0 and RESRAD 5.61

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Inhalation rate (m**3/hr)	NA	0.9589	
Inhalation rate, indoor (m**3/hr)	0.90	NA	
Inhalation rate, outdoor (m**3/hr)	1.40	NA	
Inhalation rate, gardening (m**3/hr)	1.70	NA	
Mass loading for inhalation, outdoors (g/m**3)	3.14E-6	2.00E-04	
Mass loading for inhalation, indoors (g/m**3)	1.41E-6	NA	
Mass loading for inhalation, gardening (g/m**3)	4.00E-4	NA	
Resuspension factor for indoor dust	2.82E-6	NA	
Floor dust loading g/m^2	0.1599	NA	
Dilution length for airborne dust, inhalation (m)	NA	3.000E+0	
Exposure duration (y)	NA	3.00E+01	
Shielding factor, inhalation	NA	4.000E-01	
Shielding factor, external gamma	0.5512	7.000E-01	
Fraction of time spent indoors	0.6571	5.00E-01	
Fraction of time spent outdoors (on site)	0.1101	2.50E-01	
Fraction of time spent gardening	7.99E-3	NA	
Fruits, vegetables, and grain consumption (kg/yr.)	112	160	DandD 1.0 value is sum of individual annual dietary intakes for food items.
Soil mass loading on plants	0.1		DandD 1.0 rate is high for food crops
Fruits (kg/yr.)	52.8	NA	DandD values are based on average for consumption of home-grown crops
Roots (kg/yr.)	44.6	NA	
Grain (kg/yr.)	14.4	NA	
Leafy vegetable consumption (kg/yr.)	21.4	14	
Milk consumption (L/yr.)	233	92	
Meat and poultry consumption (kg/yr.)	65.1	63	DandD 1.0 value is sum of individual annual dietary intakes for food items.
Beef consumption (kg/yr.)	39.8	NA	
Poultry consumption (kg/yr.)	25.3	NA	
Fish consumption (kg/yr.)	20.6	5.40	
Other seafood consumption (kg/yr.)	NA	0.90	

Table 4. Comparison of the basic residential farmer scenario default parameters of DandD 1.0 and RESRAD 5.61 (continued)

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Soil ingestion rate (g/yr.)	18.2625	36.5	
Drinking water intake (L/yr.)	478.5	510	
Contamination fraction of drinking water	1.0	1.00	
Contamination fraction of household water	1.0	1.00	
Contamination fraction of livestock water	1.0	1.00	
Contamination fraction of irrigation water	1.0	1.00	
Contamination fraction of aquatic food	1.0	0.50	
Contamination fraction of plant food	1.0	0.5, if area > 1000 m^2; area / 2000, if area < 1000 m^2	
Contamination fraction of meat	1.0	1.0 if area > 20,000 m^2; area / 20000, if area < 20000 m^2	
Contamination fraction of milk	1.0	1.0 if area > 20,000 m^2; area / 20000, if area < 20000 m^2	
Mass loading for foliage deposition (g/m**3)	NA	1.00E-04	
Depth of soil mixing layer (m)	NA	0.15	DandD 1.0 only models 15 cm layer of surface soil contamination.
Depth of roots (m)	NA	0.90	
Drinking water fraction from groundwater	1.0	1.0	
Household water fraction from groundwater	1.0	1.0	
Livestock water fraction from groundwater	1.0	1.0	
Irrigation fraction from groundwater	1.0	1.0	
Fraction of grain in beef cattle feed	0.0743	0.8	DandD 1.0 considers balance to be forage and hay.
Fraction of grain in milk cow feed	0.0308	0.2	DandD 1.0 considers balance to be forage and hay.
Storage times of contaminated foodstuffs (days):			
Fruits, non-leafy vegetables, and grain	NA	14.0	
Leafy vegetables	1	1.0	
Roots	14	NA	
Fruit	14	NA	
Grain	14	NA	
Milk	1	1.00	
Eggs	1	NA	

Table 4. Comparison of the basic residential farmer scenario default parameters of DandD 1.0 and RESRAD 5.61 (continued)

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Storage times of contaminated foodstuffs (days):			
Meat and poultry	NA	20.0	
Beef	20	NA	
Poultry	1	NA	
Fish	NA	7.0	DandD 1.0 assumes no hold-up time for this pathway.
Crustacea and mollusks	NA	7.0	DandD 1.0 does not consider dietary intake of freshwater mollusks and crustacea.
Well water	NA	1.0	DandD 1.0 assumes no holdup time for well water.
Surface water	NA	1.0	DandD 1.0 assumes that the residential farmer drinks well water.
Livestock fodder	0	45.0	DandD 1.0 assumes intake of stored feeds to begin at the time of harvest.

Table 5. Default bio-accumulation factors for DandD 1.0 and RESRAD 5.61

Isotope	DandD 1.0, Fish (L/kg)	RESRAD 5.61, Fish (L/kg)	RESRAD 5.61 Crustacea and Mollusks (L/kg)
H	1.0	1.0	1.0
Be	2.0	100.0	10.0
C	4,600.0	50,000.0	9,100.0
N	150,000.0	150,000.0	0.0
F	10.0	10.0	100.0
Na	100.0	20.0	200.0
Al		500.0	1,000.0
P	70,000.0	50,000.0	20,000.0
S	750.0	1,000.0	240.0
Cl	50.0	1,000.0	190.0
Ar		0.0	0.0
K	1,000.0	1,000.0	200.0
Ca	40.0	1,000.0	330.0
Sc	100.0	100.0	1,000.0
Cr	200.0	200.0	2,000.0

Table 5. Default bio-accumulation factors for DandD 1.0 and RESRAD 5.61 (continued)

Isotope	DandD 1.0, Fish (L/kg)	RESRAD 5.61, Fish (L/kg)	RESRAD 5.61 Crustacea and Mollusks (L/kg)
Mn	400.0	400.0	90,000.0
Fe	2,000.0	200.0	3,200.0
Co	330.0	300.0	200.0
Ni	100.0	100.0	100.0
Cu	50.0	200.0	400.0
Zn	2,500.0	1,000.0	10,000.0
Ge		4,000.0	20,000.0
As	100.0	300.0	300.0
Se	170.0	200.0	200.0
Br	420.0	420.0	330.0
Kr		0.0	0.0
Rb	2,000.0	2,000.0	1,000.0
Sr	50.0	60.0	100.0
Y	25.0	30.0	1,000.0
Zr	200.0	300.0	6.7
Nb	200.0	300.0	100.0
Mo	10.0	10.0	10.0
Tc	15.0	20.0	5.0
Ru	100.0	10.0	300.0
Rh	10.0	10.0	300.0
Pd	10.0	10.0	300.0
Ag	2.3	5.0	770.0
Cd	200.0	200.0	2,000.0
In	100,000.0	10,000.0	15,000.0
Sn	3,000.0	3,000.0	1,000.0
Sb	200.0	100.0	10.0
Te	400.0	400.0	75.0
Cs	2,000.0	2,000.0	100.0
Ba	200.0	4.0	200.0
La	25.0	30.0	1,000.0
Ce	500.0	30.0	1,000.0
Pr	25.0	100.0	1,000.0
Nd	25.0	100.0	1,000.0
Pm	25.0	30.0	1,000.0
Sm	25.0	25.0	1,000.0
Eu	25.0	50.0	1,000.0
Gd	25.0	25.0	1,000.0
Tb	25.0	25.0	1,000.0
Ho	25.0	25.0	1,000.0
Ta		100.0	30.0
W	1,200.0	1,200.0	10.0
Re	120.0		
Os	10.0		

Table 5. Default bio-accumulation factors for DandD 1.0 and RESRAD 5.61 (continued)

Isotope	DandD 1.0, Fish (L/kg)	RESRAD 5.61, Fish (L/kg)	RESRAD 5.61 Crustacea and Mollusks (L/kg)
Ir	10.0	10.0	200.0
Au	33.0	35.0	1,000.0
Hg	1,000.0	1,000.0	20,000.0
Tl		10,000.0	15,000.0
Pb	100.0	300.0	100.0
Bi	15.0	15.0	10.0
Po	500.0	100.0	20,000.0
Rn	0.0	0.0	0.0
Ra	70.0	50.0	250.0
Ac	25.0	15.0	1,000.0
Th	100.0	100.0	500.0
Pa	11.0	10.0	110.0
U	50.0	10.0	60.0
Np	250.0	30.0	400.0
Pu	250.0	30.0	100.0
Am	250.0	30.0	1,000.0
Cm	250.0	30.0	1,000.0
Cf	25.0	25.0	1,000.0

3.1.5 Soil-to-Plant Transfer Factors

Default soil-to-plant transfer factors are provided in Table 6. DandD 1.0 subdivides plant-based foods into four categories (leafy vegetables, roots, fruit, and grain). RESRAD 5.61 subdivides plant-based foods into two categories: (1) leafy vegetables and (2) fruits, non-leafy vegetables, and grains.

DandD 1.0, RESRAD 5.61, and other environmental dose screening models make use of soil-to-plant transfer factors. Using generic soil-to-plant transfer coefficients requires the following simplifying assumptions:

- transfer coefficients are independent of the chemical form of the radioactive material,
- transfer coefficients are independent of the soil composition,
- all food plants can be grouped into a small number of classes and a representative transfer factor can be assigned for each radionuclide and food class.

Ng (1982) observed that soil-to-plant transfer coefficients are highly variable. He attributed this to differences among plant characteristics, soil types, and other factors.

3.1.6 Plant-to-Animal Product Transfer Factors.

DandD 1.0, RESRAD 5.61, and other screening models use transfer factors to model the relationship between activity per mass of the animal product and daily intake rate of a radionuclide by the animal. Default values are provided in Table 7.

These transfer factors have been studied in the most detail for the plant-milk pathway (Ng et al., 1978; Ng, 1982). Transfer factors for beef, eggs, and poultry have also been published.

There are a number of assumptions that introduce uncertainty into the derivation of plant-to-animal product transfer factors. These uncertainties are described below:

- Published transfer coefficients are often based on limited duration studies; they may not always provide a reasonable estimate of steady state conditions. Extrapolating these values to steady state conditions results in uncertainty from assumptions that must be made concerning the partitioning among compartments, excretion, and retention of the particular isotope by the animal;

Table 6. Soil-to-plant transfer factors

Element	DandD 1.0 Leafy	DandD 1.0 Root	DandD 1.0 Fruit	DandD 1.0 Grain	RESRAD 5.61 Plant
H	0.00	0.00	0.00	0.00	4.8
Be	1.00E-02	1.50E-03	1.50E-03	1.50E-03	4.00E-03
C	3.20E-01	7.00E-01	7.00E-01	2.20E-01	5.5
N	3.00E+01	3.00E+01	3.00E+01	3.00E+01	7.5
F	6.00E-02	6.00E-03	6.00E-03	6.00E-03	2.00E-02
Na	7.40E-02	2.80E-02	1.60E-02	5.20E-03	5.00E-02
Mg	1.00	5.50E-01	5.50E-01	5.50E-01	
Al					4.00E-03
Si	3.50E-01	7.00E-02	7.00E-02	7.00E-02	
P	3.50	3.50	3.50	3.50	1
S	2.30	1.50	1.50	1.50	6.00E-01
Cl	1.60E+02	7.00E+01	7.00E+01	1.00E+03	20
Ar	0.00	0.00	0.00	0.00	0.00
K	8.40	5.50E-01	5.50E-01	1.30	3.00E-01
Ca	1.40E+01	3.50E-01	3.50E-01	1.60	5.00E-01
Sc	6.00E-03	1.00E-03	1.00E-03	1.00E-03	2.00E-03
Cr	2.20E-02	8.00E-02	4.60E-02	1.50E-02	2.50E-04
Mn	3.30E-01	1.10E+01	4.20	1.40E-01	3.00E-01
Fe	5.60E-03	2.60E-03	1.50E-03	4.80E-04	1.00E-03
Co	4.00E-02	2.90	2.20E-02	1.10E-02	8.00E-02
Ni	3.40E-02	2.50	3.40E-01	3.80E-02	5.00E-02
Cu	4.90E-01	2.60E-01	1.50E-01	4.90E-02	1.30E-01
Zn	3.10E-01	2.40E-01	1.10	5.50	4.00E-01
Ga	4.00E-03	4.00E-04	4.00E-04	4.00E-04	4.00E-01
As	4.00E-02	6.00E-03	6.00E-03	6.00E-03	8.00E-02
Se	4.90E-02	2.50E-02	2.50E-02	1.60E-01	1.00E-01
Br	1.50	1.50	1.50	1.50	7.60E-01
Kr	0.00	0.00	0.00	0.00	0.00
Rb	8.10E-01	7.00E-02	7.00E-02	7.00E-02	1.30E-01
Sr	6.40E+01	4.60E-01	2.60E-01	8.50E-02	3.00E-01
Y	1.50E-02	6.00E-03	6.00E-03	6.00E-03	2.50E-03
Zr	7.20E-02	4.70E-03	2.70E-03	8.70E-04	1.00E-03
Nb	4.60E-02	5.00E-03	5.00E-03	4.30E-03	1.00E-02
Mo	5.20E+01	6.00E-02	6.00E-02	6.00E-02	1.30E-01
Tc	3.60E+01	1.50	1.50	7.30E-01	5
Ru	1.80E-02	8.60E-03	3.00E-01	1.60E-03	3.00E-02
Rh	1.50E-01	4.00E-02	4.00E-02	4.00E-02	1.30E-01
Pd	1.20	4.00E-02	4.00E-02	1.80E-01	1.00E-01
Ag	5.50	1.00E-01	1.00E-01	1.00E-01	1.50E-01

Table 6. Soil-to-plant transfer factors (continued)

Element	DandD 1.0 Leafy	DandD 1.0 Root	DandD 1.0 Fruit	DandD 1.0 Grain	RESRAD 5.61 Plant
Cd	5.00	1.50E-01	6.70E-01	2.20E-01	3.00E-01
In	4.00E-03	4.00E-04	4.00E-04	4.00E-04	3.00E-03
Sn	4.30E-02	6.00E-03	6.00E-03	6.00E-03	2.50E-03
Sb	9.00E-01	3.00E-02	3.00E-02	3.00E-02	1.00E-02
Te	1.70E-02	4.00E-03	4.00E-03	2.50E-03	6.00E-01
I	1.60E-01	2.80E-02	1.60E-02	5.10E-03	2.00E-02
Xe	0.00	0.00	0.00	0.00	0.00
Cs	1.80E-02	3.10E-02	1.40E-01	6.60E-03	4.00E-02
Ba	3.90E-02	8.00E-03	4.60E-03	1.50E-03	5.00E-03
La	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Ce	6.40E-01	4.00E-03	2.00E-03	8.20E-04	2.00E-03
Pr	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Nd	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.40E-03
Pm	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Sm	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Eu	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Gd	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.50E-03
Tb	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.60E-03
Dy	1.00E-02	4.00E-03	4.00E-03	4.00E-03	
Ho	1.00E-02	4.00E-03	4.00E-03	4.00E-03	2.60E-03
Er	1.00E-02	4.00E-03	4.00E-03	4.00E-03	
Hf	3.50E-03	8.50E-04	8.50E-04	8.50E-04	
Ta	1.00E-02	2.50E-03	2.50E-03	2.50E-03	2.00E-02
W	3.10E-01	1.00E-02	1.00E-02	4.10E-02	1.80E-02
Re	7.50	3.50E-01	3.50E-01	9.50E-01	
Os	9.40E-02	3.50E-03	3.50E-03	3.50E-03	
Ir	1.50E-01	1.50E-02	1.50E-02	1.00E-02	3.00E-02
Au	4.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01
Hg	9.00E-01	2.00E-01	2.00E-01	2.00E-01	3.80E-01
Tl	4.00E-03	4.00E-04	4.00E-04	4.00E-04	2.00E-01
Pb	4.50E-02	9.00E-03	9.00E-03	9.00E-03	1.00E-02
Bi	3.50E-02	5.00E-03	5.00E-03	5.00E-03	1.00E-01
Po	2.50E-03	4.00E-04	4.00E-04	4.00E-04	1.00E-03
Rn	0.00	0.00	0.00	0.00	0.00
Ra	1.50E-02	1.50E-03	1.50E-03	1.50E-03	4.00E-02
Ac	3.50E-03	3.50E-04	3.50E-04	3.50E-04	2.50E-03
Th	8.50E-04	8.50E-05	8.50E-05	8.50E-05	1.00E-03
Pa	2.50E-03	2.50E-04	2.50E-04	2.50E-04	1.00E-02
U	8.50E-03	4.00E-03	4.00E-03	4.00E-03	2.50E-03

Table 6. Soil-to-plant transfer factors (continued)

Element	DandD 1.0 Leafy	DandD 1.0 Root	DandD 1.0 Fruit	DandD 1.0 Grain	RESRAD 5.61 Plant
Np	1.90E+01	1.90E-01	1.30E-01	6.80E-02	2.00E-02
Pu	4.50E-04	4.50E-05	4.50E-05	4.50E-05	1.00E-03
Am	5.50E-03	2.50E-04	2.50E-04	2.50E-04	1.00E-03
Cm	8.50E-04	1.50E-05	1.50E-05	1.50E-05	1.00E-03
Cf	1.00E-02	1.00E-02	1.00E-02	1.10E-02	1.00E-03

- The fractional uptake of the isotope by the animal is assumed to be the same regardless of the media (water, plant, or soil) ingested;

- Ingested plant material, water, and soils of all types are assumed to have the same bio-availability of radionuclides;

- The transfer factors are assumed to independent of the chemical form of the radionuclide;

- The transfer factors are assumed to be independent of the age of the animal and dietary factors.

3.1.7 Groundwater Models

The groundwater models in DandD 1.0 and RESRAD 5.61 are similar in some respects and different in others. The DandD 1.0 groundwater model is a sequence of unsteady well-mixed linear reservoirs. In this model, the contaminant concentration in each reservoir is proportional to its initial concentration and additional input. The output concentrations are equal to the concentrations in the reservoir. The unsaturated zone is usually represented as one well-mixed linear reservoir. However, it can be represented with as many as 10 reservoirs. These reservoirs all have the same thickness, porosity, moisture saturation, and retardation. The intent of the additional reservoirs is to limit the dispersion that is inherent in this type of model (due to the complete mixing assumption). Additional reservoirs slow down the simulated arrival time of contaminants to the groundwater relative to a single reservoir model.

The RESRAD 5.61 groundwater model has an unsteady well-mixed linear reservoir in the contaminated zone, a travel time model in the unsaturated zone, and either a mass balance model or non-dispersive model in the saturated zone. The unsaturated zone in RESRAD 5.61 can be represented by up to five layers with differing properties. The mass balance or non-dispersive model is user-selectable in RESRAD 5.61.

DandD 1.0 and RESRAD 5.61 use the same leaching model to estimate the concentration of contaminants in groundwater in the unsaturated zone (see Kennedy and Strenge, 1992, p.4.8-4.9 and Yu et al., 1993, p.197-199). The leaching rate is a function of the infiltration rate, moisture content, layer thickness, and retardation coefficient. As a result, the leaching rate is element-specific.

3.1.7.1 DandD 1.0 Groundwater Model

3.1.7.1.1 Contaminated Zone. The contaminated zone in DandD 1.0's groundwater model is modeled as a well-mixed linear reservoir. In DandD 1.0's model implementation, the contaminated zone is referred to as the soil plow layer and is located at land surface. DandD 1.0 allows contaminated water from the aquifer to be pumped to the soil layer for irrigation purposes. The impact would be to continually add radioactive materials to the soil layer. Therefore, the decline in radioactivity in the soil plow layer of DandD 1.0's model is slower than for a case in which no contaminated water is pumped to the soil layer. Contaminants dissolved in the soil layer water move to the unsaturated zone by infiltration. Contaminants left behind are adsorbed onto the soil particles.

DandD 1.0 formulates its model equation for the soil in terms of total activity within a well-mixed linear reservoir. Dissolved activity is transported out of the soil layer box by infiltration. Transport out of the soil layer box is dependent on the infiltration rate, the distribution coefficient, the soil bulk density, the thickness, the porosity, and the moisture saturation. These factors are combined into a transfer term that controls the rate at which contaminants move out of the

Table 7. Plant to animal product transfer factors

Isotope	DandD 1.0 Beef	DandD 1.0 Poultry	RESRAD 5.61 Beef	DandD 1.0 Milk	RESRAD 5.61 Milk	DandD 1.0 Eggs
H	0.0	0.0	1.2E-02	0.0	1.0E-02	0.0
Be	1.0E-03	4.0E-01	1.0E-03	9.0E-07	2.0E-06	2.0E-02
C	0.0	0.0	3.1E-02	0.0	1.2E-02	0.0
N	7.5E-02	1.0E-01	1.0E-02	2.5E-02	1.0E-02	8.0E-01
F	1.5E-01	1.0E-02	2.0E-02	1.0E-03	7.0E-03	2.0
Na	5.5E-02	1.0E-02	8.0E-02	3.5E-02	4.0E-02	2.0E-01
Mg	5.0E-03	3.0E-02		4.0E-03		1.6
Al			5.0E-04		2.0E-04	
Si	4.0E-05	2.0E-01		2.0E-05		8.0E-01
P	5.5E-02	1.9E-01	5.0E-02	1.5E-02	1.6E-02	1.0E+01
S	1.0E-01	9.0E-01	2.0E-01	1.5E-02	2.0E-02	7.0
Cl	8.0E-02	3.0E-02	6.0E-02	1.5E-02	2.0E-02	2.0
Ar	0.0	0.0	0.0	0.0	0.0	0.0
K	2.0E-02	4.0E-01	2.0E-02	7.0E-03	7.0E-03	7.0E-01
Ca	7.0E-04	4.4E-02	1.6E-03	1.0E-02	3.0E-03	4.4E-01
Sc	1.5E-02	4.0E-03	1.5E-02	5.0E-06	5.0E-06	3.0E-03
Cr	5.5E-03	2.0E-01	9.0E-03	1.5E-03	2.0E-03	8.0E-01
Mn	4.0E-04	5.0E-02	5.0E-04	3.5E-04	3.0E-04	6.5E-02
Fe	2.0E-02	1.5E+00	2.0E-02	2.5E-04	3.0E-04	1.3
Co	2.0E-02	5.0E-01	2.0E-02	2.0E-03	2.0E-03	1.0E-01
Ni	6.0E-03	1.0E-03	5.0E-03	1.0E-03	2.0E-02	1.0E-01
Cu	1.0E-02	5.1E-01	1.0E-02	1.5E-03	2.0E-03	4.9E-01
Zn	1.0E-01	6.5	1.0E-01	1.0E-02	1.0E-02	2.6
Ga	5.0E-04	3.0E-01	2.0E-01	5.0E-05	1.0E-02	8.0E-01
As	2.0E-03	8.3E-01	1.5E-03	6.0E-05	1.0E-04	8.0E-01
Se	1.5E-02	8.5	1.0E-01	4.0E-03	1.0E-02	9.3
Br	2.5E-02	4.0E-03	2.0E-02	2.0E-02	2.0E-02	1.6
Kr	0.0	0.0	0.0	0.0	0.0	0.0
Rb	1.5E-02	2.0	1.5E-02	1.0E-02	1.0E-02	3.0
Sr	3.0E-04	3.5E-02	8.0E-03	1.5E-03	2.0E-03	3.0E-01
Y	3.0E-04	1.0E-02	2.0E-03	2.0E-05	2.0E-05	2.0E-03
Zr	5.5E-03	6.4E-05	1.0E-06	3.0E-05	6.0E-07	1.9E-04
Nb	2.5E-01	3.1E-04	3.0E-07	2.0E-02	2.0E-06	1.3E-03
Mo	6.0E-03	1.9E-01	1.0E-03	1.5E-03	1.7E-03	7.8E-01
Tc	8.5E-03	3.0E-02	1.0E-04	1.0E-02	1.0E-03	3.0
Ru	2.0E-03	7.0E-03	2.0E-03	6.0E-07	3.3E-06	6.0E-03
Rh	2.0E-03	5.0E-01	1.0E-03	1.0E-02	5.0E-03	1.0E-01
Pd	4.0E-03	3.0E-04	1.0E-03	1.0E-02	5.0E-03	4.0E-03
Ag	3.0E-03	5.0E-01	3.0E-03	2.0E-02	2.5E-02	5.0E-01
Cd	5.5E-04	8.4E-01	4.0E-04	1.0E-03	1.0E-03	1.0E-01
In	8.0E-03	3.0E-01	4.0E-03	1.0E-04	2.0E-04	8.0E-01
Sn	8.0E-02	2.0E-01	1.0E-02	1.0E-03	1.0E-03	8.0E-01
Sb	1.0E-03	6.0E-03	1.0E-03	1.0E-04	1.0E-04	7.0E-02

Table 7. Plant to animal product transfer factors (continued)

Isotope	DandD 1.0 Beef	DandD 1.0 Poultry	RESRAD 5.61 Beef	DandD 1.0 Milk	RESRAD 5.61 Milk	DandD 1.0 Eggs
Te	1.5E-02	8.5E-02	7.0E-03	2.0E-04	5.0E-04	5.2
I	7.0E-03	1.8E-02	7.0E-03	1.0E-02	1.0E-02	2.8
Xe	0.0	0.0	0.0	0.0	0.0	0.0
Cs	2.0E-02	4.4	3.0E-02	7.0E-03	8.0E-03	4.9E-01
Ba	1.5E-04	8.1E-04	2.0E-04	3.5E-04	5.0E-04	1.5
La	3.0E-04	1.0E-01	2.0E-03	2.0E-05	2.0E-05	9.0E-03
Ce	7.5E-04	1.0E-02	2.0E-05	2.0E-05	3.0E-05	5.0E-03
Pr	3.0E-04	3.0E-02	2.0E-03	2.0E-05	2.0E-05	5.0E-03
Nd	3.0E-04	4.0E-03	2.0E-03	2.0E-05	2.0E-05	2.0E-04
Pm	5.0E-03	2.0E-03	2.0E-03	2.0E-05	2.0E-05	2.0E-02
Sm	5.0E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Eu	5.0E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Gd	3.5E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Tb	4.5E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Dy	5.5E-03	4.0E-03		2.0E-05		7.0E-03
Ho	4.5E-03	4.0E-03	2.0E-03	2.0E-05	2.0E-05	7.0E-03
Er	4.0E-03	4.0E-03		2.0E-05		7.0E-03
Hf	1.0E-03	6.0E-05		5.0E-06		2.0E-04
Ta	6.0E-04	3.0E-04	5.0E-06	3.0E-06	5.0E-06	1.0E-03
W	4.5E-02	2.0E-01	4.0E-02	3.0E-04	3.0E-04	8.0E-01
Re	8.0E-03	4.0E-02		1.5E-03		4.0E-01
Os	4.0E-01	1.0E-01		5.0E-03		9.0E-02
Ir	1.5E-03	5.0E-01	2.0E-03	2.0E-06	2.0E-06	1.0E-01
Au	8.0E-03	5.0E-01	5.0E-03	5.5E-06	1.0E-05	5.0E-01
Hg	2.5E-01	1.1E-02	1.0E-01	4.5E-04	5.0E-04	2.0E-01
Tl	4.0E-02	3.0E-01	2.0E-03	2.0E-03	3.0E-03	8.0E-01
Pb	3.0E-04	2.0E-01	8.0E-04	2.5E-04	3.0E-04	8.0E-01
Bi	4.0E-04	1.0E-01	2.0E-03	5.0E-04	5.0E-04	8.0E-01
Po	3.0E-04	9.0E-01	5.0E-03	3.5E-04	3.4E-04	7.0
Rn	0.0	0.0	0.0	0.0	0.0	0.0
Ra	2.5E-04	3.0E-02	1.0E-03	4.5E-04	1.0E-03	2.0E-05
Ac	2.5E-05	4.0E-03	2.0E-05	2.0E-05	2.0E-05	2.0E-03
Th	6.0E-06	4.0E-03	1.0E-04	5.0E-06	5.0E-06	2.0E-03
Pa	1.0E-05	4.0E-03	5.0E-03	5.0E-06	5.0E-06	2.0E-03
U	2.0E-04	1.2E+00	3.4E-04	6.0E-04	6.0E-04	9.9E-01
Np	5.5E-05	4.0E-03	1.0E-03	5.0E-06	5.0E-06	2.0E-03
Pu	5.0E-07	1.5E-04	1.0E-04	1.0E-07	1.0E-06	8.0E-03
Am	3.5E-06	2.0E-04	5.0E-05	4.0E-07	2.0E-06	9.0E-03
Cm	3.5E-06	4.0E-03	2.0E-05	2.0E-05	2.0E-06	2.0E-03
Cf	5.0E-03	4.0E-03	6.0E-05	7.5E-07	7.5E-07	2.0E-03

soil layer box. The thickness of the box is set at 0.15 m for DandD 1.0 and cannot be changed. This limitation is an artifact of the volumetric-source committed effective dose equivalent (CEDE) factors, which are dependent on a soil thickness of 0.15 m.

