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A MANUAL FOR IMPLEMENTING RESIDUAL RADIOACTIVE MATERIAL GUIDELINES

A Supplement to U.S. Department of Energy Guidelines for Residual Radioactive Material at Formerly Utilized Sites Remedial Action Program and Surplus Facilities Management Program Sites

by

T.L. Gilbert,* C. Yu, Y.C. Yuan,‡ A.J. Zielen,
M.J. Jusko, and A. Wallo III§

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*Current address: Chicago Center for Religion and Science, Chicago, Illinois
‡Current address: Dames & Moore, West Valley Demonstration Project, West Valley, New York
§U.S. Department of Energy, Office of Remedial Action and Waste Technology

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FOREWORD

In the late 1970s and early 1980s, the U.S. Department of Energy (DOE) began work at several sites of the Formerly Utilized Sites Remedial Action Program (FUSRAP) and the Surplus Facilities Management Program (SFMP). These sites became contaminated as a result of previous activities for government nuclear programs. Criteria for cleanup of these sites were proposed on a site-by-site basis by the field offices responsible for the specific remedial actions. The criteria and even the approaches to development of cleanup criteria varied. In reviewing the proposed criteria, DOE Headquarters realized that general guidelines were needed for these activities. The major requirement identified was the need for criteria for residual radioactive material in soil. At the request of DOE Headquarters, the national laboratories made several attempts to develop soil criteria applicable to remedial actions. In 1983, DOE began to consolidate these criteria and associated procedures in order to identify generic soil criteria for all DOE remedial actions.

The DOE Headquarters established a working group comprised of representatives from the concerned headquarters program offices; the Office of Environment, Safety, and Health; DOE operations offices; and the national laboratories involved in development of specific criteria for decontamination efforts. The working group activities were also coordinated with representatives of the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC). These representatives attended several meetings of the working group in an advisory capacity.

The initial charter of the working group was to develop an acceptable set of generic soil criteria. However, recommendations from the first meeting of the complete group resulted in DOE expanding the charter to include all aspects of cleanup operations. Also, recognizing that soil criteria are significantly affected by many site-specific factors, the working group recommended that a generic procedure for deriving soil criteria should be included in the guidelines rather than generic soil concentration limits. The following is a summary of the working group's findings and recommendations:

1. The guidelines should be consistent with other available standards where they are appropriate; examples cited included

    - EPA standards for Uranium Mill Tailings Remedial Action (UMTRA) (40 CFR Part 192), which were in draft status during the initial part of the working group's activities;

- NRC surface contamination limits (Guidelines for Decontamination of Facilities and Equipment Prior to Release for Unrestricted Use or Termination of Licenses for Byproduct, Source, or Special Nuclear Material, July 1982); and

- DOE Orders.

2. For its residual radioactivity guidelines, DOE should adopt and use the recommendations and system of standards and models provided in Publications 26 and 30 of the International Commission on Radiological Protection (ICRP). This includes use of the concept of effective dose equivalent rather than critical organ dose (ICRP Publication 2) for defining dose limits for the general public and adoption of the lifetime average limit of 100 mrem/yr effective dose equivalent instead of the DOE limit for the general public of 500 mrem/yr in effect at that time.

3. Soil criteria for nuclides other than those covered under the UMTRA standard (i.e., radium and thorium) should be derived for each site according to the dose limit. These criteria should be based on a conservatively assumed plausible-use (realistic) scenario.

4. The as low as reasonably achievable (ALARA) process should be incorporated into the guidelines for all phases of a remedial action.

5. No attempt should be made by DOE to define "de minimis" or "below regulatory concern" levels.

The DOE guidelines for residual radioactive material were developed in accordance with these recommendations and were first issued in February 1985. The second revision was prepared and issued in March 1987. The revisions were generally procedural in nature and were directed toward resolving implementation problems experienced with the earlier version. The guidelines are supported by a separate, but integral, implementation manual (this document) that contains:

- Pathway analysis methodology for deriving soil criteria,

- Associated dose conversion factors,

- Environmental transport factors, and

- Guidance on applying the guidelines, including hot spot criteria and ALARA.

The methodology for deriving soil guidelines is coded in a microcomputer program, RESRAD. The code and this manual (which includes a user's guide for RESRAD) have been developed to support implementation of the DOE guidelines. The manual and code have been used in draft form to allow field testing, and the comments received over this test period have been incorporated into this code and manual.