The well-mixed linear reservoir assumption appears reasonable for the 0.15 m soil layer. In most cases, plowing of the surface layer would keep radionuclides mixed with the soil and the soil layer is relatively thin. Mathematical complications would occur if the upper 0.15 m were not assumed to be well-mixed.

3.1.7.1.2 Unsaturated Zone. DandD 1.0 models the contaminants in the unsaturated zone as a well-mixed linear reservoir with one to ten layers. Input activity enters the unsaturated zone as a dissolved species from the soil plow layer, by infiltration, becomes well-mixed in the unsaturated zone box and then exits to the aquifer by infiltration. Species can be adsorbed onto the soil particles in the unsaturated zone. The unsaturated zone model equation is set up in terms of total radionuclide activity.

Usually, the modeling is done with one layer. However, if the unsaturated zone is thick, more than one modeling layer can be used. DandD 1.0's unsaturated zone model treats the unsaturated zone as a single homogenous unit even though there may be several heterogeneous units. Rather than model heterogeneities, the additional layering is used to reduce the numerical dispersion that is inherent in well-mixed linear reservoir models. This numerical dispersion has a tendency to reduce the contaminant arrival times from the contaminated zone to the aquifer relative to the advective velocity and may dilute the peak concentration depending on the system and the contaminants. These effects may be negligible, offset each other, or one may be dominant. The well-mixed linear reservoir assumption is reasonable for thin unsaturated zones or for thin layers in the unsaturated zone.

3.1.7.1.3 Saturated Zone. The saturated zone in DandD 1.0 is also modeled as a well-mixed linear reservoir. At steady state with no radioactive decay, this model resembles the mass balance aquifer model for RESRAD 5.61 (see below).

Input activity enters the aquifer box from the unsaturated zone box by infiltration, becomes well mixed within the aquifer box, and then exits the aquifer box through either one or two means. First, activity can leave the aquifer box by pumpage for irrigation and domestic use. Most of the pumped water with its corresponding activity is returned to the soil plow layer box and is recycled through the system. Recycling is a reasonable assumption for dry climates where irrigation is present. Second, if the recharge rate through the contaminated area to the aquifer box is larger than the pumping rate, activity can be removed from the aquifer box by natural groundwater flow. This activity is essentially lost from the system because it flows down-gradient from the aquifer box. In the case where the recharge rate is less than the pumping rate, up-gradient aquifer water, which is free of activity, mixes with contaminated aquifer water, thus diluting activity within the aquifer. Given no data about the aquifer, these are reasonable assumptions that maintain the water balance and radionuclide mass balance in the aquifer.

Adsorption of radionuclides onto the aquifer sediments is neglected. In most cases, this is a conservative, simplifying assumption. Adsorption reduces concentrations in the aquifer water and retains the radionuclide on the soil sediments. If a radionuclide is capable of being adsorbed onto the aquifer sediments, the no-retardation assumption tends to cause overestimates of doses from pathways related to use of groundwater. This affects doses from all isotopes except tritium.

3.1.7.1.4 Distribution Coefficients, K_d. Sorption in the unsaturated zone is modeled assuming it can be represented as a linear, reversible, equilibrium process. DandD 1.0 does not account for sorption in the saturated zone. Default distribution coefficient values are provided in Table 8.

The K_d values for the unsaturated zone are element-specific. The default values for these parameters, listed in Table 8, were selected based on a systematic parameter analysis (Beyeler, et al., 1998). The DandD 1.0 code allows the user to specify site-specific values for K_d.

3.1.7.2 RESRAD 5.61 Groundwater Model

3.1.7.2.1 Contaminated Zone. RESRAD 5.61's model of the contaminated zone is designed to provide a source term for the unsaturated zone model and, thus, is formulated in terms of a release rate from the contaminated zone. In RESRAD 5.61's model, the contaminated zone is generally buried and covered with a soil layer, but it may sit at land surface. RESRAD 5.61's model treats the contaminated zone as a well-mixed linear reservoir in that the contaminants are well mixed over the contaminated zone. This seems a reasonable assumption as radionuclides are generally either placed over the entire contaminated zone, or plowing of the soil layer keeps radionuclides well mixed. Transport from the contaminated zone is dependent on the same

Table 8. Default values of distribution coefficients in DandD 1.0 and RESRAD 5.61

Element	DandD 1.0 Value (ml/g)	RESRAD 5.61 Value (ml/g)	Basis for RESRAD 5.61 Value
H	0	na	
Be	929	na	
C	4	na	
F	5	na	
Na	0	10	unknown
P	26	na	
S	99	na	
Cl	5	2	concentration ratio model
K	5	5.5	unknown
Ca	1468	50	unknown
Sc	1	na	
Cr	101	na	
Mn	84	200	unknown
Fe	535	1000	Table E.3 mean for clay & soil*
Co	1515	1000	unknown
Ni	37	1000	Table E.3 mean for clay & soil
Cu	176	na	
Zn	1060	0	unknown
As	114	na	
Se	115	na	
Br	56	na	
Kr	0	na	
Rb	202	na	
Sr	31	30	Table E.3 mean for clay & soil
Y	789	na	
Zr	46616	na	
Nb	1	0	unknown
Mo	26	na	
Tc	7	0	unknown
Ru	1580	0	unknown
Rh	157	na	
Pd	185	na	
Ag	191	0	unknown
Cd	34	0	unknown
In	158	na	
Sn	25	na	
Sb	68268	0	unknown
Te	548	na	
I	0	60	concentration ratio model

*Table E.3 of the RESRAD users manual (Yu, et al., 1993).

Table 8. Default values of distribution coefficients in DandD 1.0 and RESRAD 5.61 (continued)

Element	DandD 1.0 Value (ml/g)	RESRAD 5.61 Value (ml/g)	Basis for RESRAD 5.61 Value
Xe	0	na	
Cs	10	1000	unknown
Ba	44	na	
La	5	na	
Ce	85	1000	Table E.3 mean for clay & soil
Pr	157	na	
Nd	158	na	
Pm	4995	na	
Sm	930	na	
Eu	940	na	
Gd	0	na	
Tb	53	na	
Ho	7	na	
W	156	na	
Re	44	na	
Os	157	na	
Ir	158	na	
Au	157	0	unknown
Hg	157	na	
Tl	158	na	
Pb	2377	100	Table E.3 mean for clay & soil
Bi	443	0	unknown
Po	26	na	
Rn	0	na	
Ra	3529	70	Table E.3 mean for clay & soil
Ac	1726	20	unknown
Th	119	60000	Table E.3 mean for clay & soil
Pa	5	50	unknown
U	2	50	Table E.3 mean for clay & soil
Np	14	na	
Pu	14	2000	Table E.3 mean for clay & soil
Am	1432	20	unknown
Cm	109084	na	
Cf	158	na	

parameters and processes as DandD 1.0. However, thickness of the contaminated zone does not have to be fixed at 0.15 m and can be specified to become thinner with time. The model does not allow for irrigation water to be returned to land surface for recycling through the unsaturated zone back to groundwater. This is a reasonable assumption in humid climates, but not in dry ones. It may result in an underestimate of potential dose when attempting to evaluate irrigated agricultural or gardening doses.

3.1.7.2.2 Unsaturated-Saturated Zone Mass Balance Model. For contaminated areas less than 1000 m^2, RESRAD 5.61 can use a mass balance model to calculate groundwater concentrations. This model treats transport in the unsaturated zone with a travel time model, which is the advection equation (the convective-dispersive equation without the dispersion term). The travel time is the time it takes a radionuclide to reach the top of the aquifer from the bottom of the contaminated zone. In the RESRAD 5.61 model's unsaturated zone, the travel times are called breakthrough times. The breakthrough times are based on infiltration, retardation, and unsaturated zone thickness. Given the travel time rates of radionuclides reaching the aquifer, concentrations based on radioactive decay and in-growth are calculated. Properties of up to five different unsaturated-zone soil-layers can be used in this model.

The mass balance model assumes that a well is pumped from the aquifer in an area located directly below the center of the contaminated area. Because of this assumption, it is further assumed that the travel time of water in the aquifer to the well is zero and the contents of the aquifer are well mixed. This is a reasonable assumption if the saturated zone is small. If volumetric recharge through the contaminated zone is greater than the pumping rate, the concentration in the aquifer is not diluted and is set to the concentration of the infiltrating water, i.e., the dilution factor is 1. However, if the volumetric recharge is less than the pumping rate, then contaminated aquifer water is diluted with enough fresh water that the recharge to the aquifer from infiltration and induced groundwater flow is equal to the pumping rate. In this case, the dilution factor is the ratio of the volumetric infiltration rate to the well pumping rate.

The mass balance is similar to DandD 1.0's well-mixed linear reservoir model for the aquifer.

3.1.7.2.3 Unsaturated-Saturated Zone Non-Dispersive Model. RESRAD 5.61 can use this model for all sizes of contaminated areas. In this groundwater model, transport in the unsaturated zone is calculated in the same manner as for the mass balance model. In the saturated zone, instead of a mass balance, an additional travel time, called a rise time, from the unsaturated-zone/aquifer interface to the well is calculated. This travel time is based on the flow of groundwater and the retardation of radionuclides in the aquifer. The well is assumed to be located in the aquifer at the down-gradient edge of the contaminated area. The additional travel time caused by flow in the saturated zone and neglecting dispersion allows for more radionuclide decay and in-growth before the contaminants reach the well. The non-dispersive assumption maximizes concentration behind the advective front.

The non-dispersive model assumes that the well is pumped from the aquifer at an area located down-gradient from the centerline of the contaminated area. It is assumed that contaminated water entering the well is well mixed and may be diluted with fresh aquifer water if necessary. The degree of dilution is dependent on the aquifer flow rate, the pumping rate, well depth, infiltration rate, and contaminated area size and length. These factors can be combined to calculate a contamination depth and a pumping zone width in the aquifer. Depending on the relationship between contamination depth to the well depth and contamination width to pumping zone width, estimates for a dilution factor can be made. For instance, if the contamination depth is deeper than the well depth and pumping zone width is less than the contaminated zone width, the dilution factor is 1. This reduces to the case where the volumetric recharge is greater than the pumping rate in the mass balance model. However, if the contamination depth is shallower than the well depth and pumping zone is wider than the contaminated zone, the dilution factor is the ratio of the volumetric recharge to the pumping rate. This reduces to the case where the volumetric recharge is less than the pumping rate in the mass balance model. There are two other cases that must be considered and they relate to how the contamination flows through the aquifer. Both cause a dilution of the pumped aquifer water. One depends on the contaminated zone being deeper than the well and the pumping zone being wider than the contaminated zone. The second depends on the contaminated zone depth being shallower than the well depth and the pumping zone width being less than the contaminated zone width.

The RESRAD 5.61 non-dispersive model assumes that dispersion does not occur as a radionuclide travels through the saturated zone to the pumped well. In general, this slows the arrival of a concentration front to the well, but allows for higher concentrations at the well when the travel time is significantly faster than the half-lives of the contaminant. However, since the pumped well is located down-gradient along the centerline of the plume at the edge of the contaminated zone, dispersion may not be significant.

RESRAD 5.61's calculation of the width of the effective pumping zone is a factor of two larger than that predicted by steady-state recharge well theory and the location of the well in relation to the contaminated zone (see Bear, 1979). This calculation is based on an implicit assumption in RESRAD 5.61 that the pumping of the well has no impact on the flow field. In reality, there is a faster, convergent flow as groundwater approaches the pumping well. Potentially, RESRAD 5.61's assumption can produce a pumping zone that is wider than the contaminated zone, while the recharge well theory produces a pumping zone width smaller than the contaminated zone width. As a result, RESRAD

5.61's assumption can produce smaller dilution factors and, thus, an underestimate of groundwater concentrations.

3.1.7.2.4 Distribution Coefficients. Sorption in the unsaturated zone is modeled as a linear, reversible, equilibrium process in the same manner it is in DandD 1.0. In contrast to DandD 1.0, RESRAD 5.61 takes sorption into account in the saturated zone.

The code is designed with default values and allows selection or utilization of four prioritized, alternative models for deriving K_d values. These models, in order of priority, are based on measurements of the groundwater concentration, estimated solubility limits, leach rate, and an empirical model based on the soil-to-plant concentration ratio. Many of the default parameter values appear to be based on the average value for clay and soil as reported in Table E.3 of the RESRAD 5.61 manual (Yu et al., 1993). Some of the K_d values are set to 0, indicating that the radionuclide is not retarded. Others are calculated using the empirical, concentration ratio model.

3.1.8 Surface Water Model

Neither DandD 1.0 nor RESRAD 5.61 model run-off or transport of contaminated sediment to the surface water.

3.1.8.1 DandD 1.0

DandD 1.0's surface water pond model is based on an infinitely fast mass transfer of radionuclides between the aquifer and an aquifer/pond combination. This model restricts the maximum pond concentration to that of the aquifer if the pond volume is small compared to the aquifer volume and prevents the creation of radioactive material if the pond volume is large compared to the aquifer volume.

This model assumes that there are no water sources or losses to the pond that can dilute or concentrate radionuclides from the groundwater. Instead, the pond has a fixed volume with no additional sources or sinks of water or radionuclides. The connection between the aquifer and the pond conserves mass between the two.

3.1.8.2 RESRAD 5.61

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

The assumptions in this model are that the infiltration through the pond watershed area is the only source of water into the pond, all infiltration reaches the pond, the pond discharge is equal to the infiltration volume, and all radionuclides entering the groundwater reach the pond. The model neglects surface water runoff that would flow into the pond and evaporation from the pond surface. To assume that all radionuclides entering the groundwater will also enter the surface water pond is conservative. It may tend to overestimate contaminant concentration into the pond due to groundwater discharge. It is unclear if this overestimation will be offset by dilution.

3.1.9 Groundwater and Surface Water Model Parameters

Groundwater model parameters are shown in Table 9. Some parameters are common to both DandD 1.0 and RESRAD 5.61. Many are not. In some cases, parameters that are input to DandD 1.0 are calculated in RESRAD 5.61 from other parameters. One example is infiltration rate. Table 9 shows that RESRAD 5.61 requires more parameters than DandD 1.0.

Some parameters that appear similar between DandD 1.0 and RESRAD 5.61 are actually different in some respects. DandD 1.0 has a restriction that the distribution coefficients are the same in both the soil layer and the unsaturated zone. RESRAD 5.61 does not have this restriction. DandD 1.0 does not permit retardation of radionuclides in the saturated zone and RESRAD 5.61 does. RESRAD 5.61 uses a total porosity for retardation coefficient calculations and an effective porosity for velocity calculations. DandD 1.0 does not make this porosity distinction. It uses the same porosity for both the retardation coefficient and the box-to-box transfer coefficient calculations.

3.1.10 Tritium Models

There are a number of significant differences between the tritium models utilized in DandD 1.0 and RESRAD 5.61.

3.1.10.1 Airborne Concentrations

3.1.10.1.1 DandD 1.0. DandD 1.0 assumes that tritium only becomes airborne as a constituent of airborne dust. Setting the dust loading value to zero results in a zero inhalation dose in instances where tritium is the only airborne constituent.

Table 9. Comparison of parameters related to groundwater pathways (Default parameter values are shown in parentheses)

Parameter	DandD 1.0	RESRAD 5.61
Contaminated Zone Thickness	Used to calculate transfer factor from the contaminated zone to the unsaturated zone and the aquifer concentration. It is the depth that a plow can be expected to disturb agricultural soil. This value is restricted to 0.15 m because the volumetric CEDE values are based on this depth.	This is an initial thickness, which is used to calculate the release rate of contaminants from the contaminated zone to the unsaturated zone. The contaminated zone thickness is allowed to erode. See "Contaminated Zone Erosion Rate." (2 m)
Unsaturated Zone Thickness	This is the depth from the bottom of the soil plow layer to the top of the water table. Used to calculate the transfer factor from the unsaturated zone to the aquifer. Larger values reduce the transfer factor. (1.2 m)	Used in the calculation of the breakthrough time though the unsaturated zone. A value is specified for each layer in the unsaturated zone. (4 m)
Number of Unsaturated Zone Layers	Used to divide the unsaturated zone to reduce dispersion. All layers have the same properties. (1)	Data on properties, e.g. porosity, hydraulic conductivity, can be supplied separately for one to five layers. (1)
Contaminated Zone Porosity	Used to calculate the transfer factor between the soil layer and the unsaturated zone and the soil layer retardation coefficient. Not broken down into total and effective porosity. (0.46)	See discussions for the "Contaminated Zone Total Porosity" and "Contaminated Zone Effective Porosity" parameters in this table.
Unsaturated Zone Porosity	Used to calculate the transfer factor between the unsaturated zone and the aquifer and the unsaturated zone retardation coefficient. Not broken down into total and effective porosity (0.46)	See discussions for the "Unsaturated Zone Total Porosity" and "Unsaturated Zone Effective Porosity" parameters in this table.
Contaminated Zone Saturation	Used to calculate the transfer factor between the soil layer and the unsaturated zone and the soil layer retardation coefficient. (0.16)	Not input. Calculated instead. Used to calculate the radionuclide release rate from the soil layer to the unsaturated zone and the soil layer retardation coefficient. Calculated from infiltration rate (which itself is calculated), contaminated zone hydraulic conductivity, and the contaminated zone 'b' parameter. Default value would be about 0.8 based on the other default values.
Unsaturated Zone Saturation	Used to calculate the transfer factor between the soil layer and the unsaturated zone, and the soil layer retardation coefficient. (0.16)	Not input. Calculated instead. Used to calculate the unsaturated zone retardation coefficient, which is used to calculate breakthrough times through the unsaturated zone, and to calculate breakthrough times in the unsaturated zone. Calculated from infiltration rate (which itself is calculated), contaminated zone hydraulic conductivity, and the contaminated zone 'b' parameter. Default value would be about 0.8 based on the other default values

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Soil Bulk Density for Contaminated Area	Used in the calculation of the transfer factor from the soil layer to the unsaturated zone and in the concentration in the aquifer layer. (1.4 g/cm^3)	Used in the calculation of the contaminated zone retardation coefficient, which is used to calculate the release rate from the contaminated zone to the unsaturated zone, and in the contaminant release rate from the contaminated zone to the unsaturated zone. (1.5 g/cm^3)
Soil Bulk Density for Unsaturated Zone	Used in the calculation of the transfer factor the unsaturated zone to the aquifer. (1.4 g/cm^3)	Used in the calculation of the unsaturated zone retardation coefficient, which is used to calculate the breakthrough time in the unsaturated zone. A value is specified for each layer in the unsaturated zone. (1.5 g/cm^3)
Volume of Water Removed from Aquifer for Domestic Use per Year	Used to calculate volume of aquifer. (118000 L)	Not used. Uses a total pumping rate instead.
Volume of Surface Water Pond	Used in the calculation of the surface water pond concentration. (1300000 L)	Not used. Uses a contaminated zone area and a watershed area to calculate a dilution factor.
Infiltration Rate	Used in the calculation of aquifer volume if annual volumetric infiltration is greater than annual pumped. (0.25 m/y)	Not directly used. Calculated from precipitation, runoff coefficient, evapo-transpiration coefficient, and irrigation rate. Default value would be 0.5 m/y if calculated from other default values.
Land Area	This is cultivated land area, the assumption being that crops are grown on the site's entire contaminated surface area. Used in the calculation of aquifer volume and aquifer concentration. (2400 m^2)	This is contaminated zone area. Used in the calculation of the release rate of radionuclides from the contaminated zone and the dilution factors. (10000 m^2)
Irrigation Rate	Used in the calculation of the aquifer volume and fraction transfer rate from the aquifer to the soil layer. (1.29 L/m^2-d)	Used in the calculation of infiltration rate (0.2 m/y)
Distribution Coefficient	Used in the calculation of the retardation coefficient. Larger values tend to hold radionuclides in the soil layer and the unsaturated zone; smaller values tend to release contaminants to the groundwater. Same value used for soil layer and unsaturated zone. (Different for various radionuclides)	Not used. Uses "Contaminated Zone Distribution Coefficient" and "Unsaturated Zone Distribution Coefficient" instead. See below.

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Length Parallel to Flow	Not used.	Distance from the up-gradient edge to the down-gradient edge of the contaminated zone in a direction parallel to flow. Used in the calculation of dilution factors for the non-dispersive model. (100 m)
Elapsed Time of Waste Emplacement	Not directly used. This is similar to the start time of the simulation. (0 d)	Time since disposal of radioactive materials. Must be greater than 0 if initial groundwater concentrations will be specified. Used to set time when radionuclide concentrations will be calculated. (0 y)
Cover Depth	Not used.	This is the distance from the top of the contaminated zone to land surface. It is allowed to erode with time. It is used in the decision process of the rise time calculation for the non-dispersive model. (0 m)
Cover Erosion Rate	Not used.	Used to calculate the removal of a cover overlying the contaminated zone. (0.001 m/y)
Contaminated Zone Erosion Rate	Not used.	Used to calculate the removal of the contaminated zone by erosion. Not used until cover is removed. (0.001 m/y)
Contaminated Zone Total Porosity	Not used. See "Contaminated Zone Porosity" above.	Used in the calculation of the contaminated zone retardation coefficient, which is used to calculate contaminant release rate from the contaminated zone to the unsaturated zone. (0.4)
Contaminated Zone Effective Porosity	Not used. See "Unsaturated Zone Porosity" above.	Used in all pathways to calculate water transport breakthrough times (0.2)
Contaminated Zone Hydraulic Conductivity	Not used.	Used in the calculation of the degree of saturation in the contaminated zone, which is used to calculate the contaminant release rate from the contaminated zone to the unsaturated zone. (10 m/y)
Contaminated Zone 'b' Parameter	Not used.	Used in the calculation of the degree of saturation in the contaminated zone, which is used to calculate the contaminant release rate from the contaminated zone to the unsaturated zone. The default value is for a silt loam. (5.3)
Humidity in Air	Not used.	Not used in groundwater model. Used to calculate average equilibrium concentration of hydrogen in air for the special tritium model. (8 g/m3)

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Evapo-transpiration Coefficient	Not used.	Used in the calculation of the infiltration rate. (0.5)
Precipitation	Not used.	Used in the calculation of the infiltration rate, which is used to calculate the contaminant release rate from the contaminated area to the unsaturated zone and the breakthrough times through the unsaturated zone. Default value is for humid areas. (1 m/y)
Irrigation Mode	Not used. Irrigation is assumed to come from groundwater.	Specifies whether irrigation is overhead or ditch. (Overhead)
Runoff Coefficient	Not used.	Used in calculation of infiltration rate. Default value is for areas characterized by flat, sandy-loam soils. (0.2)
Watershed Area for Nearby Stream or Pond	Not used.	Used to calculated dilution factor for contaminants transferred from contaminated area to surface water. (1000000 m^2)
Density of Saturated Zone	Not used.	Used to calculate retardation coefficient in the saturated zone, which is used to calculate rise times for the non-dispersive model. (1.5 g/cm3)
Saturated Zone Total Porosity	Not used.	Used to calculate retardation coefficient in the saturated zone, which is used to calculate rise times for the non-dispersive model. (0.4)
Saturated Zone Effective Porosity	Not used.	Used in the calculation of saturated zone rise times in the non-dispersive model (0.2)
Saturated Zone Hydraulic Conductivity	Not used.	Used in the calculation of Darcy flow rate in the saturated zone, which is used to calculate saturated zone rise times for the non-dispersive model, and dilution factors for the non-dispersive and mass balance models. Default value is for a silty clay loam or sandy clay loam. (100 m/y)
Saturated Zone Hydraulic Gradient	Not used.	Used in the calculation of Darcy flow rate in the saturated zone, which is used to calculate saturated zone rise times for the non-dispersive model, and dilution factors for the non-dispersive and mass balance models. (0.02)

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Saturated Zone 'b' Parameter	Not used.	Used if water table drop greater than 0 to calculate properties, e.g. breakthrough time, of new unsaturated zone that is formed. Default value is for a silt loam. (5.3)
Water Table Drop Rate	Not used.	Used to calculate an additional unsaturated zone layer and increase breakthrough times. (0.001 m/y)
Well Pump Intake Depth	Not used.	Used in the calculation of aquifer dilution factors in the non-dispersive model. (10 m below water table)
Non-dispersion or Mass Balance	Not used.	Chooses between the non-dispersive model and the mass balance model for calculating rise times and dilution factors in the saturated zone. (Non-dispersive)
Well Pumping Rate	Not used. Yearly volumes for domestic use and irrigation groundwater are supplied.	Used in the calculation of dilution factors for the mass balance and non-dispersive models. (250 m^3/y)
Unsaturated Zone Total Porosity	Not used. See "Unsaturated Zone Porosity" above.	Used to calculate unsaturated zone degree of saturation, which is used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. (0.4)
Unsaturated Zone Effective Porosity	Not used. See "Unsaturated Zone Porosity" above.	Used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. (0.2)
Unsaturated Zone Soil Specific 'b' Parameter	Not used.	Used to calculate unsaturated zone degree of saturation, which is used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. Default value is for silt loam. (5.3)
Unsaturated Zone Hydraulic Conductivity	Not used.	Used to calculate unsaturated zone degree of saturation, which is used to calculate unsaturated zone breakthrough times. A value is specified for each layer in the unsaturated zone. Default value is for clay. (10 m/y)
Contaminated Zone Distribution Coefficient	See "Distribution Coefficient" above	Used in the calculation of the retardation coefficient in the soil layer. Larger values tend to hold radionuclides in the unsaturated zone, smaller values tend to release contaminants to the unsaturated zone. (Different for various radionuclides)

Table 9. Comparison of parameters related to groundwater pathways (continued)

Parameter	DandD 1.0	RESRAD 5.61
Unsaturated Zone Distribution Coefficient	See "Distribution Coefficient" above	Used in the calculation of the breakthrough times in the unsaturated zone. Larger values tend to increase breakthrough times, thus increasing decay and ingrowth. (Different for various radionuclides)
Saturated Zone Distribution Coefficient	Not used.	Used in the calculation of the rise time for the non-dispersive model. Larger values tend to increase rise times, thus increasing decay and ingrowth. (Different for various radionuclides)
Leach Rates	Not used.	Used to calculated distribution coefficient if distribution coefficient is not supplied and certain other parameters are. (Radionuclide dependent)
Solubility	Not used.	Used to calculated distribution coefficient if distribution coefficient is not supplied and certain other parameters are. (Radionuclide dependent)

3.1.10.1.2 RESRAD 5.61. RESRAD 5.61 assumes that tritium becomes airborne as tritiated water vapor and as particulate.

RESRAD 5.61 assumes that tritium escapes from the soil, enters the atmosphere, and mixes with the ambient air to a height of the "mixing height" (2 m for people, 1 m for vegetation and animals). The average tritium concentration in air above a contaminated site is assumed to decrease as the wind speed increases. RESRAD 5.61 calculates airborne tritiated water vapor concentrations as proportional to:

$$\frac{\text{Tritium flux} \times (\text{Area})^{0.5} \times \text{Source evasion factor}}{\text{Mixing height} \times \text{Average wind speed}}$$

The mixing height concept is useful for setting a reasonable bound for the outdoor airborne concentrations that may result from small areas contaminated with tritiated water. However, this approach will result in very conservative airborne tritiated water vapor estimates for large areas of soil contaminated with tritium, particularly under unstable atmospheric conditions (that cause substantial vertical mixing).

RESRAD 5.61 assumes that tritium leaves the soil at a rate defined by product of the tritium flux and a source evasion factor. In effect, the source evasion factor is assumed to restrict the tritium inventory available for loss to the atmosphere to that initially present in the upper 30 cm of contaminated soil (the reference evasion depth). With a 30 cm thick cover, RESRAD 5.61 predicts a zero tritium flux.

The evasion source factor causes RESRAD 5.61 to calculate what appear to be non-conservative soil guidelines for scenarios involving burial of soil or debris contaminated with tritiated water. For instance, in a scenario where the only exposure pathway would be inhalation, a 0.3 m cover results in a tritium soil guideline that exceeds the specific activity of HTO.

Particularly under arid climatic conditions, the assumption of a 0.3 m reference evasion depth would appear to be unconservatively low. Arid conditions result in high evaporation rates, and surface soils with a low moisture content. Dry surface soils cause loss of moisture from underlying soils through capillary action. This capillary action will cause transfer of moisture to surface soils and to the atmosphere from depths deeper than 0.3 m.

3.1.10.2 Time Dependence of Soil Tritium Concentrations

DandD 1.0 and RESRAD 5.61 will give rather different results for surface soils contaminated with tritium because:

- the tritium content of surface soils decreases quickly with time due to loss of tritiated water from soils to the atmosphere; RESRAD 5.61's tritium flux model takes this into account, while DandD 1.0 does not;

- RESRAD 5.61 assumes that tritium is transferred from the contaminated zone to the saturated zone more quickly than DandD 1.0;

- the groundwater model in DandD 1.0 recycles irrigation water to the groundwater, while the RESRAD 5.61 model does not;

- RESRAD 5.61 calculates instantaneous dose rates, while DandD 1.0 calculates an integrated dose and reports it as an average rate.

3.1.10.3 Tritium Model Default Values

Default values for DandD 1.0 and RESRAD 5.61 are provided in Table 10.

3.1.10.4 Conclusions about Tritium Models

In conclusion, DandD 1.0 and RESRAD 5.61 model tritium differently.

DandD 1.0 ignores inhalation of tritiated water vapor, while RESRAD 5.61 ignores inhalation of tritium associated with airborne dust. Of these two inhalation exposure routes, inhalation of tritiated water vapor should be the more significant means of exposure. DandD 1.0 would appear to underestimate the inhalation dose due to tritium in many situations since it ignores inhalation of water vapor. This difference in the models has little practical impact in the residential farmer scenario, since the doses from the inhalation pathway are smaller than the doses from water related and agricultural pathways; see Table 11 and Tables A.5, A.10, and A.18 in Appendix A.

RESRAD 5.61's use of a 0.3 m reference evasion depth may result in non-conservative residual material burial guidelines for tritiated debris and soil, particularly in arid areas. This could become a concern in scenarios where a 0.3 m (or greater) cover thickness is included over tritium contaminated soil or debris and groundwater exposure pathways are not included in an exposure scenario. However, this does not cause difficulty in the application of the model to the NUREG/CR-5512 residential farmer scenario. This scenario is only concerned with a 15 cm thick surface layer of contamination with no clean soil cover. RESRAD 5.61 should give reasonable estimates of airborne tritiated water vapor concentrations for small areas having exposed tritium contaminated soils. The limited mixing height will cause airborne concentrations estimated by RESRAD 5.61 to become rather conservative for large contamination areas.

RESRAD 5.61's convention of reporting instantaneous dose rates may complicate the interpretation of simulation results for tritium, since the dose rates it calculates change very rapidly with time. In this report, we took the instantaneous dose rate computed by RESRAD 5.61 at the mid-point of the time intervals (e.g., at six months and at 4.5 years) of interest as representative of annual doses for the first and fifth years to provide a comparison over time.

RESRAD 5.61 simulations suggest that tritium moves out of the contaminated zone far more quickly than DandD 1.0 simulations, even when effort is made to provide comparable input parameters for both models. This result is illustrated by Figure 1. The large difference is related to the tritium flux model that RESRAD 5.61 has but DandD 1.0 lacks, and to the differences in the groundwater models.

With the changes to defaults identified in Tables A.3, A.9, and A.16 for the three residential farmer sub-cases, DandD 1.0 gave consistent maximum dose rates that ranged from 306 mrem/y to 317 mrem/y. In each case, DandD 1.0 identified the agricultural pathway as responsible for about 98% of the dose for the year of maximum dose rate, as shown in Table 11.

RESRAD 5.61 simulations exhibited more variability from case to case. With changes to defaults identified in Appendix sections A.2.1 through A.2.3, RESRAD 5.61 simulation results for the wet climate case showed highest maximal dose rate of 131 mrem/y while simulations for the dry climate case yielded a maximal dose rate of 9.3 mrem/y. Drinking water was the dominant exposure pathway in both of these simulations. The RESRAD 5.61 simulation having minimal changes to defaults gave a maximal dose rate of 4.8 mrem/y at time = 0 with agricultural pathways being dominant.

Tritium behaves in a more complex manner than radioactive isotopes of most other elements due to multiphase transport and barometric and hydraulic driving forces. Both models oversimplify the behavior of tritium in the environment and must be used with caution. As a case in point, neither model considers the potential inhalation exposure from tritium that diffuses through a foundation into a structure. In most respects, RESRAD 5.61 presents a more realistic approach to modeling dose from tritium to an actual residential farmer than DandD 1.0.

Table 10. Special model parameters for tritium

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
Mass Fraction of Hydrogen in Leafy Vegetables	0.10	0.10	In RESRAD 5.61 these are constants.
Mass Fraction of Hydrogen in Root	0.10	0.10	
Mass Fraction of Hydrogen in Fruit	0.10	0.10	
Mass Fraction of Hydrogen in Grain	0.07	0.10	
Mass Fraction of Hydrogen in Beef	0.10	0.066	RESRAD 5.61 value is calculated based on default value in Table L.1 and equation L.21 in Yu et al. (1993).
Mass Fraction of Hydrogen in Poultry	0.10	0.066	RESRAD 5.61 value is calculated based on default value in Table L.1 and equation L.21 in Yu et al. (1993).
Mass Fraction of Hydrogen in Milk	0.11	0.097	RESRAD 5.61 value is calculated based on default value in Table L.1 and equation L.21 in Yu et al. (1993).
Mass Fraction of Hydrogen in Eggs	0.11	NA	Ingestion of eggs is not considered in RESRAD 5.61
Mass Fraction of Hydrogen in Beef Forage	0.10	0.10	In RESRAD 5.61 these are constants.
Mass Fraction of Hydrogen in Poultry Forage	0.10	0.10	
Mass Fraction of Hydrogen in Milk Cow Forage	0.10	0.10	
Mass Fraction of Hydrogen in Layer Hens Forage	0.10	0.10	
Mass Fraction of Hydrogen in Beef Grain	0.07	0.10	
Mass Fraction of Hydrogen in Poultry Grain	0.07	0.10	
Mass Fraction of Hydrogen in Milk Cow Grain	0.07	0.10	
Mass Fraction of Hydrogen in Layer Hens Grain	0.07	NA	Ingestion of eggs is not considered in RESRAD 5.61
Mass Fraction of Hydrogen in Beef Hay	0.10	0.10	In RESRAD 5.61 these are constants.
Mass Fraction of Hydrogen in Poultry Hay	0.10	0.10	
Mass Fraction of Hydrogen in Milk Cow Hay	0.10	0.10	
Mass Fraction of Hydrogen in Layer Hens Hay	0.10	NA	Ingestion of eggs is not considered in RESRAD 5.61
Mass Fraction of Hydrogen in Soil	5.80E-03	NA	
Tritium/hydrogen ratio in animal products relative to ratio in soil product	1.00	1.00	In RESRAD 5.61 these are constants.
Tritium/hydrogen ratio in plants relative to ratio in soil	1.00	1.00	
Tritium/hydrogen ratio in plants relative to ratio in water	1.00	1.00	
Soil Moisture	0.0522	NA	
Average annual wind speed (m/sec)	NA	2.00	

Table 11. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving tritium

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 6.9	DandD 1.0 Year 1	RESRAD 5.61 Year 1.46
Inhalation	3.9E-6	0.37	3.9E-6	0.77	3.9E-6	7.9E-7
Plant	NA	3.46	NA	0	NA	1.2E-5
Meat	NA	0.49	NA	0	NA	1.7E-6
Milk	NA	0.44	NA	0	NA	1.6E-6
Soil Ingestion	8.8E-4	1.75E-3	8.8E-4	0	8.8E-4	0
Water	6.04	0	0.10	5.85	3.19	120
Fish / Aquatic	0.13	0	3.9E-3	0.62	0.096	0.74
Irrig water →→ Plant	NA	0	NA	2.93	NA	0
Irrig water →→ Meat	NA	0	NA	0.26	NA	2.13
Irrig water →→ Milk	NA	0	NA	0.49	NA	7.49
Irrigation pathways	5.36	NA	0.091	NA	2.82	NA
Agriculture	305	NA	305	NA	305	NA
Total	317	4.76	306	9.26	311	131

3.1.11 Carbon–14 Model

Both DandD 1.0 and RESRAD 5.61 have special models for carbon-14. Aspects of those models are described in this section.

3.1.11.1 Airborne Concentrations

The airborne concentration models for carbon-14 in DandD 1.0 and RESRAD 5.61 are similar to the tritium models.

3.1.11.1.1 DandD 1.0. DandD 1.0 assumes that carbon-14 only becomes airborne as a constituent of airborne dust. Setting the dust loading values to zero results in zero inhalation dose in instances where carbon-14 is the only airborne constituent.

3.1.11.1.2 RESRAD 5.61. In effect, RESRAD 5.61 assumes that all carbon-14 released to the atmosphere can be in the form of carbon-14 dioxide and also as carbon-14 contaminated particulate. RESRAD 5.61 models flux and airborne concentrations of carbon-14 dioxide using the same basic model it uses for tritium. However, the carbon-14 reference evasion depth is a parameter that can be adjusted by the user in RESRAD 5.61.

3.1.11.2 Time Dependence of Soil Carbon-14 Concentrations

DandD 1.0 and RESRAD 5.61 will give rather different results for soils contaminated with carbon-14 because:

- the carbon-14 content of surface soils decreases due to loss to the atmosphere. RESRAD 5.61 takes this into account while DandD 1.0 does not;
- the groundwater model in DandD 1.0 recycles irrigation water to groundwater, while RESRAD 5.61 does not;
- RESRAD 5.61 calculates an instantaneous dose rate, while DandD 1.0 calculates the average dose received over a year.

The simulation results presented in Appendix A demonstrate that there is a considerable difference in time dependence of carbon-14 doses between DandD 1.0 and RESRAD 5.61 for residential farmer scenarios. These results differences are depicted in Figure 2. DandD 1.0 estimates higher dose rates at years one and five under each of the residential farmer scenarios considered (see Tables A.6, A.11, and A.19). However, RESRAD 5.61 calculates very high maximum instantaneous dose rates under the dry site scenario (62,990 mrem; see Table A.11). In every case, carbon-14

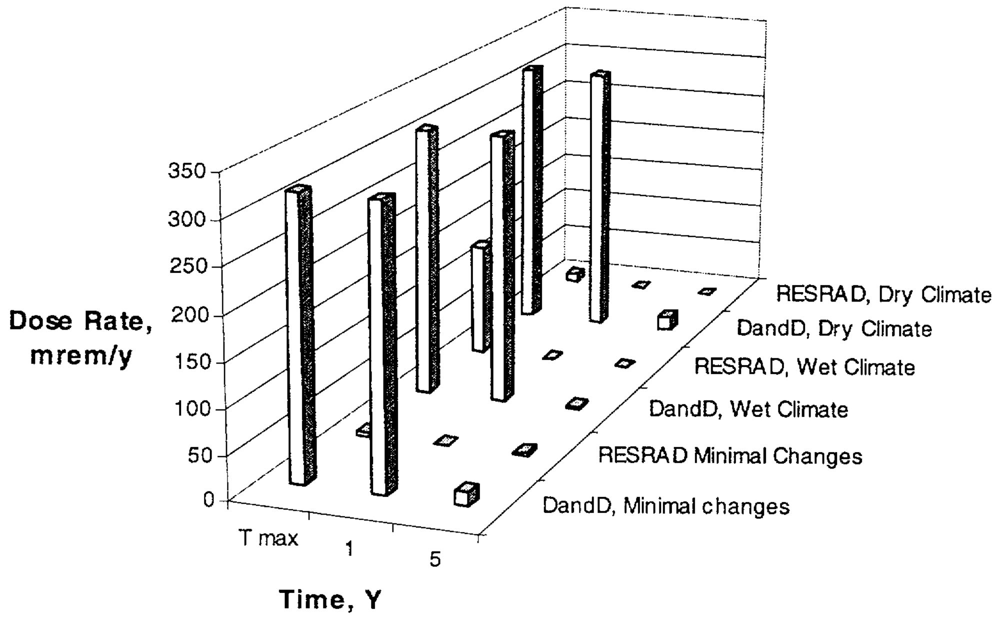

Figure 1. Comparison of tritium results for DandD and RESRAD

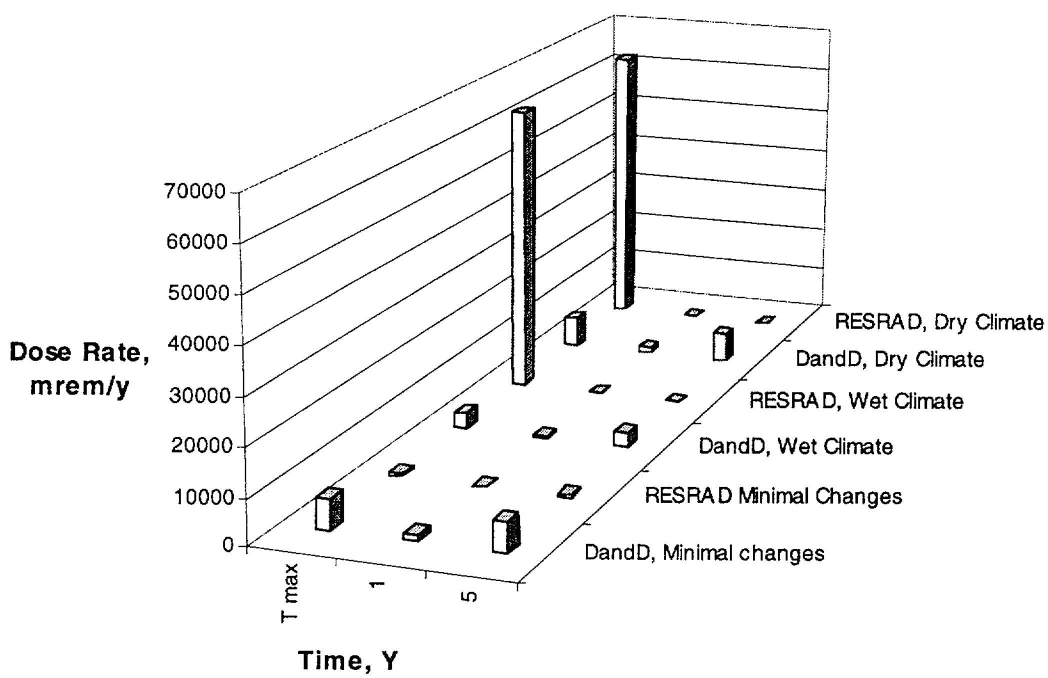

Figure 2. Comparison of Carbon-14 results for DandD and RESRAD

reached the well sooner in DandD 1.0 simulations than in RESRAD 5.61 simulations. With both models, the aquatic pathway was dominant once carbon-14 reached the well.

The maximum dose rates occurring with simulations having minimal changes to defaults occurred at five years (DandD 1.0, 6,460 mrem/y) and at 0 years (RESRAD 5.61 659 mrem/y). The maximum dose rates occurring with simulations representative of a dry climate occurred at 63 years (DandD 1.0, 390 mrem/y) and at 143 years (RESRAD 5.61 62,990 mrem/y).

3.1.11.3 Default Values for the Carbon-14 Models.

Default values for the carbon-14 models in DandD 1.0 and RESRAD 5.61 are provided in Table 12.

3.1.11.4 Carbon-14 Uptake by Plants.

RESRAD 5.61 assumes that carbon assimilated by plants comes primarily from the atmosphere (default 98%) and only a small amount of carbon-14 uptake occurs through the root system (default 2%). The soil-to-plant transfer factor used in RESRAD 5.61 contains terms that take both of these processes into account. The term for uptake from the atmosphere is dominant when default factors are used. In this case, the transfer factor is proportional to the square root of the area of carbon-14 contamination (Yu, et al., 1993).

The RESRAD 5.61 results provided in Table A.19 were obtained with both the reference depth and assimilation fractions set to the default values.

DandD 1.0 makes the simplifying assumption that the soil-to-plant transfer factors are simply a ratio of concentration of carbon-14 in the plant to the concentration in the soil. The DandD 1.0 model assumes that the transfer coefficient is independent of the surface area of the contaminated zone. The RESRAD 5.61 model for carbon-14 soil-to-plant transfer factors is based on the assumption that the soil-to-plant concentration ratio is a function of the surface area of contaminated zone. The approach taken in RESRAD 5.61 that most carbon-14 is assimilated by plants from the atmosphere is more realistic.

3.1.11.5 Conclusions about the Carbon-14 Models

For the purposes of determining compliance with 10 CFR 20 subpart E, the RESRAD 5.61 convention of reporting instantaneous dose rates complicates interpretation of simulation results as annual dose for scenarios involving carbon-14. The dose rate RESRAD 5.61 calculates for carbon-14 changes rapidly with time. Nonetheless, the maximum instantaneous dose rate reported by RESRAD 5.61 should be a conservative estimate of the annual dose.

DandD 1.0 ignores inhalation of gaseous carbon-14 compounds while RESRAD 5.61 considers inhalation of carbon-14 associated with airborne dust and gaseous compounds. Of these two inhalation exposure routes, inhalation of gaseous carbon-14 compounds should be the more significant means of exposure. This difference in the models has little practical impact in the residential farmer scenario of NUREG/CR-5512. In this scenario, the doses due to carbon-14 from water-related and agricultural pathways are much larger than the inhalation doses; see Table 13 and Appendix Tables A.6, A.11, and A.19.

RESRAD 5.61 has a carbon-14 flux model, while DandD 1.0 does not. In RESRAD 5.61 the carbon-14 reference evasion depth can be adjusted by the user. This feature allows RESRAD 5.61 to simulate the natural processes of volatilization and oxidation of carbon-14 compounds in surface soils. Neither model considers the potential inhalation dose that may result from diffusion of carbon-14 compounds through a foundation into an occupied structure, however.

RESRAD 5.61 has a more realistic formulation of soil-to-plant transfer factor than DandD 1.0, since it takes into account that atmospheric carbon dioxide is the principal source of carbon assimilated by plants.

Like tritium, carbon-14 behaves in a more complex manner than radioactive isotopes of most other elements. Because of this complexity, both the special carbon-14 models in RESRAD 5.61 and DandD 1.0 should be used with caution. In most respects, RESRAD 5.61 presents a more realistic approach to modeling dose from carbon-14 to an actual residential farmer than DandD 1.0.

3.1.12 External Exposure from Volume Soil Sources while Outdoors

DandD 1.0 assumes an infinite slab of contamination 6 inches thick. A six-inch-thick infinite area slab of soil contaminated with cesium-137 would have an Effective Dose Equivalent (EDE) rate that is about 89% of the EDE rate of a slab that is infinite in area and thickness (EPA, 1993). Consequently the external dose pathway will give reasonable dose estimates for thicker layers or contaminated soil. For contaminated areas smaller than about 500 m^2 or thinner than 15 cm, DandD 1.0 will

Table 12. Special model parameters for carbon

Parameter	DandD 1.0 Default	RESRAD 5.61 Default	Remarks
C-12 concentration in water (g/cm**3)	NA	2.00E-05	
C-12 concentration in contaminated soil (g/g)	0.03	0.03	
Fraction of vegetation carbon from soil	1.00	2.00E-02	
Fraction of vegetation carbon from air	0.00	9.80E-01	
C-14 evasion layer thickness in soil (m)	NA	3.00E-01	
C-14 evasion flux rate from soil (1/sec)	NA	7.00E-07	
C-12 evasion flux rate from soil (1/sec)	NA	1.00E-10	
Mass Fraction of Carbon in Beef	0.36	0.24	In RESRAD 5.61, these values are constants.
Mass Fraction of Carbon in Poultry	0.18	0.24	
Mass Fraction of Carbon in Milk	0.06	0.07	
Mass Fraction of Carbon in Eggs	0.16	NA	
Mass Fraction of Carbon in Beef Forage	0.11	0.09	
Mass Fraction of Carbon in Poultry Forage	0.11	0.09	
Mass Fraction of Carbon in Milk Cow Forage	0.11	0.09	
Mass Fraction of Carbon in Layer Hen Forage	0.11	0.09	
Mass Fraction of Carbon in Beef Grain	0.40	0.40	
Mass Fraction of Carbon in Poultry Grain	0.40	0.40	
Mass Fraction of Carbon in Milk Cow Grain	0.40	0.40	
Mass Fraction of Carbon in Layer Hen Grain	0.40	0.40	
Mass Fraction of Carbon in Beef Hay	0.07	0.40	
Mass Fraction of Carbon in Poultry Hay	0.07	0.40	
Mass Fraction of Carbon in Milk Cow Hay	0.07	0.40	
Mass Fraction of Carbon in Layer Hen Hay	0.07	0.40	
C-14/C-12 activity in animal products relative to ratio in soil	1	NA	
Average annual wind speed (m/sec)	NA	2.00	

Table 13. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving carbon-14

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 5	RESRAD 5.61 Year 0	DandD 1.0 Year 63	RESRAD 5.61 Year 143	DandD 1.0 Year 8	RESRAD 5.61 Year 27.5
External	5.3E-4	8.0E-3	7.1E-4	0	4.3E-4	0
Inhalation	1.0E-5	0.398	1.4E-5	0	8.5E-6	0
Plant	NA	495	NA	0	NA	0
Meat	NA	115	NA	0	NA	0
Milk	NA	49.1	NA	0	NA	0

Table 13. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving carbon-14 (continued)

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 5	RESRAD 5.61 Year 0	DandD 1.0 Year 63	RESRAD 5.61 Year 143	DandD 1.0 Year 8	RESRAD 5.61 Year 27.5
Soil Ingestion	2.4E-3	0.057	3.2E-3	0	2.0E-3	0
Water	57.5	0	1.84	12.7	24.9	230
Fish / Aquatic	5,580	0	324	62,900	3,440	62,800
Irrig water →→ Plant	NA	0	NA	24.2	NA	0
Irrig water →→ Meat	NA	0	NA	3.51	NA	7.42
Irrig water →→ Milk	NA	0	NA	4.47	NA	27.8
Irrigation pathways	813	NA	53.4	NA	22.9	NA
Agriculture	9.58	NA	12.9	NA	7.88	NA
Total	6,460	659	392	63,000	3,500	63,100

The external exposure model in RESRAD was updated with version 5.50. The external exposure model in an earlier version of RESRAD 5.61 (RESRAD 5.05) is well documented.[1] RESRAD 5.05 contains tables of EDE rates per unit activity for two different soil densities. RESRAD 5.05 estimates dose rates by performing a series of interpolations and by application of the correction factors described in Table 14.

A comparison of external dose rates among DandD 1.0, RESRAD 5.61, and Microshield® 5.03 is presented in Appendix A (Table A.25). For an infinite slab of soil 6 inches (15 cm) thick, all three codes give good agreement when consistent occupancy and shielding factors are used.

3.1.13 External Exposure from Volume Soil Sources while Indoors

Both RESRAD 5.61 and DandD 1.0 model this pathway by applying correction factors to the outdoor external dose rate. Calculation of the external dose rate is described in section 3.1.1 and Table 14. The correction factors applied to the external dose rate include a shielding factor and an occupancy factor. Both models provide default attenuation factors that are assumed to be independent of gamma energy. The correction for exposure occurring indoors is of the same form for both RESRAD 5.61 and DandD 1.0:

Indoor exposure to volume soil sources
$\propto$ Shielding Factor × External Exposure (Eq. 1)

Where the Shielding Factor in Eq. 1 is:

1 - Attenuation Fraction.

In fact, the shielding factor will differ with the method of construction (slab on grade as compared to mobile home or pier and beam), with the materials of construction (wood siding as compared to brick or stone), and with the gamma radiation energy.

Alternative shielding factors may be measured directly or estimated. Estimates of shielding factors can be derived from use of shielding models such as Microshield® 5.03 (Grove Engineering, 1998). Caution should be exercised in deriviation of alternative shielding factors using shielding models. Individual simulations may have a 15% margin of error or more. Deriving structural shielding estimates by modeling involves mathematical manipulation of several simulation results; this may result in shielding factor estimates that contain considerable accumulated error.[2]

3.1.14 Inhalation Exposure to Resuspended Soil while Outdoors

This pathway is described in Table 15.