The computer software for RESRAD has been developed under sponsorship of DOE. Any further distribution by any holder of the RESRAD software package (or other data therein) outside of DOE offices or other DOE contractors, unless otherwise specifically provided for, is prohibited without approval of the National Energy Software Center. Requests from outside DOE for DOE-developed computer software should be directed to the Director, National Energy Software Center, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439.

The RESRAD code is available on MS-DOS diskettes from the National Energy Software Center.

ACKNOWLEDGMENTS

This document is based on 1985, 1987, and 1988 draft versions. During this work, the authors were assisted by many experts from the scientific community. Special thanks are due to Keith Eckerman (Oak Ridge National Laboratory) for providing internal dose conversion factors (Chapter 3 of the 1985 draft); William Kennedy and Bruce Napier (Battelle Pacific Northwest Laboratory) for providing basic materials for the food chain pathways (Chapter 4 of the 1985 draft); Jack Healy (Los Alamos National Laboratory) and Joe Soldat (Battelle Pacific Northwest Laboratory) for contributions to earlier versions of the discussion of ALARA; and Wayne Hansen (Los Alamos National Laboratory) for providing valuable discussions and counsel for earlier versions of this document. The authors acknowledge the assistance of Carl Welty (U.S. Department of Energy [DOE] Office for Environment, Safety, and Health) and R.E. Baker (Energetics, Inc.) in reviewing the final ALARA section.

Many constructive comments and suggestions were received from those who reviewed the RESRAD code and the manual. The authors wish to thank Roy Eckart (University of Cincinnati), R.D. Freeberg (DOE), G.R. Grandbouche (DOE), Ken Karp (UNC Geotech), R. Murri (UNC Geotech), McLouis Robinet (Argonne National Laboratory), and Lars Soholt (Los Alamos National Laboratory).

Finally, we thank Dee Wyman for editorial assistance through the various drafts of this document.

NOMENCLATURE

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ALARA	as low as reasonably achievable
AMAD	activity median aerodynamic diameter
ASR	air/soil concentration ratio
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended
CFR	Code of Federal Regulations
DCF	dose conversion factor
DF	dietary factor
DSR	dose/source ratio
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ETF	environmental transport factor
FA	area factor
FAR	food/air concentration ratio
FC	cover factor
FCD	cover and depth factor
FD	depth factor
FDW	fraction of drinking water from site
FQR	radionuclide transfer factor for meat and milk
FSR	food/soil concentration ratio
FUSRAP	Formerly Utilization Sites Remedial Action Program
FWR	food/water concentration ratio
GI	gastrointestinal
GM	geometric mean
GSD	geometric standard deviation
ICRP	International Commission on Radiological Protection
LLD	lower limit of detection
MB	mass-balance (model)
NCRP	National Council on Radiation Protection and Measurements
ND	nondispersion (model)
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
QSR	fodder/soil or livestock-water/soil concentration ratio
SARA	Superfund Amendments and Reauthorization Act of 1986
SF	source factor
SFMP	Surplus Facilities Management Program
TDS	total dissolved solids
UMTRA	Uranium Mill Tailings Remedial Action
USLE	Universal Soil Loss Equation

ACRONYMS, INITIALISMS, AND ABBREVIATIONS (Cont'd)

WEF	water exposure factor
WSR	water/soil concentration ratio

UNITS OF MEASURE

cm	centimeter(s)
cm^3	cubic centimeter(s)
Ci	curie(s)
d	day(s)
g	gram(s)
h	hour(s)
ha	hectare(s)
kg	kilogram(s)
L	liter(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
min	minute(s)
mm	millimeter(s)
mrem	millirem(s)
µs	microsecond(s)
ms	millisecond(s)
pCi	picocurie(s)
s	second(s)
yr	year(s)

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ABSTRACT

This manual presents information for implementing U.S. Department of Energy (DOE) guidelines for residual radioactive material at sites identified by the Formerly Utilized Sites Remedial Action Program (FUSRAP) and the Surplus Facilities Management Program (SFMP). It describes the analysis and models used to derive site-specific guidelines for allowable residual concentrations of radionuclides in soil and the design and use of the RESRAD computer code for calculating guideline values. It also describes procedures for implementing DOE policy for reducing residual radioactivity to levels that are as low as reasonably achievable.