1 a description of the new model is on the RESRAD web page http://www.ead.anl.gov/~resrad/

2 The same is true of other similar shielding codes.

Table 14. External exposure from volume soil sources

Factor	DandD 1.0	RESRAD 5.05
Basic DCF for volume contamination of soil	Infinite layer, 15 cm thick. Effective Dose Equivalent dose conversion factors are taken from FRG-12.	Infinite in depth and areal extent.
Bremstrahlung for beta emitters	Included	Neglected.
Correction for soil density	none	Interpolation or extrapolation based on values tabulated for density = 1.0 g/cm^3 and 1.8 g/cm^3 (Table A.1).
Correction for areal extent	none	Interpolation based on a table of area correction factors that are not dependent on radionuclide or energy. (Table A.2)
Correction for depth of contamination	none	A correction for depth is applied that depends on nuclide. The value of the correction is based on interpolations between values tabulated for two soil densities as well as contamination depths (Table A.3, Equation A.2).
Time dependence for thickness of contaminated zone	none	Erosion of contaminated zone is assumed to occur in a linear fashion once the cover has been eroded away. 1 mm/y default erosion rate. Equation A.4.
Cover attenuation correction outdoors	Default value of 1. Alternate values may be calculated by the user and input into program.	Correction for cover attenuation is interpolated from Table A.3, Equation A.5.
Time dependence for thickness of contaminated zone.	none	Cover is assumed to erode at a linear rate. Default of 1 mm/y is provided.
Correction for attenuation provided by a structure.	A default value of 0.55 is provided. Alternate values must be calculated by user and input into program.	A default value of 0.7 is provided. Alternate values must be calculated by user and input into program.
Correction for fractions of time spent outdoors, indoors and in uncontaminated areas.	Default values of 240 d/y (66%) inside, 40.2 d/y (11%) outside, 2.92 d/y (0.8%) outside engaged in gardening activities, 82.13 d/y (23%) in uncontaminated areas provided.	Default values of 50% inside, 25% outside and 25% in uncontaminated areas are provided.

Table 15. Factors related to EDE resulting from inhalation exposure to resuspended soil while outdoors

Factor	DandD 1.0	RESRAD 5.61
Outdoor airborne dust concentration (non-gardening outdoor activities)	DandD 1.0 currently uses a default airborne dust mass loading value of 3.14 μg/m³.	RESRAD 5.61 uses a default outdoor airborne concentration of 200 μg/m³.
Outdoor airborne dust concentration (gardening only)	DandD 1.0 currently uses a default airborne dust mass loading value of 400 μg/m³.	Not separately considered.
Correction to airborne dust concentration due to finite size of contaminated area.	None	RESRAD 5.61 uses an area factor that represents the fraction of airborne mass loading of dust that is contaminated. The area factor takes the Form: $FA_2 = (Area)^{0.5}/((Area)^{0.5} + DL)$, Where Area is the area that is contaminated and DL is the dilution length. A default dilution length of 3 m is provided.
Allowance for dilution of contaminated soil with a mixing layer	None	Assumes that mixing occurs over the upper 15 cm of soil. When the cover is less than 15 cm thick, mixing of the cover with the contaminated layer is assumed. When no cover is present and the contaminated layer is less than 6 inches thick, mixing with sub-soils is assumed (Yu, 1993, Eq. B.5).
Correction for occupancy	Yes; defaults are 2.92 d/y gardening; 40.2 d/y other outdoor activities.	Yes; a default occupancy factor of 0.25 is provided.
Respiration rate	1.4 m³/h for non-gardening outdoor activities; 1.7 m³/h for gardening outdoor activities	Default value of 8400 m³/y (0.96 m³/h).

DandD 1.0 assumes that a certain airborne dust concentration is present due to resuspension of contaminated dust, and that the airborne dust concentration is independent of the size of the contaminated area. The default air mass loadings given in Table 4 are reasonable given that gardening is modeled as a distinct outdoor activity.

RESRAD 5.61 assumes that the contaminated fraction of airborne dust is related to the size of the contaminated area; the contaminated fraction is modeled by an empirical formula (Eq. 2).[3]

$$\frac{\text{Area of Contamination}^{1/2}}{\text{Area of Contamination}^{1/2} + \text{Dilution Length}} \quad \text{(Eq. 2)}$$

Using the default dilution length value of 3 meters in Eq. 2 leads to rather high contamination fraction results for small contaminated areas. This becomes apparent when one considers that the terminal settling velocity of 10 μm particles of density 2.3 g/cm³ is on the order of 0.6 cm/s (Burton, 1984), and the average wind speed at the ground surface is about 2 m/s. This high contamination fraction estimate is of little consequence in the residential farmer scenario unless one is concerned about potential dose from hot spots of residual radioactivity following a remedial action.

The default outdoor mass loading assumed by RESRAD-5.61, 200 μg/m³, seems high for a time weighted average

[3] An improved area factor model for airborne concentrations has been incorporated into RESRAD versions 5.75 and later (Chang et al., 1998). The new area factor is based on a Gaussian plume model.

concentration in the breathing zone, particularly for insoluble isotopes whose dose is primarily the result of deposition in the pulmonary region of the lung.[4]

3.1.15 Inhalation Exposure to Resuspended Soil while Indoors, and to Resuspended Surface Sources of Soil Tracked Indoors

Both DandD 1.0 and RESRAD 5.61 model the inhalation exposure to dust occurring indoors. The differences in approach are described in Table 16. To summarize, RESRAD 5.61 models indoor inhalation exposures taking into consideration only the outdoor air mass loading and a scale factor. DandD 1.0 includes two indoor dust inhalation pathways: resuspension of dust tracked indoors, and infiltration of airborne dust from outdoors. DandD 1.0 requires three inputs:

- the floor dust loading factor,
- a resuspension factor, and
- the indoor airborne dust loading from processes other than resuspension of dust tracked into the structure.

The approaches taken by either model should be suitable for dose screening purposes.

3.1.16 Plant – Human Pathways

Assumptions common to all Plant – Human pathways are provided in Table 17. DandD 1.0 assumes that plant foods are held briefly upon harvest, and then consumed over a period of time. RESRAD 5.61 does not take into account that plant foods may be consumed over a period of time. DandD 1.0 also calculates an average dose received over a year while RESRAD 5.61 calculates an instantaneous dose rate.

Default values for Plant—Human pathways are provided in Table 4.

3.1.16.1 Irrigation Water— Plant— Human Pathways

The irrigation water – plant – human pathways include the following:

- Irrigation water – plant – human (retention of irrigation water on leaf surfaces),
- Irrigation water – soil – plant –human.

These pathways are discussed in section 5.4.1 of NUREG/CR 5512 Volume 1 and in Appendix D of the RESRAD manual (Yu et al., 1993). DandD 1.0 and RESRAD 5.61 use the same fundamental approach to modeling the doses due to the irrigation – plant – human pathways. Assumptions common to all irrigation water – plant – human pathways are summarized in Table 18. However, there are important differences in the groundwater models that cause differences in the doses from these pathways. The time dependence and magnitude of dose rates from groundwater related pathways tended to be very different in this study. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, DandD 1.0 simulations showed contaminants at the well sooner than RESRAD 5.61 simulations, but maximal dose rates were not always higher with one model or the other.

The irrigation water – soil – plant – human pathway in both DandD 1.0 and RESRAD 5.61 assumes that soil-to-plant transfer factors depend on radioisotope but are independent of soil type and largely independent of the plant species. Soil-to-plant transfer factors may be modified by users in both DandD 1.0 and RESRAD 5.61.

3.1.16.2 Soil—Plant—Human Pathways

The soil – plant – human pathways include the following

- Soil – root uptake by plant – human,
- Soil – resuspension and deposition on plant surfaces – human.

These pathways are discussed in section 5.3.1 of NUREG/CR 5512 Volume 1 and in Appendix D of Yu et al. (1993). DandD 1.0 and RESRAD 5.61 use fundamentally the same approach to modeling the doses due to these pathways.

The basic assumptions in the soil-to-plant (root uptake) pathways are:

- those inherent in the use of soil-to-plant transfer factors (both DandD 1.0 and RESRAD 5.61), and
- the plant concentration for each decay chain member radionuclide is in equilibrium with the soil concentrations at all times.

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[4] The default value for outdoor mass loading has been decreased to 100 $\mu g/m^3$ in RESRAD version 5.781 and later.

Table 16. Inhalation exposure to resuspended soil while indoors

Factor	DandD 1.0	RESRAD 5.61
Indoor Airborne Dust Concentration	DandD 1.0 is supplied with a default airborne indoor dust mass loading value of 1.41 μg/m^3. This value is modeled as independent of the outdoor mass loading value. The concentration does not include the contribution from dust tracked indoors.	RESRAD 5.61 applies a scale factor to outdoor airborne dust loading to obtain the indoor dust loading. The default indoor airborne dust loading is 80 μg/m^3. This value follows from the default outdoor airborne concentrations of 200 μg/m^3 and a scale factor of 0.4.
Indoor Airborne Dust Concentration Resulting from Resuspension of Dust Tracked Indoors	DandD 1.0 multiplies a resuspension factor by a floor dust loading to obtain a resuspension concentration. The default values of 2.82E-6 m^{-1} (resuspension) and 0.1599 g/m^2 (floor dust loading) provide an default value of 0.45 μg/m^3 for Indoor Airborne Dust Concentration Resulting from Resuspension	Not distinguished from the Indoor Airborne Dust Concentration described above.
Total Indoor Airborne Dust Concentration	Sum of the Indoor Airborne Dust Concentration and the Indoor Dust Concentration resulting from resuspension.	RESRAD 5.61 takes the Total Indoor Airborne Dust Concentration to be the product of the Outdoor Airborne Dust Loading and a scale factor. Resuspension of dust tracked indoors is not *explicitly* included.
Correction for occupancy	Yes; default is 240 days per year	Yes, default is 0.5 (equivalent to 182.6 d/yr for 365.25 d simulation).

Table 17. Assumptions related to all plant – human pathways

Factor	DandD 1.0	RESRAD 5.61
Harvested plants are held for a short period of time prior to consumption by humans.	Yes. Radioactive decay during the hold-up period between harvest and commencement of consumption is taken into account. The default values are dependent on the food item. Defaults are provided in Table 2.	Same as DandD.
Radioactive decay over the food consumption period is taken into account	Yes. Food products are assumed to be consumed over a period of one year. This is taken into account by NUREG/CR-5512, Eq. 5.9.	Not accounted for.

Table 17. Assumptions related to all plant – human pathways (continued)

Factor	DandD 1.0	RESRAD 5.61
Corrections for areal extent of contamination and contamination fraction for the plant – human pathway.	There is no specific correction for areal extent of contamination for this pathway. The users can manually enter a single value for contamination fraction, which is applied, to all food types. The default fraction is 1.0.	RESRAD 5.61 uses corrections to account for areal extent of contamination as the default option. The default action has the effect of calculating the contamination fraction of "plant food" ingested (Yu, 1993, Eq D.5). The user may enter a single contamination fraction for "plant food." See Table 4 for the means RESRAD 5.61 uses to calculate a contamination fraction.
Adjustments to the dietary intake of plant foods	The user may specify annual ingestion rates for four different plant groups: leafy vegetables, fruits, roots and grains.	The user may specify separate annual ingestion rates for two different plant groups: (1) leafy vegetables, and (2) fruits, vegetables and grains.
Is equilibrium assumed to continually occur between the radionuclide concentrations in soil and radionuclide concentrations in edible portions of the plant.	Yes.	Yes.
Translocation of material deposited on plant surfaces to edible portions of plant.	Adjustable by user.	Not adjustable in RESRAD 5.61 but can be adjusted in version 5.82.

Table 18. Assumptions related to all irrigation water – plant – human pathways

Factor	DandD 1.0	RESRAD 5.61
Time dependence of the concentration of radionuclides in irrigation water.	Assumed constant over growing season at the average value.	RESRAD 5.61 computes the concentration at an instant in time.
Is there a distinction between overhead irrigation and ditch irrigation?	Yes. The default settings in DandD 1.0 are appropriate for overhead irrigation. To model ditch irrigation, the Translocation Factors should be set to zero.	Yes. Overhead irrigation is the default.

Table 18. Assumptions related to all irrigation water – plant – human pathways (continued)

Factor	DandD 1.0	RESRAD 5.61
Deposition of contaminated irrigation water on foliage.	Yes. The default settings of DandD 1.0 assume that overhead irrigation occurs; that a portion of the radioactivity in irrigation water equal to the interception fraction (r_v) is retained on the plant, and that "translocation" of a portion of this activity (T_v) to edible portions of the plant occurs.	In the case of ditch irrigation, no deposition of contamination from irrigation water onto foliage is assumed to occur. RESRAD 5.61 and DandD 1.0 use the same approach to model overhead irrigation.
Removal of contaminants deposited on plant surfaces from irrigation water.	The translocated activity from overhead irrigation is assumed to be removable through weathering, with a weathering constant of 0.0495 per day.	RESRAD 5.61 and DandD 1.0 use the same approach to modeling the removal of activity deposited by overhead irrigation. RESRAD 5.61 uses a weathering constant of 0.055 per day.
Is radioactivity deposited in the soil from irrigation water removed by both leaching and radioactive decay?	Yes. By decay during the timestep it is deposited (eq. 5.26 NUREG/CR 5512 V1) and by leaching after the deposition timestep.	Yes. For the purposes of this pathway, it is assumed to be re-moved by both radioactive decay and leaching.
Is mixing of contaminated layer with uncontaminated soil taken into account?	No.	Not applicable to these pathways.

The (soil-to-plant) resuspension and deposition pathway in DandD 1.0 and RESRAD 5.61 differ notably. DandD 1.0 assumes that there is a static ratio between radionuclide concentrations in dried plant foods and in soil on a pCi/kg basis (NUREG/CR 5512, Eq. 5.5); this ratio is called the mass loading factor (ML_v). The default value of 0.1 used by DandD 1.0 suggests that dried foods could be 10% soil by weight. This value seems too high for plant foods consumed by humans. For several isotopes, this value leads to much higher dose agricultural pathway estimates in DandD 1.0 simulations than in RESRAD 5.61 simulations (see Tables 19, 20, and Appendix A).

RESRAD 5.61 assumes a kinetic relationship between these quantities:

- there is a constant deposition rate,
- removal is controlled by a first order weathering constant, and
- deposition and removal occur over the growing season (Yu, et al., 1993).

During the comparison of DandD 1.0 and RESRAD 5.61, it was found that with DandD 1.0 the default mass loading factor dominated the ingestion dose for radionuclides that do not have a high degree of root uptake by plants. This was particularly notable for the thorium-232 (Table 20) and radium-226 decay chains (Table 19).

In reviewing the basis for the default mass loading factors in NUREG/CR 5512 volume 1, it was found that the data used to support the default value are for unwashed produce, roots, leafy vegetables, grain, and forage crops. While these data may be appropriate for estimating animal ingestion of soil, they are not appropriate for estimating human consumption. Sheppard (1995) compiled soil loading data for washed, edible portions of plants and reports that the geometric mean of the data is 0.001 grams of soil per gram of dry plant, indicating that the default mass loading factor for vegetation consumed by humans could be reduced by as much as two orders of magnitude. The data for mass loading reported in Sheppard (1995) for human food products range from a minimum value of 0.00003 for harvested grain to 0.008 for washed root crops. It is

Table 19. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving radium-226 with progeny

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 80	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 4	RESRAD 5.61 Year 0
External	3,780	5,630	4,610	5,340	4,590	5,340
Inhalation	1.31	23.3	1.98	1.24	1.94	1.24
Radon	NA	25,900	NA	30,800	NA	30,800
Plant	NA	1,830	NA	1,830	NA	1,830
Meat	NA	153	NA	153	NA	153
Milk	NA	113	NA	113	NA	113
Soil Ingestion	80.0	235	123	243	122	243
Water	2,550	0	0.552	0	137	0
Fish / Aquatic	21,900	0	7.05	0	1,520	0
Irrig water →→ Plant	NA	0	NA	0	NA	0
Irrig water →→ Meat	NA	0	NA	0	NA	0
Irrig water →→ Milk	NA	0	NA	0	NA	0
Irrigation pathways	3,290	NA	1.74	NA	11.0	NA
Agriculture	26,200	NA	40,400	NA	39,900 *	NA
Total	57,800	33,900	45,200	38,500	46,300	38,500

* Decreasing the plant mass loading value from 0.1 to 0.01 for plant foods directly consumed by humans decreases the EDE from the agricultural pathway from 39,900 to 8,380 mrem/y.

Table 20. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving thorium-232 with progeny

Pathway	Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0.17	DandD 1.0 Year 1	RESRAD 5.61 Year 0
External	6,530	7,596	6,530	7,600
Inhalation	122	77.3	122	77.3
Radon	NA	334	NA	334
Plant	NA	891	NA	886
Meat	NA	48.9	NA	48.4
Milk	NA	57.6	NA	57.6
Soil Ingestion	70.5	141	70.5	141
Water	0.058	0	4.35	0
Fish / Aquatic	0.21	0	12.7	0
Irrig water →→ Plant	NA	0	NA	0

Table 20. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving thorium-232 with progeny (continued)

Pathway	Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0.17	DandD 1.0 Year 1	RESRAD 5.61 Year 0
Irrig water →→ Meat	NA	0	NA	0
Irrig water →→ Milk	NA	0	NA	0
Irrigation pathways	0.20	NA	6.6E-3	NA
Agriculture	19,400	NA	19,400*	NA
Total	26,100	9,150	26,100**	9,141

*Decreasing the plant mass loading value from 0.1 to 0.01 for plant foods directly consumed by humans decreases the EDE from the agricultural pathway from 19,400 to 2,020 mrem/y.
**This value decreases to 9,520 mrem/y if the if the plant mass loading is decreased to 0.01.

recommended that the sources on mass loading data in Sheppard (1995), NUREG/CR 5512, and more recent studies be evaluated to provide a PDF for each class of vegetation and feed crop in the DandD 1.0 model.

3.1.17 Animal Product – Human Pathways

Animal product – human pathways may be subdivided into those involving irrigation water and those involving soil. DandD 1.0 assumes that animal products are held briefly upon harvest, and then consumed over a period of time. RESRAD 5.61 does not take into account that animal products may be consumed over a period of time. DandD 1.0 also calculates an average dose received over a year while RESRAD 5.61 calculates an instantaneous dose rate.

Default values for animal product – human pathways are provided in Table 4.

3.1.17.1 Irrigation Water – Animal Product – Human Pathways

Assumptions common to all these pathways are summarized in Table 21.

Both RESRAD 5.61 and DandD 1.0 allow the user to specify the contamination fraction of irrigation water used for livestock. RESRAD 5.61 also allows the user to specify whether irrigation water is surface water or well water. The irrigation water – animal product – human pathways include the following:

- Irrigation water – forage – animal product – human (Table 22),
- Irrigation water – soil – forage – animal product – human (Table 23),
- Irrigation water – stored hay – animal product – human (Table 24),
- Irrigation water – soil – stored hay – animal product – human (Table 25),
- Irrigation water – stored grain – animal product – human (Table 24),
- Irrigation water – soil – stored grain – animal product – human (Table 25),
- Irrigation water – soil – animal product – human (Table 26)
- Irrigation water – animal product – human,

These pathways are generally discussed in section 5.4.2 of NUREG/CR-5512 Volume 1 and in Appendix D of Yu et al. (1993). DandD 1.0 and RESRAD 5.61 use fundamentally the same approach to modeling the doses due to the irrigation water – animal product – human pathways. However, there are important differences in the groundwater models that cause differences in the doses from these pathways. The time dependence and magnitude of dose rates from groundwater-related pathways tended to be very different in this study. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, DandD 1.0 simulations had faster arrival times for contaminant to the well, but the DandD 1.0 maximal dose rates for these pathways were not always higher.

Table 21. Assumptions common to all irrigation water – animal product – human pathways

Factor	DandD 1.0	RESRAD 5.61
Time dependence of concentrations of radionuclides in irrigation water.	Assumed constant over the growing season (i.e. an annual average concentration is used).	RESRAD 5.61 computes the concentration at an instant in time.
Material deposited onto plant surfaces is assumed to be removed at a rate determined by a weathering constant.	Yes. The translocated activity from overhead irrigation is assumed to be removable through weathering, with a weathering constant of 0.0495 per day. The weathering rate may be changed by the user.	Yes. RESRAD 5.61 and DandD 1.0 use the same approach to modeling the removal of activity deposited by overhead irrigation. RESRAD 5.61 uses a weathering constant of 0.055 per day. The weathering rate cannot be changed within the program by the user.*
All irrigation pathways include a radionuclide specific transfer factor termed F_{aj} in NUREG/CR 5512. This factor relates the concentration in an animal product to the daily intake via feed, water, and soil.	Yes. This factor is assumed to be independent of media ingested, but is dependent on the animal product (Kennedy and Strenge, 1992, section 5.4.2).	Yes. This factor is assumed to be independent of media ingested, but is dependent on the animal product (Yu, et al, 1993, Eq. D.15, Table D.4).
Animal products ingested	DandD 1.0 provides separate transfer factors for beef, milk, poultry and eggs. Default values are found in Table 7.	RESRAD 5.61 does not provide separate transfer factors for beef and poultry. RESRAD 5.61 does not consider ingestion of poultry eggs by humans as an exposure pathway. See Table 7 for defaults.
Radionuclide concentrations in soil are assumed to be continuously in equilibrium with radionuclide concentrations in the edible portions of the plant.	Yes.	Yes.
Animals ingest soil while grazing	Yes.	Yes.
The concentrations in animal products are immediately in equilibrium with the concentrations in intake (feed, water, and soil).	Yes, this assumption is made by both DandD 1.0 and RESRAD 5.61. For isotopes that are rapidly cleared from the body, this is a good approximation. However, it will be conservative for elements that are retained in edible tissues for long periods of time. Based on retention data in ICRP 30 and 54, which is based on animal and human studies, the following are likely to take two years or more to reach a steady state concentration in animal flesh: Co-60, Cd-109, Ce-144, Pb-210, Th isotopes, Pu, and transuranics (liver).	
Animal products are harvested continuously over the feeding period and then held for a short time before distribution for human consumption.	Yes	Dose rates are computed based on concentrations present in media at a particular point in time. There is a brief holdup period before consumption by humans.
Source of irrigation water for livestock	Assumed to be well water. User may specify a contamination fraction.	User may choose surface water or well water and specify a contamination fraction.

Table 22. Irrigation water – forage – animal product – human pathway

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in forage as a result of irrigation water.	Taken to be the average concentration for the feeding period.	Concentration is evaluated at an instant in time that is specified by the user.
Time dependence of radionuclide concentration in animal product over the forage period.	Taken to be the average concentration for the feeding period. Instantaneous equilibrium between forage and the animal product is assumed via plant to animal product transfer factors.	Concentration is evaluated at an instant in time that is specified by the user.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time	Radionuclide ingrowth and decay in the forage is taken into account over the holding time
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

Table 23. Irrigation water – soil – forage – animal product – human pathway

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in soil as a result of irrigation water.	Taken to be the average concentration for the forage period.	Concentration is evaluated at an instant in time that is specified by the user.
Time dependence of radionuclide concentration in forage as a result of irrigation water.	Taken to be the average concentration for the forage period. Concentrations in edible part of plant are assumed to be in equilibrium with soil concentrations via the soil-to-plant transfer factors.	Concentration is evaluated at an instant in time that is specified by the user. Concentrations in edible part of plant are assumed to be in equilibrium with soil concentrations via the soil-to-plant transfer factors.
Time dependence of radionuclide concentration in animal product over the forage period.	Taken to be the average concentration for the feeding period. Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.	Concentration is evaluated at an instant in time that is specified by the user. Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the forage is taken into account over the consumption period.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

Table 24. **Irrigation water – stored hay or grain – animal product – human pathway**

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in stored hay or grain as a result of irrigation water.	Taken to be the concentration at the time of harvest.	Same as DandD 1.0
Length of holding time between when feed is harvested and when it is first used.	Zero.	Fodder is held for a short time before intake by animals.
Time dependence of radionuclide concentration in animal product over the period when the feed is consumed.	Radionuclide ingrowth and decay in the stored hay/grain is taken into account over the stored hay/grain consumption period. Instantaneous equilibrium between stored hay/grain and the animal product is assumed via plant-to-animal product transfer factors.	Not considered.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the stored product is taken into account over the holding time.	A holding time is assumed, see Table 4 for defaults, with decay taken into account.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the stored hay/grain is taken into account over the consumption period.	Not taken into account.

Table 25. **Irrigation water – soil – stored hay/grain – animal product – human pathway**

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in soil as a result of irrigation water.	Deposition, ingrowth and decay of radionuclides in soil are assumed to occur over the time the crop is in the field.	Same as DandD 1.0.
Time dependence of radionuclide concentration in the crop as a result of irrigation water.	Concentrations in edible part of plant are assumed to be in equilibrium with soil concentrations via the soil-to-plant transfer factors. Ingrowth and decay of radionuclides in soil is assumed to occur over the time the crop is in the field.	Same as DandD 1.0.
Initial radionuclide concentration in stored hay or grain.	Taken to be the concentrations at the time of harvest. Crop is continuously in equilibrium with soil via soil-to-plant transfer factors.	Same as DandD 1.0.
Length of holding time between when hay/grain is harvested and when it is first used.	Zero.	There is a holding time. Default values provided in Table 4. Decay is accounted for.

Table 25. Irrigation water – soil – stored hay/grain – animal product – human pathway (continued)

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in animal product over the period when stored hay/grain is consumed.	Radionuclide ingrowth and decay in the stored hay/grain is taken into account over the stored hay/grain consumption period. Instantaneous equilibrium between stored hay/grain and the animal product is assumed via plant to animal product transfer factors.	Not considered.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the animal product is taken into account over the holding time. See Table 4 for default values.	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the animal product is taken into account over the consumption period.	Not considered.

Table 26. Irrigation water – soil – animal product – human pathway

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in soil as a result of irrigation water.	Taken to be the average concentration for the forage period.	Concentration is evaluated at an instant in time that is specified by the user.
Time dependence of radionuclide concentration in animal product over the forage period.	Taken to be the average concentration for the feeding period. Instantaneous equilibrium between forage and the animal product is assumed via plant to animal product transfer factors.	Concentration is evaluated at an instant in time that is specified by the user. Instantaneous equilibrium between forage and the animal product is assumed via plant to animal product transfer factors.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the animal product is taken into account over the holding time. See defaults in Table 4.	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the animal product is taken into account over the consumption period.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

3.1.17.2 Soil – Animal Product – Human Pathways

Assumptions made by DandD 1.0 that are common to all of these pathways are provided in Table 27. The soil – animal product – human pathways include the following:

- Soil – forage – animal product – human (Table 28),
- Soil – stored hay – animal product – human (Table 29),
- Soil – stored grain – animal product – human (Table 29),
- Soil – animal product – human.

Table 27. DandD 1.0 assumptions common to all soil – animal product – human pathways

Assumption	DandD 1.0	RESRAD 5.61
Fresh forage crops are eaten continuously (starting at time 0) over the entire feeding period of the animal.	yes	yes
Stored feed crops are eaten continuously during a feeding period offset by the stored feed crop's growing period (i.e. feeding begins at harvest).	yes	not specifically assumed
The harvested crops are immediately available for feeding to animals.	yes	Available after a short holding time.
A combination of fresh and stored feeds is assumed for each type of animal product.	yes	yes
Stored feeds may consist of hay or grain.	yes	yes
Instantaneous equilibrium occurs between the radionuclide concentration in the soil and the concentration in the plants (fresh forage and stored feed plants).	yes	yes
Instantaneous equilibrium occurs between daily intake in the feed and the radionuclide concentration in the animal product.	yes	yes
Animal products are harvested (milked, slaughtered, or eggs gathered) continuously over the feeding period and then distributed for consumption.	yes	No. Dose rates from animal products are evaluated at a specific point in time.
The human consumption period is equal in length to the feeding period for each animal product type, offset by the time between harvest and consumption.	yes	not considered
Decay during the hold-up time between animal product harvest and consumption by humans is evaluated.	yes	yes

Table 28. Soil – forage – animal product – human

Assumption	DandD 1.0	RESRAD 5.61
Concentration in soil as a function of time	Declines due to radioactive decay and leaching.	Declines due to radioactive decay and leaching.
Radionuclide concentration in forage crops.	Continuously in equilibrium with soil via soil-to-plant transfer factors.	Continuously in equilibrium with soil via soil-to-plant transfer factors.

Table 28. Soil – forage – animal product – human (continued)

Assumption	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in animal product over the forage period.	Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.	Instantaneous equilibrium between forage and the animal product is assumed via plant-to-animal product transfer factors.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the forage is taken into account over the holding time. See Table 4 for defaults.	Same as DandD 1.0.
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the forage is taken into account over the consumption period.	No correction for radioactive ingrowth and decay occurring over the consumption time is considered.

Table 29. Soil – stored hay/grain – animal product – human

Factor	DandD 1.0	RESRAD 5.61
Time dependence of radionuclide concentration in stored hay or grain as a result of root uptake.	At time of harvest, crop is continuously in equilibrium with soil via soil-to-plant transfer factors.	Same as DandD 1.0.
Length of holding time between when hay/grain is harvested and when it is first used.	Zero.	Held for a short period before consumption, see Table 4.
Time dependence of radionuclide concentration in animal product over the period when stored hay/grain is consumed.	Radionuclide ingrowth and decay in the stored hay/ grain is taken into account over the stored hay/grain consumption period. Instantaneous equilibrium between stored hay/grain and the animal product is assumed via plant to animal product transfer factors.	NA. Dose rates are evaluated at a specific point in time.
Holding time between time of slaughter (or collection of milk or eggs) and consumption by humans.	Radionuclide ingrowth and decay in the stored animal product is taken into account over the holding time. See Table 4 for defaults.	Same as DandD 1.0
Period of time over which the animal product is consumed.	Radionuclide ingrowth and decay in the animal product is taken into account over the consumption period.	Not considered.

3.1.18 Comparison of RESRAD 5.61 and DandD 1.0 Simulation Results

Three variations of the residential farmer scenario were considered. In the first set of comparisons, RESRAD 5.61 and DandD 1.0 were run with minimal changes to default values for tritium, carbon-14, cesium-137, and radium-226. The changes to default values for these simulations are described in Appendix A, Tables A.3 and A.4. In the second set of comparisons, RESRAD 5.61 and DandD 1.0 parameters were adjusted to represent a residential farmer in an arid climate. The changes to default values that were made for this series of simulations are described in "Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer in Dry Climatic Conditions" in Appendix A. In the third set of simulations, parameters were adjusted to represent a residential farmer in a wet climate. The changes to default values that were made for this series of simulations are described in "Comparison of DandD 1.0 and RESRAD 5.6.1 Results for a Residential Farmer in Wet Climatic Conditions" in Appendix A. The dry climate and wet climate simulations were completed for tritium, carbon-14, cesium-137, radium-226, thorium-232, and cobalt-60.

To illustrate the differences in simulation results over time, each set of simulation results are presented for the first year and the fifth year of the scenario in Appendix A, and in Figures 1 through 6. A comparison of maximal dose rates is provided Figures 1 through 6 and in Tables 11, 13, 19, 20, 30, and 31.

It was concluded that the agricultural pathway in DandD 1.0 simulations tends to dominate the Total Effective Dose Equivalent (TEDE) when the default plant mass loading factor is used. The default value for this parameter is that plant foods contain 10% soil on a dry weight basis. Decreasing the value of this factor to 1% results in reasonable agreement between agricultural doses predicted by RESRAD 5.61 and DandD 1.0 for most isotopes. This empirical observation is very evident in two examples, radium-226 plus progeny (Table 19) and thorium-232 plus progeny (Table 20). In the radium case, decreasing the plant mass loading factor in DandD 1.0 from 0.1 to 0.01 results in a decrease in dose from the agricultural pathway from 39,900 mrem/y to 8,380 mrem/y.

Although decreasing the value of the plant mass loading factor to a more realistic value produces closer agreement in the doses simulated using RESRAD 5.61 and DandD 1.0, the models of diet are still dissimilar. Hence, there remain significant differences in the simulated doses for some isotopes. The agricultural pathway in DandD 1.0 corresponds to the sum of the plant, meat, and milk pathways in RESRAD 5.61, which is 2,100 mrem/y. This RESRAD 5.61 result is based on the assumption that one-half of the food consumed is grown in the contaminated area, while the DandD 1.0 result is based on assumption that all of the food grown on-site is grown in the contaminated area. The two diets are not equivalent and as a result, the revised DandD 1.0 agricultural dose of 8,380 mrem/y (with a plant mass loading of 0.01 for plant foods consumed by humans) is about twice the dose calculated by RESRAD 5.61.

As discovered during the parameter analysis for DandD (Beyeler et al., 1998) and based on values found in the literature for soil mass loading on washed plant foods consumed by humans (e.g., Sheppard, 1995), the plant mass loading values in DandD 1.0 for plants foods consumed by humans appear to be implausibly high. It is recommended that the default values for these values be reconsidered.

In this comparison, parameters related to diet were not adjusted in RESRAD 5.61 to match DandD 1.0 values because basic differences in way the computer codes model the ingestion pathway make it difficult to derive parameter values that result in comparable diets. These differences include:

RESRAD uses a <u>single</u> animal soil intake rate. NUREG/CR-5512 and DandD 1.0 have separate soil ingestion rates that are a function of forage intake rate for beef cattle, dairy cattle, poultry and layer hens. The value chosen for RESRAD 5.61 needs to be representative for layer hens, poultry, dairy and beef cattle.

RESRAD does not include intakes of eggs and poultry, NUREG/CR-5512 and DandD 1.0 do. In principle, the contribution of eggs and poultry can be included in the "meat" component of the diet. This leads to the difficulty that transfer coefficients for beef, eggs and poultry are very different for some isotopes.

Examples:

	Beef	Poultry	Eggs
Po-210	3E-4	0.9	7
Pb-210	3E-4	0.2	0.8

Derivation of a composite transfer coefficient that would make the diet in RESRAD 5.61 equivalent to the DandD 1.0 default diet is problematic because of the orders of magnitude difference in the transfer coefficient for beef

Table 30. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving cobalt-60

Pathway	Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 0
External	6,200	7,570	6,200	7,570
Inhalation	0.013	8.5E-3	0.013	8.51E-3
Plant	NA	30.1	NA	31.1
Meat	NA	23.5	NA	23.5
Milk	NA	3.03	NA	3.03
Soil Ingestion	0.36	0.76	0.36	0.76
Water	2.6E-6	0	1.9E-4	0
Fish / Aquatic	3.3E-5	0	1.9E-3	0
Irrig water →→ Plant	NA	0	NA	0
Irrig water →→ Meat	NA	0	NA	0
Irrig water →→ Milk	NA	0	NA	0
Irrigation pathways	2.0E-5	NA	2.9E-5	NA
Agriculture	667	NA	667	NA
Total	6,870	7,630	6,870	7,630

verses poultry and eggs. If a composite transfer coefficient could be derived, it would need to be changed whenever site-specific variations in diet are made.

RESRAD 5.61 uses a single soil to plant transfer coefficient for all plant foods. The values chosen need to representative for the diets of humans, poultry, layer hens, dairy and beef cattle. This leads to difficulties in choosing a representative value because of differences in diet among these organisms.

RESRAD 5.61 uses a single animal food, fodder. DandD 1.0 uses separate interception fractions, translocation fractions and crop yields for each animal product for forage, grain and hay. Representative values of these parameters would need to be calculated for the diets of layer hens, poultry, dairy and beef cattle.

Wet and dry interception fractions are coupled in RESRAD 5.82 and cannot be independently adjusted. This leads to difficulty in modeling the dose from resuspended soil on plants. In RESRAD 5.82, this can be compensated for, to a degree, by setting the soil mass loading for deposition to zero and increasing the amount of soil directly ingested by animals. DandD 1.0 allows for separate plant mass loading values for hay, forage, and grain for each animal food.

Devising a robust method for matching non-equivalent parameters in these two models was beyond the scope of this analysis.

RESRAD 5.61 and DandD 1.0 tend to agree well for doses resulting from direct irradiation, inhalation, and soil ingestion, provided that an effort is made to match input parameter values. This is due to the fact that the models for these pathways are very similar. The dose from incidental soil ingestion in each of the RESRAD 5.61 simulations summarized in Tables 11, 13, 19, 20, 30, and 31 and in Appendix A is twice as high as in the corresponding DandD 1.0 simulation because of differences in the incidental soil ingestion rates. 100 mg per day was used in the RESRAD 5.61 simulations, while 50 mg/d was used in the DandD 1.0 simulations.

Table 31. Comparison of DandD 1.0 and RESRAD 5.61 maximum dose rate results for a residential farmer scenario involving cesium-137

Pathway	Maximum EDE Rate, mrem/y, Minimal Changes to Defaults		Maximum EDE Rate, mrem/y, Dry Climate		Maximum EDE Rate, mrem/y, Wet Climate	
	DandD 1.0 Year 6	RESRAD 5.61 Year 0	DandD 1.0 Year 1	RESRAD 5.61 Year 0	DandD 1.0 Year 11	RESRAD 5.61 Year 0
External	1,380	1,778	1,460	1,690	218	0.065
Inhalation	1.9E-4	0.023	1.96e-3	1.24E-3	2.9E-4	0
Plant	NA	29.0	NA	29.0	NA	1.14E-3
Meat	NA	45.0	NA	45.0	NA	1.73E-3
Milk	NA	15.9	NA	15.9	NA	6.13E-4
Soil Ingestion	0.066	1.37	0.70	1.41	0.10	5.43E-5
Water	562	0	0.099	0	192	511
Fish / Aquatic	23,700	0	7.56	0	11,600	5,460
Irrig water →→ Plant	NA	0	NA	0	NA	0
Irrig water →→ Meat	NA	0	NA	0	NA	47.3
Irrig water →→ Milk	NA	0	NA	0	NA	59.0
Irrigation pathways	3,840	NA	1.40	NA	69.8	NA
Agriculture	53.6	NA	567	NA	84.6	NA
Total	28,300	1,870	2,040	1,780	12,100	6,070

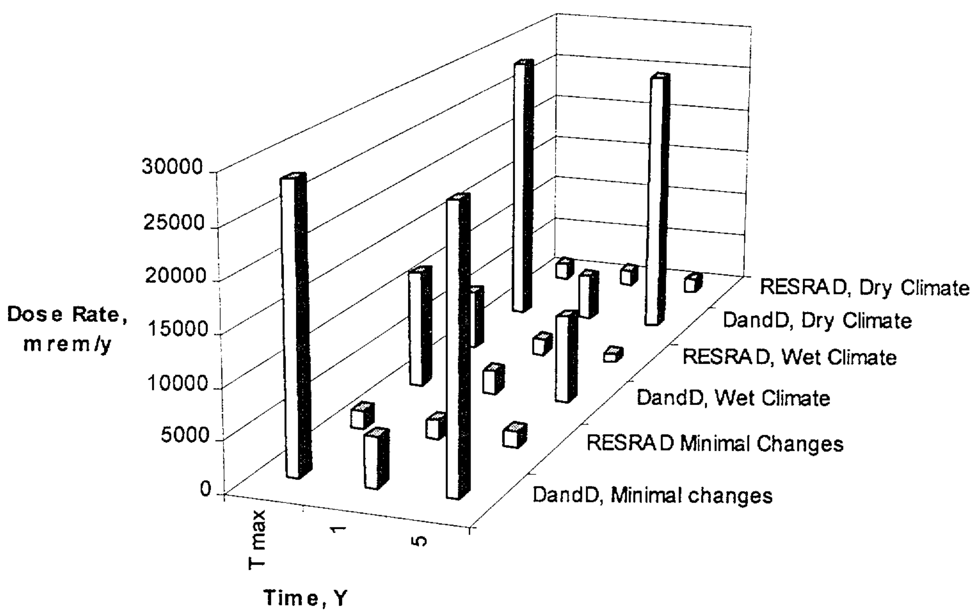

Figure 3. Comparison of Cesium-137 results for DandD and RESRAD

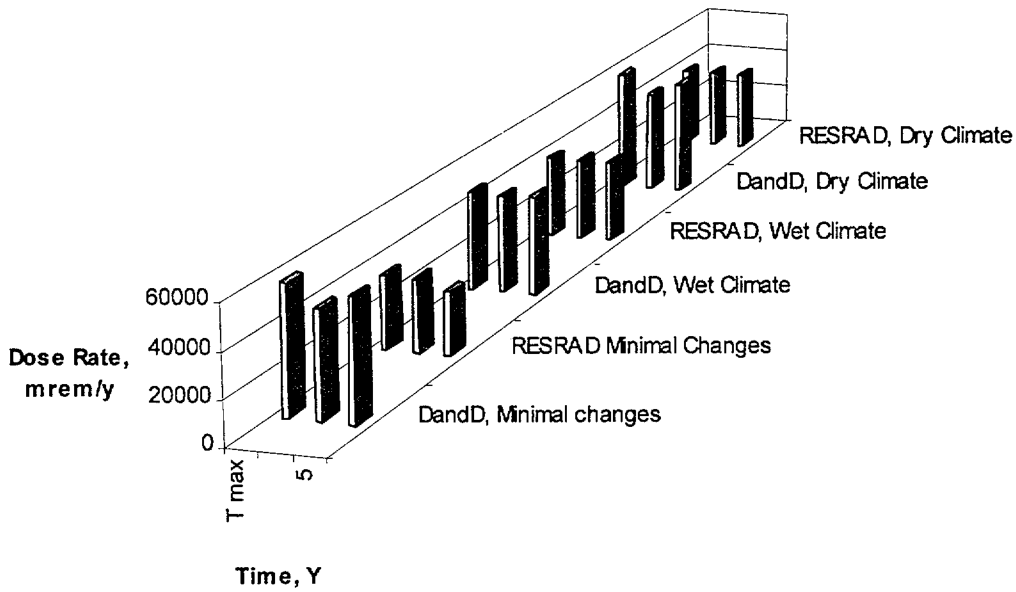

Figure 4. Comparison of Radium-226 + chain results for DandD and RESRAD

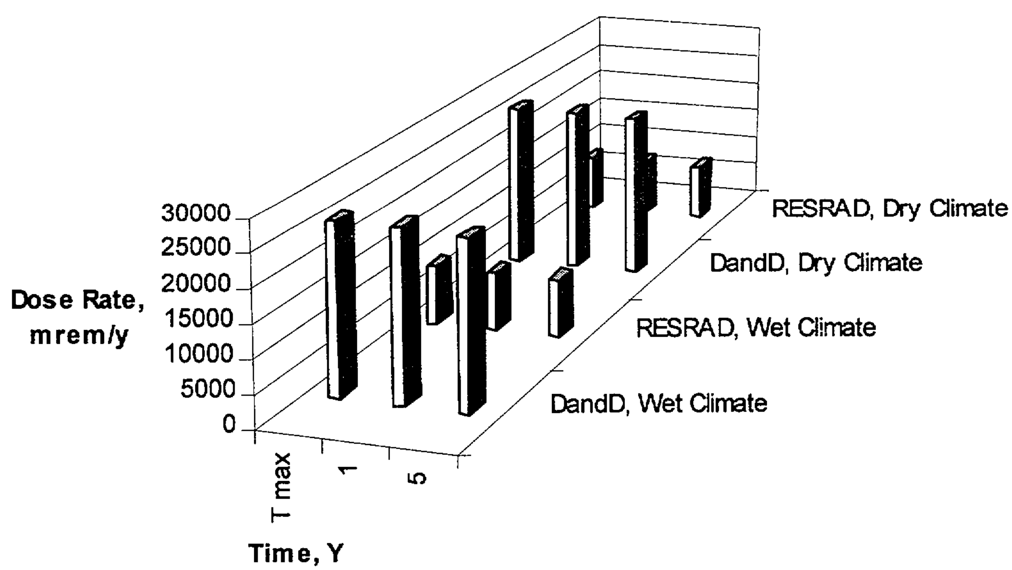

Figure 5. Comparison of Th-232 + chain results for DandD and RESRAD

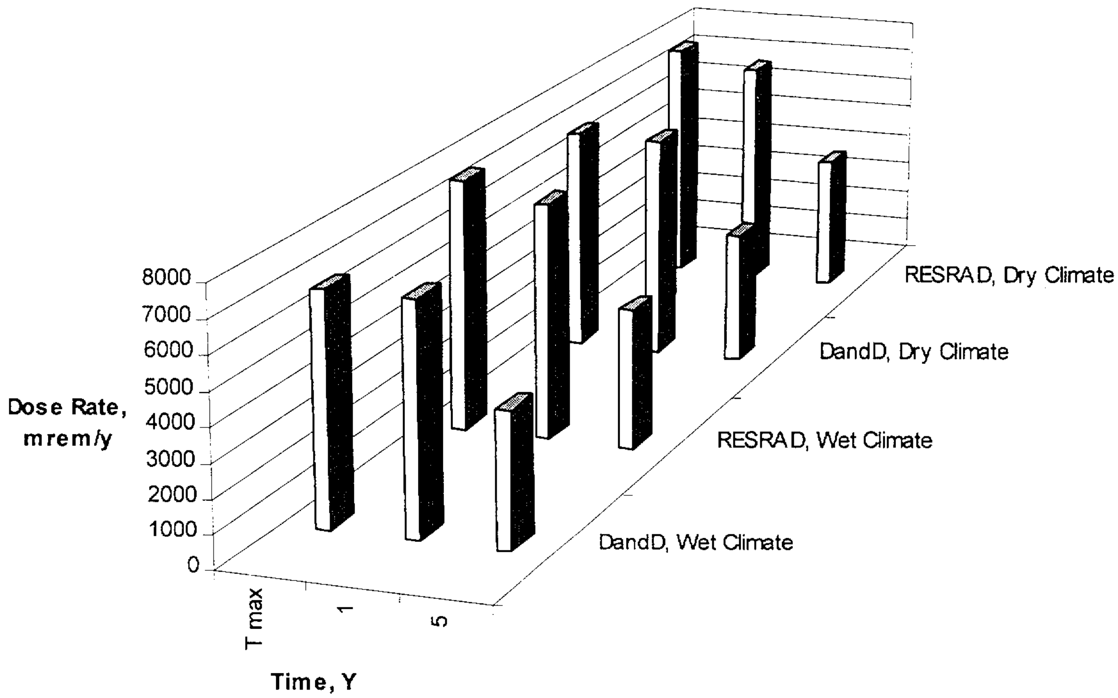

Figure 6. Comparison of Co-60 results for DandD and RESRAD

Because RESRAD 5.61 and DandD 1.0 groundwater models differ in significant ways, the time dependence and magnitude of doses from groundwater pathways tended to be very different when the models are applied to the residential farmer scenario. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, contaminants reached the well sooner in DandD 1.0 simulations.

A primary difference in the water pathway calculations performed by DandD 1.0 and RESRAD 5.61 can be attributed to the method in which they model the unsaturated zone. In the unsaturated zone DandD 1.0 uses a well-mixed linear reservoir model, which has inherent, probably large, dispersion due to the mixing assumption. This dispersion causes the arrival time from the contaminated zone to the aquifer to be zero when a single layer is used. Thus, DandD 1.0 simulations show radionuclides reaching the aquifer in a very short time, but at a low mass flow rate.

The concentrations in the aquifer in RESRAD 5.61 are based in part on travel time from the contaminated zone to the aquifer. This means that no radionuclides from the contaminated zone can reach the aquifer until the model simulation time exceeds the travel time. The travel time in RESRAD 5.61 is proportional to the retardation coefficient. A radionuclide, such as tritium, has a retardation coefficient of 1 because it is not adsorbed onto soil particles and, thus, travels through the unsaturated zone at the same speed as water. Carbon-14 and many other radionuclides are retarded and take much longer to reach the water table than tritium in the RESRAD 5.61 model. This is why doses were not seen for water-dependent pathways at one year or five years for isotopes other than tritium in the RESRAD 5.61 code.

Three of the isotopes considered in simulations showed a tendency to enter groundwater readily. This included the isotopes cesium-137, tritium, and carbon-14. With these isotopes, maximum dose rates for water dependent pathways depend strongly on the values of parameters used.

Three of the isotopes considered in simulations showed little tendency to enter groundwater: radium-226, thorium-232, and cobalt-60. For each of these isotopes, DandD 1.0 and RESRAD 5.61 results were consistent. If a more realistic default plant mass loading values are adopted into DandD 1.0, the differences, in the simulated doses for these isotopes between DandD 1.0 and RESRAD 5.61, would be significantly reduced.

3.2 DandD 1.0 and RESRAD-Build 1.50

DandD 1.0 and RESRAD-Build 1.50 differ in the exposure pathways considered for an industrial occupancy scenario, and they differ in the treatment of those pathways. The pathways considered are provided in Table 32.

The major pathway differences between RESRAD-Build 1.50 and DandD 1.0 for application of the industrial occupant scenario of NUREG/CR-5512 can be summarized as follows:

- RESRAD-Build 1.50 considers dose due to submersion in a cloud of radioactive material, while DandD 1.0 does not.
- RESRAD-Build 1.50 considers external exposure to dust that has been airborne and settled on floors, while DandD 1.0 does not consider this to be a separate exposure pathway.
- RESRAD-Build 1.50 considers dose due to inhalation of radon and radon progeny. DandD 1.0 does not include a radon model.

In addition, there are many significant differences between the two models. These are summarized below.

- RESRAD-Build 1.50 is a dynamic model of a structure, while DandD 1.0 is a static model. This leads to numerous differences in the parameters needed to run the models. DandD 1.0 was designed to model the four scenarios in NUREG/CR-5512 while RESRAD-Build 1.50 is a general purpose dose assessment model for scenarios related to remediation and occupancy of structures.
- RESRAD-Build 1.50 will model dose from finite sources; it addresses area sources, volume sources, point sources, and line sources. The DandD 1.0 industrial occupant scenario only considers dose from infinite area sources.
- RESRAD-Build 1.50 contains a ventilation model, so some of the radioactive material that becomes airborne can be exhausted from the building. DandD 1.0 does not contain a ventilation model.
- In RESRAD-Build 1.50, a structure can be modeled with up to three rooms using numerous sources of contamination. DandD 1.0 assumes that the contamination is present in a single room.
- In RESRAD-Build 1.50, it is necessary to specify the location and occupancy of a receptor relative to each source. The location does not matter with DandD1.0, since the receptor is located on an infinite area source.
- RESRAD-Build 1.50 assumes that a fraction of contamination is removed from the building over a period of time specified by the user through ordinary traffic or housekeeping activities. DandD 1.0 only accounts for loss of material through radioactive decay.

3.2.1 Isotopes Considered

The RESRAD-Build 1.50 library of isotopes contains 67 isotopes having a half-life of six months or longer. RESRAD-Build 1.50 uses the same convention as RESRAD 5.61 for treatment of radioactive progeny (see section 3.1.2 of this report). The isotope library and conventions concerning progeny utilized by DandD 1.0 are described in section 3.1.2. DandD 1.0's isotope library contains 249 primary isotopes. The DandD 1.0 isotope library includes many more short-lived primary isotopes than the RESRAD-Build 1.50 isotope library.

3.2.2 Dose Rate Reporting Basis

The dose rate reporting basis of RESRAD-Build 1.50 is the same as described for RESRAD 5.61 in section 3.1.1 of this report. RESRAD-Build 1.50 calculates instantaneous dose rates while DandD 1.0 calculates dose received over a year.

3.2.3 External Exposure

The only external exposure pathway considered by DandD 1.0 is direct exposure to an infinite area source

Table 32. Industrial occupant scenario exposure pathways considered by DandD 1.0 and RESRAD-Build 1.50

Pathway	DandD 1.0	RESRAD-Build 1.50
External Exposure due to Source	√	√
External Exposure due to Air Submersion		√
External Exposure to Material Deposited on Floor		√
Inhalation of Airborne Radioactive material	√	√
Inhalation of Radon Progeny		√
Inadvertent Ingestion of Radioactive Material	√	√

of contamination. RESRAD-Build 1.50 can model external exposure to:

- sources of contamination in a number of different geometries, area, volume, line, and point. The default geometry is a volume source.
- exposure due to submersion in a infinite cloud of airborne contamination, and
- exposure to radioactivity that has been resuspended, transported via the indoor air quality model, and subsequently deposited on horizontal surfaces.

3.2.3.1 DandD 1.0

DandD 1.0 calculates the EDE to an industrial occupant due to surface contamination using the following basic relationship (Kennedy and Strenge, 1992, Eq 3.15):

External dose (mrem for 1 year) =
[Exposure duration for occupancy] (Eq. 3)
× [Surface Source Dose Rate Factor]
× [Average Surface Activity per Unit Area]

The *Surface Source Dose Rate Factors* are taken from Table III.3 of Federal Guidance Report (FGR)12 (EPA, 1993). These factors represent the EDE rate for exposure to an infinite planar source of the isotope of interest.

In the case where the contaminant is uniformly distributed on a floor, assuming an infinite planar distribution is conservative. In the case of gamma emitters, DandD 1.0 substantially overestimates external dose other than low energy gamma emitters for small rooms that only have contamination on the floor. To estimate how conservative, the Microshield® computer code (Grove Engineering, 1998) was used to compute exposure rates at one meter above different sizes of circular area sources of 0.1 MeV gamma emitters. The ratios of exposure rates for finite disks to disks of effectively infinite radius were estimated from Microshield® simulations. These ratios are presented in Figure 7 as a function of radius. In the case of 0.1 MeV gamma emitters, a disk 50 meters in diameter has roughly one-half of the exposure rate of an infinite planar source.

As indicated above, DandD 1.0 assumes that contamination is distributed on an infinite planar floor. In real structures, the highest contamination levels are usually on the floor and the lower parts of walls. Typically, comparatively little contamination is present on the upper portions of walls and on ceilings. With this pattern of contamination in mind, Microshield® 5.03 was used to estimate external EDE rates for a Cs-137 contaminated room. As a reference case, the external EDE rate was estimated for an infinite planar source. Then the external EDE rates were estimated for circular rooms having a height of 3 meters and diameters of 6 and 12 meters. In each case, the floor was assumed to have the same surface contamination level as the infinite planar source. Walls and ceilings were assumed to have one-half and one-tenth of this surface contamination level respectively. Based on Microshield® simulations, the rooms with 6 and 12 meter diameters had external EDE rates that were 40% and 56% of the reference value for an infinite planar source. Based on this limited evaluation, the assumption of an infinite planar source of contamination is a reasonable screening model for surface contamination of a room having contamination on the walls and ceiling as well as the floor.

Additional commentary is provided in Table 33 that relates to the use of dose conversion factors from FGR 12 for a planar source of radioactive material.

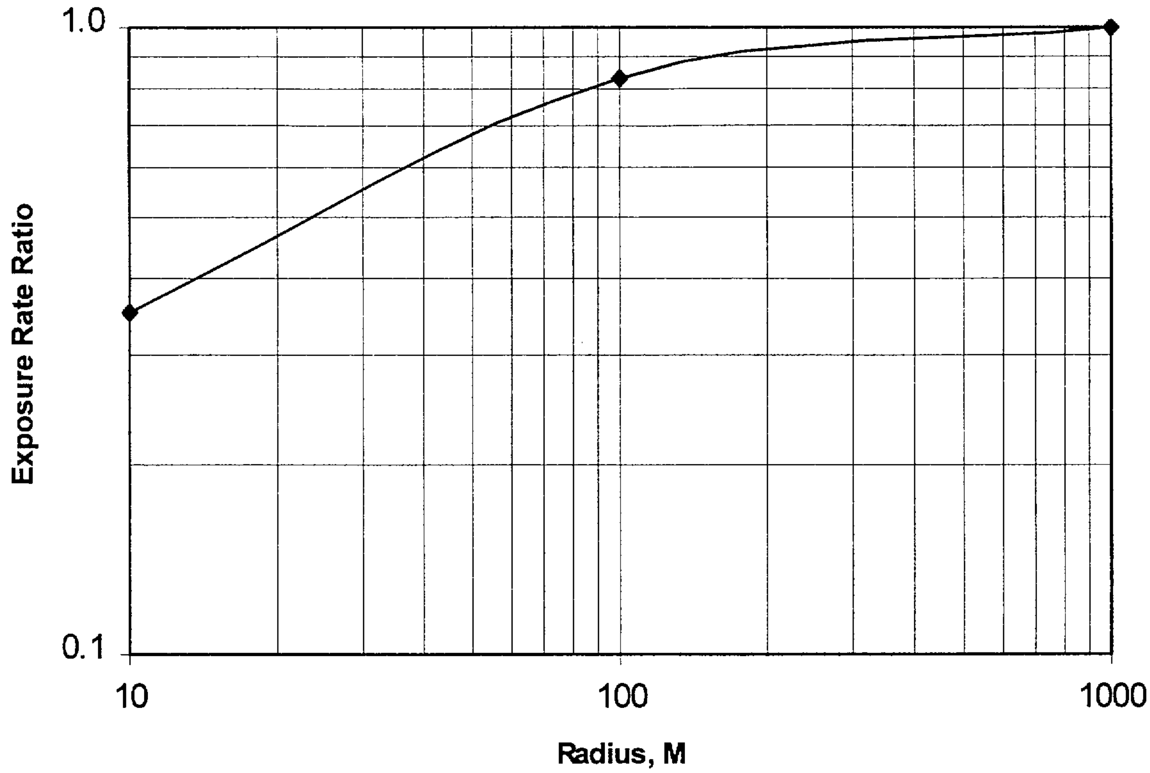

Figure 7. Gamma exposure rate ratio for 0.1 MeV photons: finite disk/infinite plane

3.2.3.2 RESRAD-Build 1.50

RESRAD-Build 1.50 calculates external exposures for a number of geometries: planar source, volume source, line source, and point source. RESRAD-BUILD 1.50's planar source geometry corresponds most closely to the spatial configuration assumed in the building occupant scenario. RESRAD-Build 1.50 external dose coefficients are based on FGR 12 (EPA, 1993).

3.2.3.2.1 Planar Source. RESRAD-Build 1.50 calculates external EDE for planar source geometry in a similar fashion to DandD 1.0, however, RESRAD-Build 1.50 incorporates four correction factors into external EDE estimates (Yu, et al., 1994, Appendix F):

- A correction that takes into account the finite area of the source,
- A correction that takes into account any offset of the receptor from the axis of the disk of contamination,
- A shielding correction that can be applied to account for attenuation by material covering the disk source (e.g. an intervening walls or floors), and
- The distance between the source and the receptor.

Each of these correction factors tends to reduce the estimated EDE from a finite area source in comparison to an infinite area source.

An important difference between the two codes is that DandD 1.0 always assumes the floor is contaminated, while RESRAD-Build 1.50 can be used to model external EDE from to up to 10 sources present on walls, ceiling, floor, in another room, or on another floor. The external dose calculations performed by RESRAD-Build 1.50 are much more complex than those provided by DandD 1.0. RESRAD-Build 1.50 should be capable of providing more accurate estimates of external EDE than DandD 1.0 where site-specific modeling is required. However, to take advantage of the more sophisticated external dose modeling capability afforded by RESRAD-Build 1.50, more site-specific information is required. For example:

- Information concerning the spatial distribution of surface contamination,

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
Dose Conversion Factor for exposure to a planar source of radioactive material	FGR 12 factors	FGR 12 factors. Factors can be edited from within RESRAD-BUILD 1.50. In RESRAD-BUILD 2.37 these factors cannot be edited by the user.	The assumption of a planar infinitely thin perfectly flat and smooth source of radioactive contamination is a limiting conservative case. In real situations, this value is decreased by a number of factors: surface roughness; residual radioactive contamination largely may be associated with cracks between flooring material so that residual contamination is actually located within the surface. Furniture and building contents provide shielding that serves to reduce external EDE to a building occupant. As photon energies decrease, these factors cause external EDE estimates to become increasingly conservative.
			Both programs use FGR 12 factors to convert distributed radioactive contamination levels to EDE. However, the Radiological Criteria for License Termination standard is written in terms of TEDE, which is the sum of the deep dose equivalent (measured at a tissue depth of 1 cm) from external radiation sources and the CEDE from intakes of radioactive material. For a given distribution of radioactive materials, the deep dose equivalent usually exceeds the EDE. External dose conversion factors for EDE thus provide a non-conservative estimate of deep dose equivalent. Typically, the deep dose equivalent can exceeds the EDE by 25 to 50% or more (ICRU, 1988, Figure B.16). The difference between deep dose equivalent and EDE from external irradiation increases as the photon energy decreases.
Inhalation Dose Conversion Factors	FGR 11 factors	DOE (1988) factors. Factors can be edited from within RESRAD-BUILD 1.50.	Both sets of dose conversion factors are based on an assumed of 1 Tm activity median aerodynamic diameter (AMAD). Both FGR 11 and DOE (1988) are based in the same system of dosimetry, ICRP publication 30 (ICRP, 1977), and there should be few substantive differences between the inhalation dose conversion factors used by RESRAD-Build 1.50 and DandD 1.0.
		RESRAD-BUILD 2.37 uses factors from FGR 11; they cannot be modified by the user.	
			The new lung model described in ICRP publication 66 (ICRP 1994) recommends that 5 Tm AMAD particles be assumed for occupational exposures in the absence of site-specific information to the contrary. Newer dose conversion factors found in ICRP 68 (ICRP, 1994) are tabulated for both 1 Tm and 5 Tm AMAD particles. Assuming a 1 Tm particle size distribution instead 5 Tm introduces a conservative bias on the order of 30% for most particulate beta and gamma emitters. For long lived alpha-emitting thorium and plutonium isotopes that are cleared slowly from the lung, 1 Tm AMAD particles produce around twice the EDE per unit concentration as 5 Tm AMAD particles.

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50 (continued)

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
			The AMAD particle size encountered in occupational exposure situations frequently will exceed 5 μm, introducing additional conservatism into the 1 μm particle size assumption.
			Where more than one lung clearance class is identified in ICRP publication 30, both DandD 1.0 and RESRAD-Build 1.50 tend to conservatively assume the more restrictive form of the isotope is present. This often provides a conservative estimate of the EDE by less than a factor of two. However this convention becomes rather conservative for a number of isotopes, for example: •Uranium-238, class D versus class Y; factor of 50, •Strontium-90, class D versus class Y; factor of 6, •Technetium-99, class D versus class W; factor of 8.
Ingestion Dose Conversion Factors	FGR 11 factors	DOE (1988) factors. Factors can be edited from within RESRAD-BUILD 1.50. RESRAD-BUILD 2.37 uses factors from FGR 11 (they cannot be modified by the user).	Both FGR 11 and DOE (1988) are based in the same system of dosimetry, ICRP publication 30 (ICRP, 1977), and there should be few substantive differences between the ingestion dose conversion factors used by RESRAD-Build 1.50 and DandD 1.0.
			In some instances, ICRP publication 30 provides different GI absorption factors for isotopes depending on lung clearance class (uranium is an example). In such cases, both computer codes use the larger value as the default factor. The GI tract absorption factors used in ICRP publication 30 are based on data from animal experimentation and limited human studies. The default factors will be inappropriate for specific chemical forms of some radionuclides. For example, ICRP 30 uses a GI tract absorption factor of 0.10 for barium, but the fractional absorption of barium sulfate via the GI tract is orders of magnitude lower. The factors could be non-conservative for unusual chemical forms of some radionuclides.
Length of the Exposure Period	365.25 days (default). Can be edited within DandD 1.0.	365 days (default) Can be edited within RESRAD-Build 1.50.	
Occupancy Factor	--	50 % (default). Can be edited within RESRAD-Build 1.50.	The high *Occupancy Factor* of RESRAD-Build 1.50 is reflective of the fact that defaults values of its parameters are not specifically based on the industrial occupant scenario of NUREG/CR-5512.

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50 (continued)

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
Time in Building per Year	97.46 days (default) (i.e. 45 hours/week, 52 weeks/yr.) Can be edited within DandD 1.0	Default values of *Length of Exposure Period* and *Occupancy Factor* correspond to 182.5 days or 84 hours per week.	The value of *Time in Building per Year* is reasonable for the average member of the exposed population. The default values of *Length of Exposure Period* and *Occupancy Factor* in RESRAD-Build 1.50 are very conservative for an industrial occupant scenario.
Resuspension Factor	1.42E-5 m^{-1}		The *resuspension factor* in DandD 1.0 is not directly comparable to the *resuspension rate* used in RESRAD-Build 1.50 because the resuspension models are so different. DandD 1.0 utilizes a static resuspension model while RESRAD-Build 1.50 is based on a dynamic resuspension model.
Resuspension Rate		5E-7 s^{-1}	
Volumetric Breathing Rate	1.4 m^3/h	18 m^3/day	The default volumetric breathing rate for an industrial occupant in the DandD 1.0 computer code is 1.4 m^3/h, which is well within the range of literature values used by the ICRP. For comparison, ICRP publication 2 (1959) assigned *Standard Man* a breathing rate of 1.25 m^3/h while occupationally exposed. ICRP publication 23 (1974) assigned *Reference Man* a breathing rate of 1.2 m^3/h for light activity. ICRP publication 66 assigned breathing rates of 1.2 m^3/h for light work and 1.69 m^3/h for heavy work. The breathing rate of 18 m^3/day used by RESRAD-Build 1.50 is within the range of estimates provided in EPA (1985). However, the breathing rate for an occupational worker involved in light activity is apt to be underestimated (as 0.75 m^3/h) when this average value is used to provide an estimate for an active part of the day. In such cases, a use of a breathing rate of about 30 m^3/day (1.25 m^3/h) in RESRAD-Build 1.50 will provide a more conventional estimate for an industrial occupant.
Effective transfer rate for ingestion (from surfaces to mouth)	1.11E-5 m^2/h	1E-4 m^2/h	These factors are not completely comparable because in RESRAD-Build 1.50 this only represents the transfer rate for material that has been suspended in air and then redeposited. To make the two models comparable, RESRAD-Build 1.50 must also have a non-zero value for direct ingestion of the source.
Air Exchange Rates	NA	0.8 / h (default) in case of one compartment structure.	Users need to recognize that the RESRAD-Build 1.50 IAQ model (Yu, et al., 1994, Appendix A) assumes ideal (complete) mixing behavior of air between compartments and between a compartment and outside air. However, this ideal behavior is seldom approached in real structures. Inefficiencies in mixing of air often result in layering, channeling, and the occurrence of dead air spaces within ventilated structures. These cause the *Effective* Air Exchange Rate to be lower than the ideal Air Exchange Rate. The *Effective* Air Exchange Rate is often 10% to 33% of the Air Exchange Rate (NIOSH, 1973). The *Effective Air Exchange Rate* is the appropriate value for use in RESRAD-Build 1.50.

Table 33. Discussion of industrial occupant scenario parameters in DandD 1.0 and RESRAD-Build 1.50 (continued)

Parameter	DandD 1.0	RESRAD-Build 1.50	Comments
			A default *Air Exchange Rate* of 0.8/h seems rather high considering that it is actually the *Effective Air Exchange Rate* that is of interest. In the 1970s, industrial buildings were built with a design specification of as little as 5 cfm of outdoor air per person (SMACNA, 1988) and some buildings may not have actually performed to specification.
Radon Release Fraction	NA	0.1 (default) for area source	DandD 1.0 Does not compute a dose due to emanated radon from residual radium contamination. Consideration of the dose resulting from emanated radon is not a requirement of the final rule on Radiological Criteria for License Termination (NRC, 1997). RESRAD-Build 1.50s assumes that 10% of the radon present in residual radium contamination is available for release to indoor air. This default value is too low for many chemical forms of surface contamination by radium. It is not unusual for the emanation fraction of surface soils contaminated by uranium mill tailings to emanate 30% of the radon they produce.

- Locations and characteristics of shielding, and
- Occupancy factors for specific locations in the structure.

3.2.3.2.2 Immersion. RESRAD-Build 1.50 conservatively estimates the EDE arising from immersion in an infinite cloud of radioactive material utilizing dose conversion factors from FGR 12 (EPA, 1993). RESRAD-Build 1.50 calculates the immersion EDE as the product of the *airborne concentration* and the *concentration to dose rate conversion factor* for an infinite cloud. The following considerations limit the practical importance of this exposure mechanism in the industrial occupant scenario:

- A person would have to be situated in a very large (football stadium-sized) volume of contaminated air in order for the immersion EDE rate to begin to approach the value that would result from immersion in an semi-infinite cloud of moderate energy to high energy gamma emitters[5]. This point is illustrated by Figure 8.
- In the case of immersion in a cloud of beta emitters, the skin, muscle, and fat tissues receive almost the entire dose equivalent. The dose equivalents to these tissues are not included in the calculation of EDE due to external irradiation.
- For isotopes that are a practical concern, other exposure pathways, such as inhalation or ingestion, would be much more significant than immersion.[6]

3.2.4 Inhalation

The inhalation models of DandD 1.0 and RESRAD-Build 1.50 differ significantly in the means used to compute airborne concentrations. These differences are illustrated in Figure 9; the models are described in the following section.

3.2.4.1 DandD 1.0

DandD 1.0 assumes a simple and static linear relationship between the amount of loose surface contamination

[5] The ratio of dose rates (finite ÷ infinite) for hemispherical clouds of gamma emitters is calculated as:

Ratio = $1-\exp(-\mu * R)$, where μ is the linear energy absorption coefficient of air and R is the radius of the cloud (after Member, 1983, eq. 6.40).

[6] Isotopes for which immersion in an infinite cloud causes a higher EDE than inhalation tend to be short-lived activation products and noble gases that are produced during the operation of devices such as nuclear reactors and linear accelerators. However, immersion dose could be important in building decontamination scenarios where respiratory protection is utilized and airborne gamma-emitting isotopes are present in the air at many times the derived air concentration (DAC).

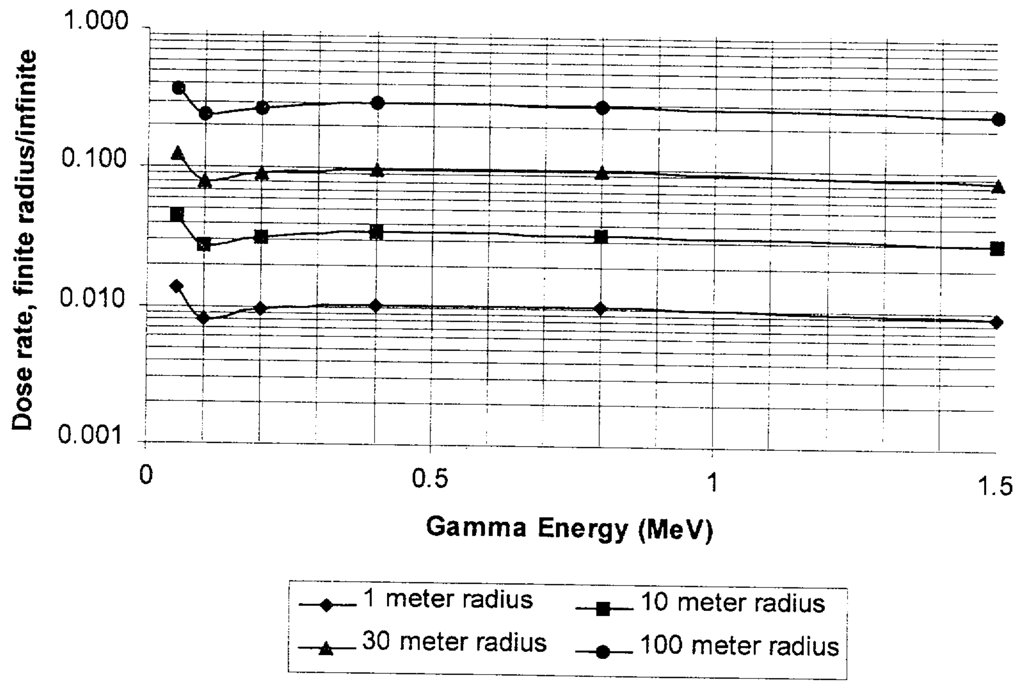

Figure 8. Dose rates from hemispheres of contaminated air having various radii relative to the dose rate from an infinite hemisphere of contaminated air.

and the airborne concentration. Concentrations of airborne radioactive materials are computed by DandD 1.0 as the product of a *resuspension factor*, which has the units of m^{-1} , and the *removable activity per unit area*, which has the units of pCi/m^2 (Kennedy and Strenge, 1992, Eq. 3.17). DandD 1.0 takes into account radioactive ingrowth and decay. No other time dependence is present in the air concentration model. DandD 1.0 uses standard factors based on ICRP publication 30 to convert airborne concentrations to CEDE. Specifically, dose conversion factors used in DandD 1.0 are obtained from FGR 11 (EPA, 1988). In instances where more than one lung clearance class is given in FGR 11, the more conservative (larger) value is used in DandD 1.0.

3.2.4.2 RESRAD-Build 1.50

The airborne concentration model used by RESRAD-Build 1.50 is provided in Appendix A of Yu, et al. (1994). This is a dynamic model that takes into consideration kinetics of the introduction and removal of radioactive material to or from indoor air. Radioactive material may be released into the air from each direct source and also from resuspension of loose radioactive material deposited on horizontal surfaces in each compartment of the structure (Yu, et al., 1994, Eq. D.1). Once airborne, radioactive material is subject to transport among the compartments of the structure, deposition on horizontal surfaces, and removal by air exchange between the structure and outdoor air. Radioactive ingrowth and decay are taken into account.

The user specifies occupancy factors and respiration rates for each receptor. For up to three rooms in the structure, the user also specifies the:

- dimensions of the rooms,
- deposition velocity,
- resuspension rate,
- air exchange rates,
- initial surface contamination level,
- removable fraction of contamination, and
- air release fraction of contamination

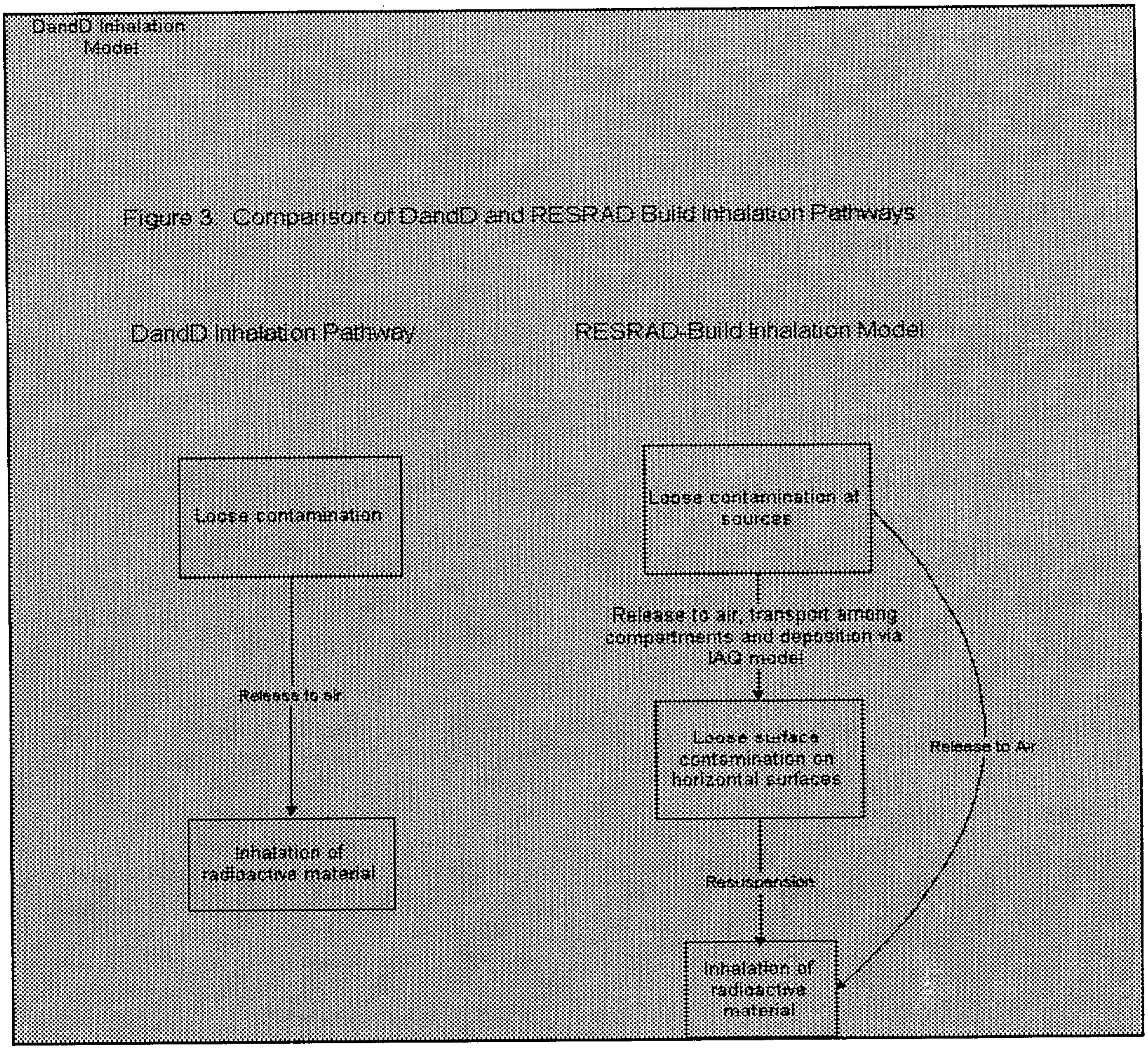

Figure 9. DandD and RESRAD build inhalation pathways

A CEDE is calculated for each receptor. RESRAD-Build 1.50 uses dose conversion factors from DOE (1988).[7] These factors are based on the ICRP-30 system of dosimetry.

The inhalation dose estimates provided by RESRAD-Build 1.50 depend strongly on the relative magnitudes of the *resuspension rate* and *air exchange rates*. Both of these factors will vary by more than an order of magnitude depending on the activities of the building occupants, characteristics of the surface contaminants, and building design and use. Air exchange rates are discussed further in Table 33.

In RESRAD-Build 1.50, the rate of release of radioactive material into a compartment, from a surface, is defined by step functions that are time-dependent. When the elapsed time exceeds a specified value, no loose contamination is assumed to be present, and concentrations of non-radon particulates are assumed to be zero. At lesser times, loose contamination is assumed to be available for release to the air (see Yu, et al., 1994, Eq. D.2).

The step function controlling the rate of release into the structure causes ingestion and inhalation doses estimated

[7]The newer version, RESRAD-BUILD 2.37, uses inhalation coefficients from FGR 11 (EPA, 1998).

by RESRAD-Build 1.50 to have a very different time dependence than DandD 1.0. DandD 1.0 only removes material from the building through radioactive decay. As a consequence, DandD 1.0 ingestion and inhalation dose estimates decline gradually. RESRAD-Build 1.50 ingestion and inhalation doses drop to zero once the time required for removal of loose contamination is exceeded.

The RESRAD-BUILD 1.50 ventilation model also removes a portion of the inventory of radioactive material from the structure, since it assumes that exchange of outdoor air with indoor air occurs. This process removes a portion of airborne radioactive material that would otherwise be redeposited in the structure. RESRAD-BUILD 1.50's ventilation model causes dose rates to drop more quickly than in simulations run in DandD 1.0.

3.2.5 Inhalation – Radon Progeny

The exposure scenario for industrial occupancy given in NUREG/CR-5512 does not address inhalation of radon and radon progeny.

3.2.5.1 DandD 1.0

DandD 1.0 does not directly calculate a dose due to radon progeny released from residual radium contamination.

3.2.5.2 RESRAD-Build 1.50

In the case of an area source, such as that assumed by the occupancy scenario, RESRAD-Build 1.50 assumes a default radon release fraction of 0.1 from an area source. Concentrations of radon progeny are estimated taking into account ingrowth, decay, air exchange rates, attachment, and plate-out (Yu, et al., 1994, Appendix C).

3.2.6 Ingestion

Both DandD 1.0 and RESRAD-Build 1.50 provide estimates of EDE from ingestion of loose surface contamination. However, RESRAD-Build 1.50 models the EDE resulting from this pathway in a more complex manner. It requires additional site-specific data to take advantage of the features of the ingestion dose model. The overall pathways of each model are depicted in Figure 10.

3.2.6.1 DandD 1.0

The DandD 1.0 computer code estimates dose to a building occupant due to incidental ingestion as the product of several factors (Kennedy and Strenge, 1992, Eq. 3.19):

[Dose] = [Exposure duration]

× [Effective Transfer Rate, m^2/h]

× [Ingestion dose factor] (Eq. 4)

× [Average Surface Activity per Unit Area]

The *Effective Transfer Rate* used by DandD 1.0 has the units of m^2/h for the building occupant scenario. Ingestion dose factors are taken from FGR 11 (EPA, 1988). DandD 1.0 computes the final term, Average Surface Activity per Unit Area, from initial concentrations input by the user; it takes into account radioactive decay and ingrowth of radioactive daughters.

3.2.6.2 RESRAD-Build 1.50

RESRAD-Build 1.50 includes two incidental ingestion pathways as described in Appendix E of Yu, et al. (1994). The first means of ingestion depicted in Figure 10 is very similar to the pathway as modeled by DandD 1.0; loose contamination from the original area of contamination is ingested at a specific rate per hour. In RESRAD-Build 1.50, the *Effective Transfer Rate* for this means of ingestion has the units of h^{-1}, while the *Effective Transfer Rate* in DandD 1.0 has the units of m^2/h. The *Effective Transfer Rate* in RESRAD-Build 1.50 multiplied by the area of the contaminated source is comparable to the *Effective Transfer Rate* in DandD 1.0. **Note:** the default *Effective Transfer Rate* for direct ingestion of the source is set to zero in RESRAD-Build 1.50, making this ingestion pathway inactive unless the default is changed by the user.

The second means of ingestion of loose contamination is concerned only with the ingestion of activity that has become airborne, transported throughout the structure via RESRAD-Build 1.50's indoor air quality model, and subsequently deposited on horizontal surfaces (Yu, et al., 1994, Appendices A and B). The *Effective Transfer Rate* for this means of ingestion has the units of m^2/h, which is consistent with DandD 1.0.

The step function discussed in the section 3.2.4 of this report also restricts the ingestion dose to zero for times greater than the time required for removal of loose contamination.

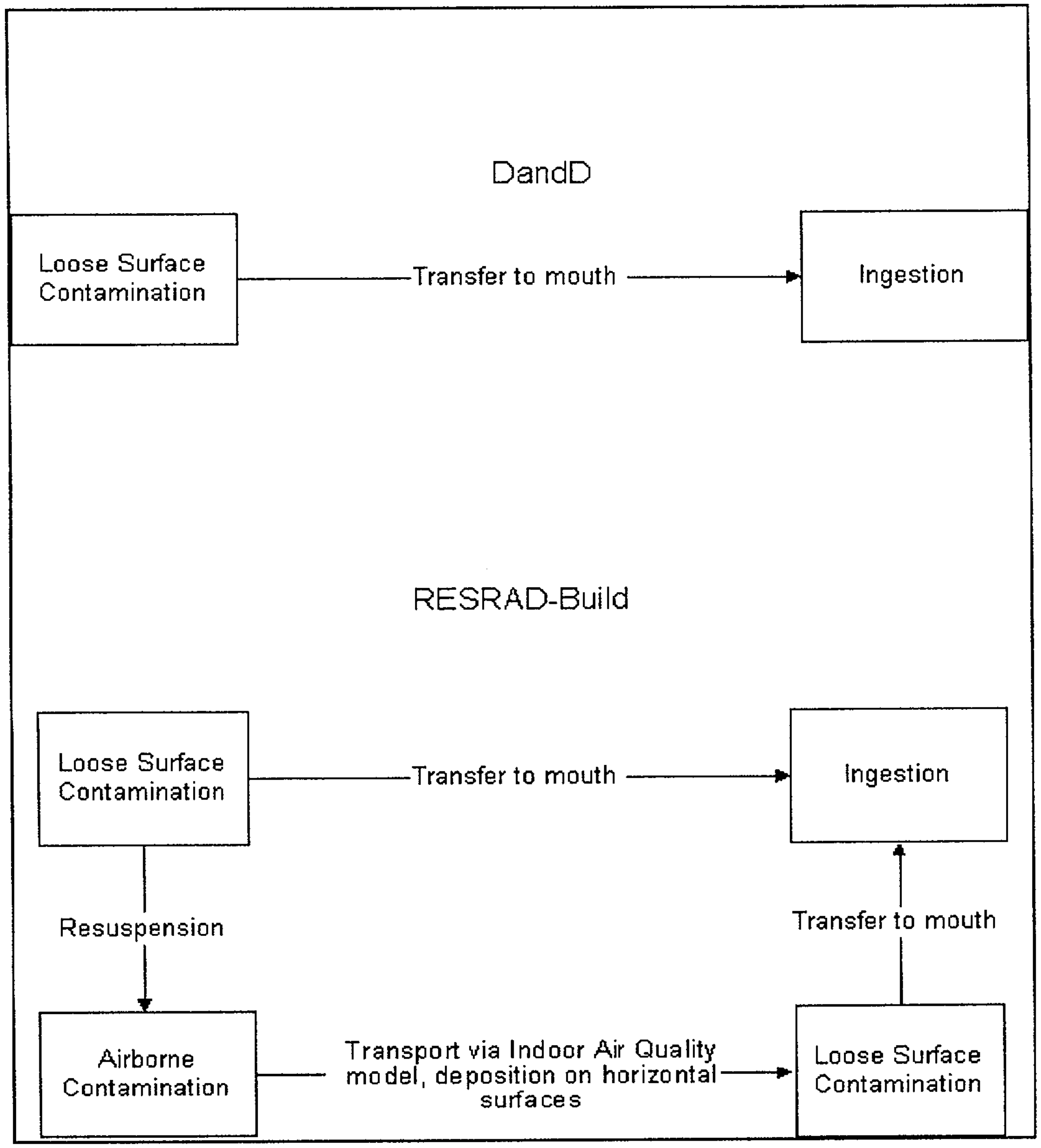

Figure 10. Ingestion models

3.2.7 Industrial Occupant Scenario Parameter Values

To evaluate the building occupancy scenario using DandD 1.0 and RESRAD-Build 1.50, the following parameters are required.

- Dose Conversion Factor for exposure to a planar source of radioactive material,
- Inhalation Dose Conversion Factors,
- Ingestion Dose Conversion Factors,
- Length of the Exposure Period,
- Occupancy Factor (RESRAD-Build 1.50 only),
- Time in Building per Year (DandD 1.0 only),
- Resuspension Factor (DandD 1.0 only),
- Resuspension Rate (RESRAD-Build 1.50 only),
- Volumetric Breathing Rate,

- Effective transfer rate for ingestion (from surfaces to mouth),
- Air Exchange Rates (RESRAD-Build 1.50 only), and
- Radon Release Fraction (RESRAD-Build 1.50 only).

Each of these parameters is provided with default values. Because of differences in the models underlying DandD 1.0 and RESRAD-Build 1.50, not all values are directly comparable. Each of these parameters is discussed in Table 33.

3.2.8 Comparisons of DandD 1.0 and RESRAD Build Simulations for the Industrial Occupant Scenario

3.2.8.1 Approach

A series of 12 DandD 1.0 and RESRAD-Build 1.50 simulations were run to provide a comparison of results when minimal changes are made to default settings and when an effort is made to match input parameters. The following isotopes were included in this evaluation: Pu-238, Pu-239, Cs-137, and Co-60.

Simulations with minimal changes to default values were run with only the following scenario specific changes:

- isotope concentration: 27 pCi/m^2 (1 Bq/m^2), and
- RESRAD-Build 1.50 was set to model surface contamination (volume contamination is the default).

Because RESRAD-Build 1.50 is a kinetic model with many more free parameters than DandD 1.0, undoubtedly there is more than one way to make it resemble DandD 1.0. The changes described below might not have been the best approach to doing this. In the series of simulations where an effort was made to match input data, the following additional changes to default settings were made in RESRAD-Build 1.50:

- Deposition rate = 0
- Resuspension rate = 0,
- Air exchange rate with environment = 14.42 per hour,
- Time for removal of source = 81.59 days,
- Contamination area = building area = 1000 m^2,
- Rate for direct ingestion of source = 1.11E-8 per h,
- Resuspended contamination ingestion rate (e.g. surface ingestion rate) = 0 m^2/h,
- Fraction removable = 1.0,
- Fraction released to air = 1.0,
- Respiration rate = 33.6 m^3/d,
- Fraction of time spent in the building = 0.267.

Selection of these values forced the value of the initial airborne concentration calculated by RESRAD Build to be 1.42E-5 Bq/m^3. This is the concentration that DandD 1.0 would calculate based on a default resuspension factor of 1.42E-5 m^{-1}. It also forced the ingestion rate of surface contamination computed by RESRAD-Build 1.50 to be equal to the DandD 1.0 default value (1.11E-5 m^2/h). The adjustments to the occupancy fraction and volume of air breathed were made to provide consistency with DandD 1.0.

Results of this comparison are provided in Table 34 and depicted in Figures 11, 12, 13, and 14.

3.3 Summary

3.3.1 Residential Farmer Scenario: RESRAD 5.61 and DandD 1.0

RESRAD 5.61 and DandD 1.0 tend to agree for doses resulting from direct irradiation, inhalation, and soil ingestion, provided that an effort is made to match input parameter values.

Because RESRAD 5.61 and DandD 1.0 groundwater models differ in significant ways, the time dependence and magnitude of doses from groundwater pathways tended to be very different in this study. This affected the doses resulting from the irrigation pathways, the drinking pathway, and the aquatic pathway. In general, DandD 1.0 simulations showed contaminants at the well sooner than RESRAD 5.62 simulations, but maximal dose rates were not always higher with one model or the other depending on the relative importance of dispersion and decay on the simulated contaminant concentration. The groundwater models in NUREG/CR-5512 Volume

Table 34. Comparison of results obtained from RESRAD-Build 1.50 and DandD 1.0 simulations for the Industrial Occupant Scenario

Isotope/pathway	RESRAD-Build 1.50 result with minimal changes to defaults, mrem/y	RESRAD-Build 1.50 result with effort to emulate DandD 1.0, mrem/y	DandD 1.0 result, mrem/y	Ratio, DandD 1.0 result to RESRAD-Build 1.50 result (with effort to emulate DandD 1.0)
Cs-137 ingestion	3.28E-4	3.50E-5	3.47E-5	0.99
Cs-137 inhalation	7.89E-5	4.01E-5	3.97E-5	0.99
Cs-137 external	2.45E-4	2.93E-4	4.61E-4	1.57
Cs-137 deposition	1.36E-4	0.0		
Cs-137 total	7.9E-4	3.7E-4	5.36E-4	1.45
Co-60 ingestion	1.51E-4	1.82E-5	1.77E-5	0.97
Co-60 inhalation	3.30E-4	1.88E-4	2.58E-4	1.37
Co-60 external	9.74E-4	1.17E-3	1.85E-3	1.58
Co-60 deposition	4.80E-4	0.0		
Co-60 total	1.9E-3	1.4E-3	2.13E-3	1.52
Pu-238 ingestion	0.0254	2.68E-3	2.24E-3	0.84
Pu-238 inhalation	1.15	0.58	0.49	0.84
Pu-238 external	7.38E-7	6.70E-7	7.02E-7	1.05
Pu-238 deposition	4.18E-7	0.0		
Pu-238 total	1.2	0.58	0.49	0.84
Pu-239 ingestion	0.029	3.01E-3	2.48E-3	0.82
Pu-239 inhalation	1.29	0.64	0.54	0.84
Pu-239 external	4.42E-7	3.00E-7	3.09E-7	1.03
Pu-239 deposition	2.52E-7	0.0		
Pu-239 total	1.32	0.64	0.54	0.84

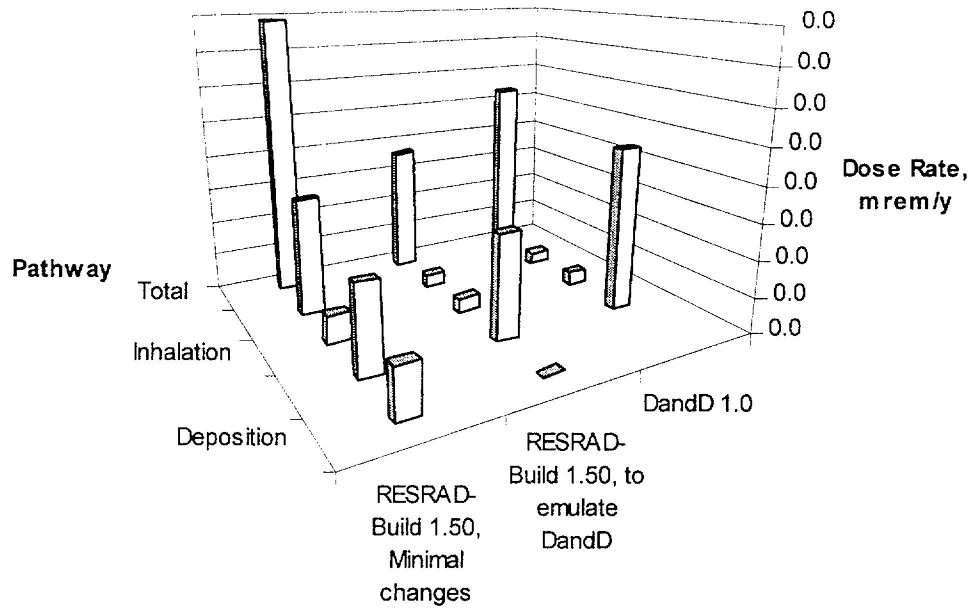

Figure 11. Comparison of RESRAD-Build and DandD results for Cesium-137

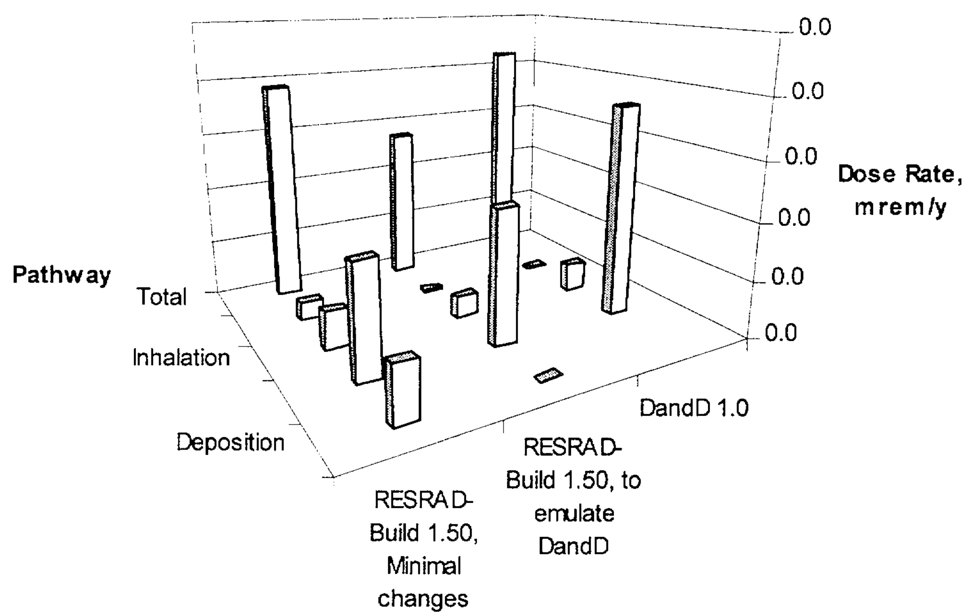

Figure 12. Comparison of RESRAD-Built and DandD results for Cobalt-60

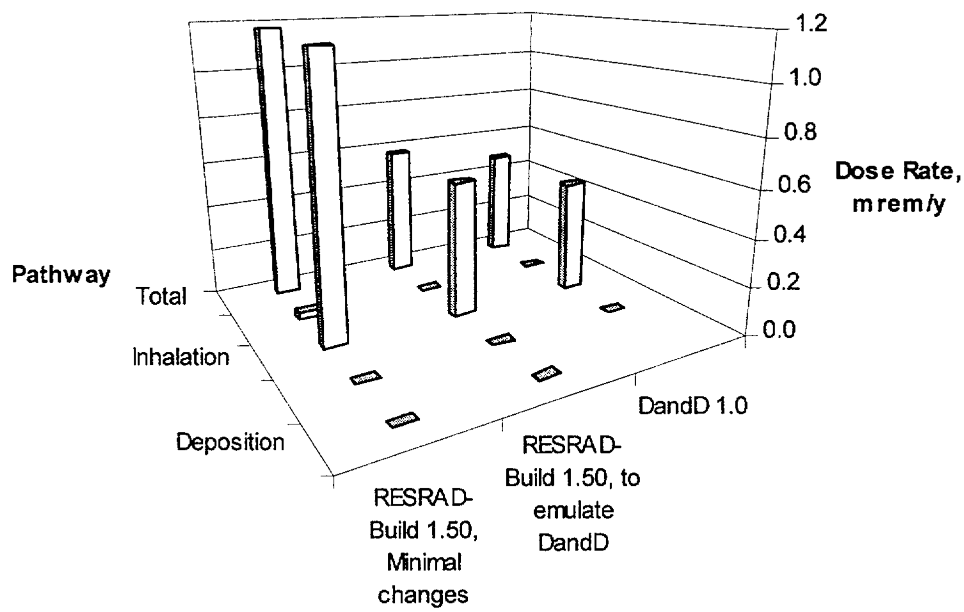

Figure 13. Comparison of RESRAD-Build and DandD results for Pu-238

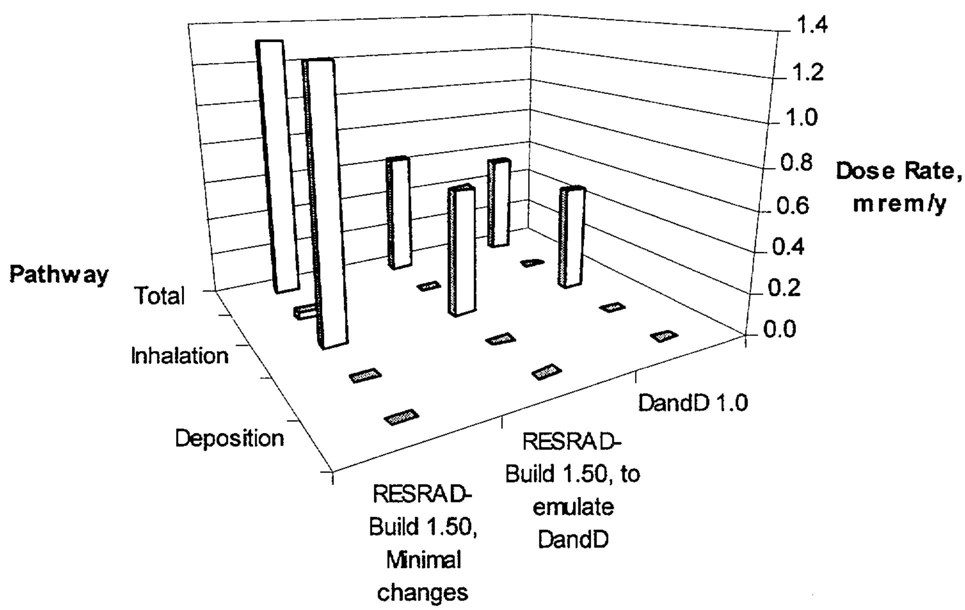

Figure 14. Comparison of RESRAD-Built and DandD results for Pu-239

1 are evaluated in greater detail in NUREG/CR-5621 (Cole et al., 1993).

Tritium and carbon-14 results in DandD 1.0 and RESRAD 5.61 are different, in part because DandD 1.0 lacks a gas or vapor flux model that would deplete the contaminated zone by release of water vapor and volatile carbon compounds to the atmosphere. DandD 1.0 models incorporation of carbon-14 by plants as a root uptake process. In contrast, RESRAD 5.61 assumes that 98% (default) of carbon incorporated into plants is a result of exchange through leaf surfaces.

The lack of a carbon-14 or tritium flux model in DandD 1.0 may cause dose from inhalation to be underestimated. This is a minor exposure pathway for these isotopes in standard residential farmer scenarios, but it could become significant in site-specific scenarios where groundwater is not potable or suitable for irrigation.

Neither DandD 1.0 nor RESRAD 5.61 model the inhalation dose due to diffusion of tritium or carbon-14 from underlying soils into a structure. This potential exposure pathway should be evaluated.

3.3.2 Industrial Occupant Scenario: RESRAD-BUILD 1.50 and DandD 1.0

In the comparison of DandD 1.0 and RESRAD-Build 1.50, there is good agreement between the initial external dose rate results for plutonium isotopes. These isotopes have a low energy 17 KeV x-ray that is rapidly attenuated by air. The size of the contaminated zone used in the comparison, 1000 m^2, is effectively infinite because of this attenuation by air.

The disagreement between initial external dose rate results for cesium-137 and cobalt-60 largely is attributable to the limited size of the contaminated zone. The low attenuation of these gamma rays by air makes a 1000 m^2 area "non-infinite" and this causes RESRAD-Build 1.50 external dose results to be smaller than those predicted by DandD 1.0. The RESRAD-Build 1.50 external dose estimates would be the more realistic.

Initial dose rate estimates for the inhalation and ingestion pathways were in reasonable agreement.

The time dependence of the DandD 1.0 and RESRAD-Build 1.50 models will be very different for two reasons. First, the step function described in section 3.2.5.2 causes all loose (removable) contamination to disappear from the structure after a specified time. Second, the air exchange between the structure and the environment that is included in RESRAD-Build 1.50's indoor air quality model causes removal of loose contamination from the structure.

Both of these factors should cause the dose rate versus time to drop more rapidly in RESRAD-Build 1.50 simulations than in DandD 1.0 simulations.

3.4 Conclusions and Recommendations

This report provides a comparison of the concepts and assumptions in three environmental dose assessment computer codes that have been used to assess compliance with license termination requirements promulgated by the Nuclear Regulatory Commission (NRC) (NRC, 1997). The computer codes compared were DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50. The comparison was largely limited to two standard exposure scenarios given in NUREG/CR-5512: a residential farmer and an industrial occupant.

The largest source of missed dose in DandD 1.0 simulations is apt to be inhalation of radon and radon-progeny.

DandD 1.0 is specifically designed as a screening model to be used within the NUREG-1549 decision framework. It is not meant to be used to set site-specific clean-up levels. If calculated doses exceed the NRC standard, the user is encouraged not only to change the default parameters to justifiable site-specific values, but more importantly, is directed to consider *site-specific models*. Given that the DandD 1.0 models are both simplistic and defensible with minimal data, site-specific models should virtually always lead to lower doses and higher associated clean up levels and therefore lower costs. The development of default parameter values for DandD 1.0 was based on a systematic, transparent, and quantitative approach that allows the user to bound the risk of making an incorrect decision and at the same time provides a clear starting point for users who need to know the potential value of collecting information prior to collecting it.

Default soil mass loading values in DandD 1.0 for plant foods consumed by humans appear to be implausibly high; the default values for these factors should be reevaluated.

In the residential farmer scenario, DandD 1.0 does not model tritium and carbon-14 in a realistic manner. It neglects inhalation of gaseous forms of these isotopes.

This neglected pathway could be significant in site specific modeling where groundwater is not potable and not suitable for use. Modification of the model to account for gaseous tritium and carbon-14 is recommended.

Neither RESRAD 5.61 nor DandD 1.0 address the inhalation of carbon-14 or tritium that has diffused from underlying soils into structures. The significance of this pathway should be evaluated.

RESRAD 5.61 potentially will provide non-conservative soil guidelines for tritium contaminated debris or soil covered by 30 cm of soil or more. This does not affect RESRAD 5.61's ability to model the residential farmer scenario given in NUREG/CR-5512 however.

RESRAD 5.61 was not specifically designed to evaluate the generic scenarios or criteria for NRC license termination. As a result there are several issues that must be addressed when applying the code to NRC DandD sites, including: translating instantaneous dose rates to average annual dose, irrigation return flow, and appropriateness of parameter values. Because of the large number of options available to the user, NRC should provide guidance to licensees on how RESRAD 5.61 should be set to run simulations on a screening level. This becomes important because some RESRAD 5.61 options, such as the choice of non-dispersive versus mass balance groundwater models, can change the simulation results by more than one order of magnitude.

Both RESRAD 5.61 and RESRAD-Build 1.50 lend themselves to assessing doses to hot-spots of residual contamination more readily than DandD 1.0.

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Appendix A: Comparison of DandD 1.0 and RESRAD 5.61 Simulations

Average Dose Rates Versus Instantaneous Dose Rates

RESRAD 5.61 calculates instantaneous dose rates and reports the result in units of mrem/y. Cleanup standards in 10 CFR 20, Subpart E "Radiological Criteria for License Termination" contain a TEDE criterion for annual dose, and not a limitation of the instantaneous dose rate. The difference between instantaneous dose rates calculated by RESRAD 5.61 and annual average dose should be most marked in the cases of tritium and carbon-14 (which are rapidly lost from surface soils) and short-lived isotopes, such as Zr/Nb-95.

To illustrate the significance of this point, RESRAD 5.61 was run twice for a residential farmer scenario involving tritium. In one instance, the annual dose rate for the first year was taken to be the instantaneous dose rate at 0.5 years (the midpoint). In the other instance, the dose rate for the first year was taken to be the average of the instantaneous dose rates calculated by RESRAD 5.61 at 0 y, 0.2 y, 0.4 y, 0.6 y, 0.8 y, and 1.0 y. The results of the two simulations are provided in Table A.1. Changes from default settings used to run these simulations are provided in Table A.2.

Comparison of the two simulations shows that the RESRAD 5.61 convention of reporting instantaneous rates can lead to difficulties in interpreting the results for the purposes of determining compliance with 10 CFR 20, Subpart E. Using the maximal instantaneous dose rate may result in rather high annual dose estimates for short-lived isotopes and isotopes which are rapidly lost from surface soils. It is suggested that RESRAD 5.61 be modified to report annual dose so that direct comparison with regulatory limits can be made.

Comparison of DandD 1.0 and RESRAD 5.61 Simulations

A comparison of DandD 1.0 and RESRAD 5.61 was completed for residential farmer scenarios for a variety of isotopes. This involved a comparison of :

- time dependence,
- results when only minimal changes were made to default values,
- a series of simulations involving wet climate sites, and
- a series of simulations involving dry climate sites.

The wet and dry climate site comparisons were made with an effort to ensure the input values of the two computer codes were comparable.

The comparison involved the following isotopes:

- Tritium and carbon-14 (both RESRAD 5.61 and DandD 1.0 have special models for these isotopes),
- Cs-137/Ba-137m,
- Radium-226 in equilibrium with radon-222 and progeny (RESRAD 5.61 has a special model for radon while DandD 1.0 does not),
- Thorium-232 in equilibrium with radon-220 and progeny,
- Cobalt-60.

DandD 1.0 simulations were used to estimate doses for the first year (0 – 365.25 days) and the fifth year (1461 – 1826.25 days) to provide a comparison of doses at different time periods. The resulting values were compared directly to RESRAD 5.61 dose rate estimates at 0.5 years and at 4.5 years. Simulations were also run for longer time periods so that each model would provide a maximum dose rate estimate.

Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer With Minimal Changes to Default Values

Approach

For this series of comparisons, DandD 1.0 was run with the changes to default values given in Table A.3. RESRAD 5.61 was run with the changes to default values given in Table A.4.

Results

Simulation results are provided in Table A.5 (tritium), Table A.6 (C-14), Table A.7 (Cs-137), and Table A.8 (Ra-226 chain).

Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer in Dry Climatic Conditions

Approach

For this series of comparisons, DandD1.0 was run with the changes to default values given in Tables A.3 and A.9. RESRAD 5.61 was run with the changes to default values given in Tables A.2 and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0.

Results

Simulation results are provided in Table A.10 (tritium), Table A.11 (C-14), Table A.12 (Cs-137), Table A.13 (Ra-226 chain), Table A.14 (Th-232), and Table A.15 (Co-60).

Comparison of DandD 1.0 and RESRAD 5.61 Results for a Residential Farmer in Wet Climatic Conditions

Approach

For this series of comparisons, DandD1.0 was run with the changes to default values given in Tables A.3 and A.16. RESRAD 5.61 was run with the changes to default values given in Tables A.4 and A.17. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0.

Results

Simulation results are provided in Table A.18 (tritium), Table A.19 (C-14), Table A.21 (Cs-137), and Table A.22 (Ra-226 chain Th232 and Co60).

Discussion

Groundwater Pathways

A primary difference in the water pathway calculations performed by DandD 1.0 and RESRAD 5.61 can be attributed to the method in which they model the unsaturated zone.

DandD 1.0 uses a well-mixed linear reservoir model, which has an inherent dispersion term in it. This causes the arrival time for radionuclides from the contaminated zone to the aquifer to be zero. Thus, DandD 1.0 simulations show radionuclides reaching the aquifer in a very short time, but at a low mass flow rate.

The unsaturated zone model in RESRAD 5.61 is based on travel time from the contaminated zone to the aquifer. This means that no radionuclides can reach the aquifer until the model simulation time exceeds the travel time. The travel time in RESRAD 5.61 is proportional to the retardation coefficient. A radionuclide, such as tritium, has a retardation coefficient of 1 because it is not adsorbed onto soil particles and, thus, travels through the unsaturated zone at the same speed as water. Carbon-14 and other radionuclides are retarded, so they take much longer to reach the water table in the RESRAD 5.61 model. This is why doses were not seen for water-dependent pathways at one year or five years for isotopes other than tritium.

Soil Ingestion

Soil ingestion doses were twice as high in RESRAD 5.61 simulations than in DandD 1.0 simulations. Upon inspection, it was determined that RESRAD 5.61 soil ingestion rates were set at the default value of 100 mg/day; this is twice as high as the DandD 1.0 default soil ingestion rates (50 mg/d). There would have been no significant difference in doses calculated for soil ingestion if consistent soil ingestion rates had been used in the comparison.

Inhalation

DandD 1.0 inhalation doses were approximately 50% higher than those calculated by RESRAD 5.61 even after the RESRAD 5.61 occupancy factors and the inhalation shielding factor were adjusted for consistency with DandD 1.0. The difference in inhalation doses largely is attributable to the RESRAD 5.61's use of a single respiration rate, while DandD 1.0 uses activity specific respiration rates for indoor, outdoor, and gardening activities.

Inhalation dose results of DandD 1.0 and RESRAD 5.61 are not comparable for radon, carbon-14, and tritium because DandD 1.0 does not have a flux model that simulates release of these isotopes to the atmosphere.

External Dose Rates

In this comparison, the primary differences in external dose rate estimates generated by DandD 1.0 and RESRAD 5.61 resulted from two factors:

- the residential shielding factors in RESRAD 5.61 and DandD 1.0 were not adjusted to be consistent with one another; DandD 1.0 was run with an external shielding factor of 0.5512 (the default value) while RESRAD 5.61 was run with an external shielding factor of 0.7 (the default value);
- DandD 1.0 does not apply a soil density correction to external dose rates; the density of soils in this study were assumed to be 1.431 g/cm^3 while the external dose conversion factor data in DandD 1.0 are based on a soil density of 1.6 g/cm^3 a density to match the value used in RESRAD for the unsaturated zone.

External doses calculated by both RESRAD 5.61 and DandD 1.0 agree well with one another when residential shielding factors and occupancy factors are assigned consistent values. The external dose results of both codes agree well with those calculated by Microshield® version 5.03 (see Table A.25).

Agricultural Pathway Doses

In this study, doses from the agricultural pathways calculated by DandD 1.0 tended to be much higher than those calculated by RESRAD 5.61. This is primarily due to the differences in the plant mass loading assumptions of the two models. RESRAD 5.61 models the plant mass loading as the net result of two processes: (1) deposition of resuspended soil on edible portions of plant foods at a constant rate, and (2) removal of soil from surfaces according to a first order (exponential) process. DandD 1.0 assumes a default plant mass loading of 10%, and this plant mass loading dominates the agricultural pathway for many isotopes.

Smaller differences in the simulated doses in this study are due to the differences in how the diet of food grown on the contaminated site is modeled. These differences occur in both the composition of the diet and transfer factors. The primary difference between DandD 1.0 and RESRAD 5.61 values for consumption rates of homegrown foods are that the DandD 1.0 values are based on production and consumption values for the specified critical group (people who garden), while RESRAD 5.61 values are based on national average consumption rates and the assumption that 50% of the entire diet is grown on site

Tritium

The results for a residential farmer scenario involving tritium, with minimal changes to defaults (see Table A.5), differed by a factor of more than 100,000 for the initial year, with DandD 1.0 providing the higher result. This result is based on the convention used throughout this report of comparing DandD 1.0 annual doses with RESRAD 5.61 mid-year dose rates. For this scenario, agreement is much better between DandD 1.0 annual dose for the first year (317 mrem/y) and the *initial* dose rate calculated by RESRAD5.61(4.8 mrem). For the fifth year of the scenario the results were in reasonable agreement; the DandD 1.0 result was only a factor of 5 higher than the RESRAD 5.61 result. A similar trend is seen in the residential farmer scenario involving tritium under dry climate conditions (see Table A.10) or wet climate conditions (see Table A.18).

It must be remembered that DandD 1.0 estimates the dose received in a year, while RESRAD 5.61 reports an instantaneous dose rate. Because RESRAD 5.61 rapidly transports tritium out of the contaminated zone and the codes have a different dose reporting basis the time dependence of the dose values reported by the two codes are different.

Carbon-14

The results for the residential farmer scenario involving carbon-14, with minimal changes to defaults, differed by a factor of more than 20,000,000 for the initial year, with DandD 1.0 providing the higher result (see Table A.6). For the fifth year of the scenario, the results were in better agreement, although the DandD 1.0 result still was a factor of 13 higher than the RESRAD 5.61 result. The results for the residential farmer scenario for a dry climate (see Table A.11) and wet climate (see Table A.19) obtained from DandD 1.0 and RESRAD 5.61 were not in good agreement for the irrigation, agricultural and aquatic pathways.

For all of the DandD 1.0 simulations involving a residential farmer scenario with carbon-14, the agricultural, irrigation, and aquatic pathways tended to be predominant. This is partly due to the absence of a carbon-14 flux model in DandD 1.0 that would allow loss to the atmosphere.

The results obtained from RESRAD 5.61 depend strongly on the reference evasion depth assumed for carbon-14. This factor determines the maximum depth from which carbon-14 can be lost via flux to the atmosphere (default 0.3 m). The RESRAD 5.61 results also depend strongly on the relative fractions of carbon assimilated by the plant from the soil and the atmosphere (defaults: soil 2%, plant 98%). The RESRAD 5.61 results provided in Table A.19 were obtained with both the reference depth and assimilation fractions set to the default values.

It is not reasonable to do so, but running RESRAD 5.61 for this scenario with the reference evasion depth set to 0 and the fraction of carbon assimilated from the soil to 100%, improves agreement with DandD 1.0, as shown in Table A.20. These changes to default parameters set the carbon-14 flux to the atmosphere to zero, and set the carbon dioxide absorption rate through leaf surfaces to zero to more closely mimic the model used in DandD 1.0.

The initially higher dose rates due to the aquatic pathway in DandD 1.0 are partly due to the faster transport of carbon-14 to groundwater relative to the transport rate associated with the RESRAD 5.61 mass balance model. Since carbon-14 moves rapidly through environmental media, the different dose rate reporting bases of the two models precludes direct comparison of the results.

Cesium-137

The results for a residential farmer scenario involving cesium-137, with minimal changes to defaults, initially were in reasonable agreement. The result DandD 1.0 provided was a factor of three greater than the RESRAD 5.61 result. However, for the fifth year of the scenario, the difference was much larger. The DandD 1.0 result was about 15 times greater than the RESRAD 5.61 result. This difference primarily is due to the much higher doses calculated for the aquatic and irrigation pathways by DandD 1.0.

Radium-226 in Secular Equilibrium with Progeny

The overall results for a residential farmer scenario involving radium-226 initially were in good agreement. However, there are large differences in the distribution of dose among pathways (see Tables A.8, A.13, and A.22). DandD 1.0 simulations suggested that agricultural pathways were the dominant source of dose to a residential farmer.

In the case of radium-226 in a dry climate, the dose calculated by DandD 1.0 from the agricultural pathway is almost entirely due to soil mass loading on foods. Better agreement between RESRAD 5.61 and DandD 1.0 is obtained for this pathway when plant mass loading is changed in DandD 1.0 from the default value of 0.1 to 0.01.

In the 5.61 simulations doses from inhalation of radon and radon progeny were the dominant exposure pathway. DandD 1.0 does not have a radon gas flux model, this causes DandD 1.0 to underestimate inhalation doses due to radon.

Thorium-232 in Secular Equilibrium with Progeny

The overall results for the residential farmer scenarios involving thorium-232 did not give good agreement when default values of plant mass loading were used. Adjusting the DandD 1.0 plant mass loading value to 0.01 and decreasing the fraction of foods grown onsite from the default values to approximate the diet in RESRAD results in significantly closer results. These adjustments cause the agricultural pathway doses calculated by DandD 1.0 for the residential farmer-dry climate scenario (Table A.14) to drop from 19,400 mrem/y to 1,220 mrem. For comparison, RESRAD 5.61 estimated the doses for this pathway to be 999 mrem/y.

Co-60

The overall results for the residential farmer scenarios involving Co-60 did not give good agreement when default values of plant mass loading were used. Adjusting the DandD 1.0 plant mass loading value to 0.01, and decreasing the fraction of foods grown onsite yields similar results for the agricultural pathway. These adjustments cause the agricultural pathway doses calculated by DandD 1.0 for the residential farmer-dry climate scenario to drop from 667 mrem/y to 292 mrem/y; for comparison, RESRAD 5.61 estimated the doses for this pathway to be 54 mrem/y.

Table A.1. Comparison of annualized dose for a residential farmer for a scenario involving tritium using RESRAD 5.61

Time (y)	Instantaneous Dose Rates (mrem/y)	Instantaneous Dose Rate at Interval Mid-Point (mrem/y)
0.0	5.055	
0.2	0.410	
0.4	3.33E-2	
0.5	--	9.49E-3
0.6	2.70E-3	
0.8	2.20E-4	
1.0	1.78E-5	
Annual estimate*	1.10 (arithmetic mean)	9.49E-3 (mid-point)

* Of course, users of RESRAD 5.61 could use more sophisticated means of estimating annual dose than those presented in Table A-1.

Table A.2. Changes to default settings used to run RESRAD 5.61 for comparison of estimated annualized and instantaneous doses. Scenario: Residential farmer, dry site, mass balance groundwater concentrations

Factor	Setting	Remarks
Contaminated zone thickness, m	0.15	Chosen for consistency with DandD 1.0
Initial Tritium Concentration, pCi/g	1000	Scenario value
Density of all zones, g/cm^3	1.431	Chosen for consistency with DandD 1.0
Total porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Effective porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Evapotranspiration coefficient	0.95	Scenario value
Precipitation Rate, m/y	0.2	Scenario value
Irrigation Rate, m/y	1.0	Scenario value
Runoff coefficient	0.4	Scenario value
Watershed area for nearby stream or pond, m^2.	10,000	Scenario value
Thickness of unsaturated zone, m	1.229	Chosen for consistency with DandD 1.0
Well pumping rate, m^3/y	1.012E4	Scenario value
Groundwater model	mass balance	Chosen for consistency with DandD 1.0
Watertable drop rate, m/y	0	Chosen for consistency with DandD 1.0
Mass loading for inhalation, mg/m^3	0.030	Chosen for consistency with DandD 1.0
Inhalation shielding factor	0.062	Chosen for consistency with DandD 1.0
Fraction of time spent indoors	0.6571	Chosen for consistency with DandD 1.0
Fraction of time spent outdoors (onsite)	0.1181	Chosen for consistency with DandD 1.0

Table A.3. DandD 1.0 changes to defaults values in residential farmer scenario

Factor	Value	Remarks
H-3	1,000 pCi/g	

Table A.3. DandD 1.0 changes to defaults values in residential farmer scenario

Factor	Value	Remarks
C-14	1,000 pCi/g	
Cs-137/Ba-137m	1,000 pCi/g	
Ra-226 + chain	1,000 pCi/g	
start time (first year), d	365.25	Times chosen to ensure that DandD 1.0 gave the dose for the time interval of interest.
stop time (first year), d	365.25	
start time (fifth year), d	1461	
stop time (fifth year), d	1826.25	

Table A.4. RESRAD5.61 changes to defaults values in residential farmer scenario

Factor	Value	Remarks
H-3	1,000 pCi/g	
C-14	1,000 pCi/g	
Cs-137/Ba-137m	1,000 pCi/g	
Ra-226 + chain	1,000 pCi/g	
dose rate evaluation time (first year), y	0.5	Time corresponds to midpoint of first year.
dose rate evaluation time (fifth year), y	4.5	Time corresponds to midpoint of fifth year.
Thickness of contaminated zone, m	0.15	Chosen to make source term and geometry comparable to DandD 1.0.

Table A.5. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Inhalation	3.89E-6	0	1.49E-4	0.0
Plant	NA	NA	1.38E-3	0.0
Meat	NA	NA	1.96E-4	0.0
Milk	NA	NA	1.75E-4	0.0
Soil Ingestion	8.81E-4	1.60E-5	6.99E-7	0.0
Water	6.04	5.34	0.0	2.853
Fish / Aquatic	0.127	0.113	0.0	1.76E-4
Irrig water → → Plant	NA	NA	0.0	0.121
Irrig water → → Meat	NA	NA	0.0	6.27E-2
Irrig water → → Milk	NA	NA	0.0	0.188
Irrigation pathways	5.36	4.74	NA	NA
Agriculture	305	5.54	NA	NA
Total	317	15.7	1.92E-3	3.26

Table A.6. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	5.27E-4	0	0
Inhalation	1.28E-4	1.03E-5	0	0
Plant	NA	NA	4.31E-5	0
Meat	NA	NA	1.00E-5	0
Milk	NA	NA	4.28E-6	0
Soil Ingestion	2.95E-2	2.37E-3	0	0
Water	10.6	57.5	0	120
Fish / Aquatic	1,030	5,580	0	327
Irrig water → → Plant	NA	NA	0	22.3
Irrig water → → Meat	NA	NA	0	8.01
Irrig water → → Milk	NA	NA	0	18.4
Irrigation pathways	150	813	NA	NA
Agriculture	119	9.58	NA	NA
Total	1,310	6,460	5.74E-5	495

Table A.7. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Cs-137, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	1,460	169	1,750	1,570
Inhalation	1.96E-3	2.27E-4	2.30E-2	2.03E-2
Plant	NA	NA	28.6	25.1
Meat	NA	NA	44.3	38.9
Milk	NA	NA	15.7	13.8
Soil Ingestion	0.70	8.10E-2	1.35	1.18
Water	58.0	550	0	0
Fish / Aquatic	2,440	23,200	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	396	3,760	NA	NA
Agriculture	567	65.6	NA	NA
Total	4,930	27,800	1,840	1,650

Table A.8. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain, with the changes to default values given in Tables A.3 and A.4

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	4,610	4,540	5,530	4,830
Inhalation	1.98	1.86	23.0	20.2
Radon	NA	NA	25,450	22,010
Plant	NA	NA	1,800	1,580
Meat	NA	NA	151	133
Milk	NA	NA	111	96.8
Soil Ingestion	123	117	232	205
Water	326	1,110	0	0
Fish / Aquatic	2450	8,870	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	475	1,530	NA	NA
Agriculture	40,400	38,600	NA	NA
Total	48,400	54,700	33,300	28,900

Table A.9. Changes to default parameters used in DandD 1.0 simulations for a residential farmer scenario in a dry climate

Factor	Setting
Surface layer ratio	0.683
Unsaturated zone ratio	0.683
Infiltration rate,	0.056
Cultivated area, m^2	10,000
Irrigation rate, L/m^2d	2.738

Table A.10. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Inhalation	3.89E-6	2.87E-7	1.46E-3	0
Plant	NA	NA	6.33E-3	0
Meat	NA	NA	8.99E-4	0
Milk	NA	NA	8.02E-4	0

Table A.10. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Soil Ingestion	8.81E-4	6.50E-5	3.40E-6	0
Water	1.03E-1	5.67E-1	0	0
Fish / Aquatic	3.93E-3	2.16E-2	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	9.15E-2	5.04E-1	NA	NA
Agriculture	305	22.5	NA	NA
Total	306	23.6	9.49E-3	1.47E-24

Table A.11. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	4.75E-3	0	0
Inhalation	1.28E-4	9.29E-5	5.79E-6	0
Plant	NA	NA	7.22E-3	0
Meat	NA	NA	1.68E-3	0
Milk	NA	NA	7.17E-4	0
Soil Ingestion	2.95E-2	2.14E-2	0	0
Water	2.24E-2	5.14E-1	0	0
Fish / Aquatic	3.93	90.3	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	6.49E-1	1.49	NA	NA
Agriculture	119	86.3	NA	NA
Total	124	192	9.62E-3	0

Table A.12. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving cesium-137 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	1460	1160	1,650	1,370
Inhalation	1.96E-3	1.55E-3	1.21E-3	1.00E-3
Plant	NA	NA	28.3	23.4
Meat	NA	NA	44.0	36.4
Milk	NA	NA	15.6	12.9
Soil Ingestion	6.99E-1	5.54E-1	1.38	1.14
Water	9.91E-2	2.27	0	
Fish / Aquatic	7.56	173	0	
Irrig water → → Plant	NA	NA	0	
Irrig water → → Meat	NA	NA	0	
Irrig water → → Milk	NA	NA	0	
Irrigation pathways	1.40	31.9	NA	NA
Agriculture	567	449	NA	NA
Total	2040	1820	1,741	1,440

Table A.13. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	4610	4600	5,340	5,330
Inhalation	1.98	1.96	1.24	1.24
Radon	NA	NA	30,800	30,700
Plant	NA	NA	1,834	1,830
Meat	NA	NA	153	153
Milk	NA	NA	113	113
Soil Ingestion	123	123	243	243
Water	5.52E-1	2.02	0	0
Fish / Aquatic	7.05	28.5	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	1.74	5.84	NA	NA

Table A.13. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0 (continued)

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Agriculture	40,400	40,200	NA	NA
Total	45,200	45,000	38,500	38,400

Table A.14. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Th-232 + chain in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,530	6,490	7,590	7,560
Inhalation	122	121	77.3	76.6
Radon	NA	NA	338	332
Plant	NA	NA	892	889
Meat	NA	NA	49.0	48.8
Milk	NA	NA	57.6	57.5
Soil Ingestion	70.5	69.8	141	140
Water	0.058	1.45	0	0
Fish / Aquatic	0.21	5.36	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	0.20	5.11	NA	NA
Agriculture	19,400	19,200	NA	NA
Total	26,100	25,900	9,140	9,110

Table A.15. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Co-60 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,200	3,660	7,090	4,189
Inhalation	1.3E-2	7.7E-3	8.0E-3	4.7E-3

Table A.15. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Co-60 in a dry climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0 (continued)

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Radon	NA	NA	NA	NA
Plant	NA	NA	29.1	17.2
Meat	NA	NA	22.0	13.0
Milk	NA	NA	2.83	1.67
Soil Ingestion	0.36	0.21	0.71	0.42
Water	2.6E-6	4.1E-5	0	0
Fish / Aquatic	3.2E-5	5.2E-4	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.0E-5	3.2E-4	NA	NA
Agriculture	667	394	NA	NA
Total	6,870	4,060	7,150	4,220

Table A.16. Changes to default parameters used in DandD 1.0 simulations for a residential farmer scenario in a wet climate

Factor	Setting	Remarks
Surface layer ratio	0.7727	Based on equations given in RESRAD 5.61 users manual (Yu, et al. 1993)
Unsaturated zone ratio	0.7727	Based on equations given in RESRAD 5.61 users manual (Yu, et al. 1993)
Infiltration rate,	0.30	
Cultivated area, m^2	10,000	
Irrigation rate, L/m^2d	0	

Table A.17. Changes to Default settings used to run RESRAD 5.61 simulations for scenarios involving a residential farmer, wet site, mass balance groundwater concentrations

Factor	Setting	Remarks
Contaminated zone thickness, m	0.15	Chosen for consistency with DandD 1.0
Density of all zones, g/cm^3	1.431	Chosen for consistency with DandD 1.0
Total porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Effective porosity of all zones	0.4599	Chosen for consistency with DandD 1.0
Evapotranspiration coefficient	0.50	

Table A.17. Changes to Default settings used to run RESRAD 5.61 simulations for scenarios involving a residential farmer, wet site, mass balance groundwater concentrations (continued)

Factor	Setting	Remarks
Precipitation Rate, m/y	1.0	
Irrigation Rate, m/y	0.0	
Runoff coefficient	0.4	
Watershed area for nearby stream or pond, m^2	10,000	
Thickness of unsaturated zone, m	1.229	Chosen for consistency with DandD 1.0
Well pumping rate, m^3/y	118	
Groundwater model	mass balance	Chosen for consistency with DandD 1.0
Mass loading for inhalation, mg/m^3	0.030	Chosen for consistency with DandD 1.0
Inhalation shielding factor	0.062	Chosen for consistency with DandD 1.0
Fraction of time spent indoors	0.6571	Chosen for consistency with DandD 1.0
Fraction of time spent outdoors (onsite)	0.1181	Chosen for consistency with DandD 1.0

Table A.18. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving tritium in a wet climate

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Inhalation	3.89E-6	5.20E-16	2.75E-3	0
Plant	NA	NA	4.25E-2	0
Meat	NA	NA	6.04E-3	0
Milk	NA	NA	5.39E-3	0
Soil Ingestion	8.81E-4	1.18E-13	2.58E-5	0
Water	3.19	1.45	0	3.80E-6
Fish / Aquatic	9.58E-2	4.36E-2	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.82	1.28	NA	NA
Agriculture	305	4.08E-8	NA	NA
Total	311	2.78	5.66E-2	4.13E-6

Table A.19. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a wet climate

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	1.39E-3	0	0
Inhalation	1.28E-4	2.72E-5	5.11E-6	0
Plant	NA	NA	6.38E-3	0

Table A.19. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a wet climate

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
Meat	NA	NA	1.48E-3	0
Milk	NA	NA	6.34E-4	0
Soil Ingestion	2.95E-2	6.25E-3	0	0
Water	1.55	21.9	0	0
Fish / Aquatic	214	3020	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	1.43	20.1	NA	NA
Agriculture	119	25.3	NA	NA
Total	337	3090	8.51E-3	0

Table A.20. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving carbon-14 in a wet climate. RESRAD 5.61 was run assuming the reference depth for carbon-14 flux to be zero, and that carbon is only assimilated through the root systems of plants

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6.57E-3	1.39E-3	6.64E-3	2.0E-3
Inhalation	1.28E-4	2.72E-5	7.0E-5	2.1E-5
Plant	NA	NA	325	96.2
Meat	NA	NA	75.6	22.3
Milk	NA	NA	32.4	9.57
Soil Ingestion	2.95E-2	6.25E-3	0.051	1.5E-2
Water	1.55	21.9	0	0
Fish / Aquatic	214	3020	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	1.43	20.1	NA	NA
Agriculture	119	25.3	NA	NA
Total	337	3090	433	128

Table A.21. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving cesium-137 in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	1,460	683	1,570	849
Inhalation	1.96E-3	9.14E-4	1.15E-3	6.22E-4
Plant	NA	NA	26.9	14.6
Meat	NA	NA	41.7	22.6
Milk	NA	NA	14.8	8.01
Soil Ingestion	6.99E-1	3.27E-1	1.31	0.71
Water	7.22	131	0	0
Fish / Aquatic	433	7,890	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.62	47.7	NA	NA
Agriculture	567	265	NA	NA
Total	2,470	9,020	1,650	895

Table A.22. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Ra-226 + chain in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	4,610	4,590	5,340	5,320
Inhalation	1.98	1.94	1.23	1.23
Radon	NA	NA	30,800	30,700
Plant	NA	NA	1,830	1,830
Meat	NA	NA	153	153
Milk	NA	NA	113	112
Soil Ingestion	123	121	243	243
Water	40.2	145	0	0
Fish / Aquatic	410	1610	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.97	11.7	NA	NA
Agriculture	40,400	39,800	NA	NA
Total	45,600	46,300	38,500	38,300

Table A.23. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Th-232 + chain in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,530	6,360	7,571	7,414
Inhalation	122	116	76.9	73.7
Radon	NA	NA	332	324
Plant	NA	NA	891	878
Meat	NA	NA	48.9	48.1
Milk	NA	NA	57.6	56.8
Soil Ingestion	70.5	67.5	140	136
Water	4.35	107	0	0
Fish / Aquatic	12.7	311	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	6.64E-003	0.165	NA	NA
Agriculture	19,400	18,600	NA	NA
Total	26,100	25,500	9,120	8,930

Table A.24. Comparison of DandD 1.0 and RESRAD 5.61 results for a residential farmer scenario involving Co-60 in a wet climate. Changes to default values were made in accordance with Tables A.3, A.9, A.2, and A.4. In addition, distribution or partition coefficient values used in RESRAD 5.61 simulations were chosen to be consistent with those provided in DandD 1.0

Pathway	DandD 1.0, mrem/y		RESRAD 5.61, mrem/y	
	year 1	year 5	year 1	year 5
External	6,200	3,650	7,090	4,170
Inhalation	1.31E-2	7.71E-3	8.0E-3	4.7E-3
Radon	NA	NA	NA	NA
Plant	NA	NA	29.1	17.1
Meat	NA	NA	21.9	12.9
Milk	NA	NA	2.83	1.67
Soil Ingestion	0.357	2.10E-1	0.71	0.42
Water	1.94E-4	3.13E-3	0	0
Fish / Aquatic	1.92E-3	3.1E-2	0	0
Irrig water → → Plant	NA	NA	0	0
Irrig water → → Meat	NA	NA	0	0
Irrig water → → Milk	NA	NA	0	0
Irrigation pathways	2.91E-5	4.69E-4	NA	NA
Agriculture	667	393	NA	NA
Total	6,870	4,040	7,140	4,210

Table A.25. Comparison of External Radiation dose results from RESRAD 5.61, DandD 1.0, and Microshield 5.03. Default values are given in parenthesis.

Factor	DandD 1.0	RESRAD 5.61
Indoor exposure time (days)	(240)	240 (182.5)
Outdoor exposure time (days)	(40.2)	43.12 (91.25)
Gardening exposure time (days)	(2.92)	---
Gamma shielding factor	(0.5512)	(0.7)
Cs-137 result (mrem/y) for 1000 pCi/g soil	1,460 (see Table A.7)	1,778 (see Table A.7)
Microshield result (mrem/y) for 1000 pCi/g Cs-137	1,391	1,672
Ra-226 + chain result (mrem/y) for 1000 pCi/g soil	4,610 (see Table A.8)	5,530 (see Table A.8)
Microshield result (mrem/y) for 1000 pCi/g Ra-226 + chain	4,358	5,239

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202 U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG/CR-5512, Volume 4
2. TITLE AND SUBTITLE Comparison of the Models and Assumptions used in the DandD 1.0, RESRAD 5.61, and RESRAD-Build 1.50 Computer Codes with Respect to the Residential Farmer and Industrial Occupant Scenarios Provided in NUREG/CR-5512 Draft for Comment	3. DATE REPORT PUBLISHED MONTH: October YEAR: 1999 4. FIN OR GRANT NUMBER W6227
5. AUTHOR(S) Rick Haaker (1), Theresa Brown (2), David Updegraff (3)	6. TYPE OF REPORT NUREG/CR 7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

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Washington, DC 20555 -0001

10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

This report provides a detailed comparison of the models, simplifying assumptions, and default parameter values implemented by the DandD 1.0, RESRAD 5.61, and RESRAD Build 1.50 computer codes. Each of these codes is a potentially useful tool for demonstrating compliance with the License Termination Rule, 10 CFR 20, Subpart E. The comparison was limited to the industrial occupant and residential farmer scenarios defined in NUREG/CR-5512, Volume 1. This report is intended to describe where and how the models and default parameter values in each of the codes differ for the specified scenarios. Strengths, weaknesses and limitations of the models are identified. The practical impacts of the identified differences to dose assessment results are discussed.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*	13. AVAILABILITY STATEMENT
Decommission Decontamination License Termination software DandD screening dose assessment	unlimited 14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified 15. NUMBER OF PAGES 16. PRICE