1 INTRODUCTION

This manual presents information for implementing U.S. Department of Energy (DOE) guidelines for residual radioactive material at sites identified by the Formerly Utilized Sites Remedial Action Program (FUSRAP) and the Surplus Facilities Management Program (SFMP). These guidelines (DOE 1987) are referred to herein as the "DOE guidelines" and are reproduced in Appendix A. The manual describes the analysis and models used to derive site-specific guidelines for allowable residual concentrations of radionuclides in soil and the design and use of a computer code for calculating guideline values. It also describes procedures for implementing DOE policy for reducing residual radioactivity to levels that are as low as reasonably achievable (ALARA).

A guideline is defined as a radionuclide concentration or a level of radiation or radioactivity that is acceptable if a site is to be used without radiological restrictions. Guidelines are expressed as (1) concentrations of residual radionuclides in soil, (2) concentrations of airborne radon decay products, (3) levels of external gamma radiation, (4) levels of radioactivity from surface contamination, and (5) concentrations of residual radionuclides in air and water. Soil is defined as unconsolidated earth material, including rubble and debris that may be present in earth material. Generic guidelines for thorium and radium in soil, airborne radon decay products, external gamma radiation, surface contamination, and residual radionuclides in air and water are specified in the DOE guidelines. Soil guidelines for other radionuclides must be derived on a site-specific basis using the DOE residual radioactive material code (RESRAD) described in Chapter 4 of this manual.

To derive site-specific soil guidelines, a basic radiation dose limit of 100 mrem/yr (as specified in the DOE guidelines) is applied to a member of a critical population group. The radiation dose is defined here as the effective dose equivalent from external radiation plus the committed effective dose equivalent from internal radiation (International Commission on Radiological Protection [ICRP] 1984, Section 2.1). The radiation dose limit is based on radiation protection standards and requirements specified in DOE Order 5400.xx (DOE 1989). The critical population group is a relatively small, homogeneous group that is representative of those individuals in the population expected to potentially receive the largest radiation dose. It is assumed, for the purpose of deriving soil guidelines, that the critical population group is a family that establishes residence on a site after the site has been released for use without radiological restrictions. The controlling principles for all guidelines are (1) the annual radiation dose received by a member of the critical population group from the residual radioactive material -- predicted by a realistic but reasonably conservative analysis and averaged over a time interval of 50 years -- should not exceed the basic dose limit of 100 mrem/yr and (2) doses should be kept as low as reasonably achievable. Final cleanup standards (authorized limits), and in some cases guidelines, may be based on a different scenario if the resident family scenario is not appropriate for the specific property or if another plausible-use scenario would result in significantly greater potential for exposure.

All significant exposure pathways for the critical population group must be considered in deriving soil guidelines. These pathways include:

- Direct exposure to external radiation from the contaminated soil material;
- Internal radiation from inhalation of airborne radionuclides; and

- Internal radiation from ingestion of
  - Plant foods grown in the contaminated soil,
  - Meat and milk from livestock fed with contaminated fodder and water,
  - Drinking water from a contaminated well, and
  - Fish from a contaminated pond.

The contribution from inhalation of radon decay products is not included in the current version of RESRAD because generic guidelines have been established for the concentration of radium in soil, which is the only source of radon.

The residues at some FUSRAP and SFMP sites might include material that is hazardous because of its chemical (nonradiological) toxicity. An analysis of the risks from chemical toxicity is outside the scope of this manual. If, however, there is evidence that residues with potential nonradiological hazards are present, a separate analysis should be carried out that is consistent with the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, or other appropriate regulations; the purpose of this analysis would be to identify applicable or relevant and appropriate requirements and to ensure that the public is adequately protected.

Estimating the collective (population) dose is outside the scope of this manual because soil concentration guidelines do not explicitly take into account the collective dose to the general population. The collective dose is, however, an important consideration for applying the DOE policy of reducing the radiation dose received by all individuals (workers, critical groups, and the general population) to ALARA levels. Estimates of the collective dose to the general population may be provided in the documentation produced during the environmental analyses for site remedial action. The methods presented in this manual for deriving the dose to a critical population group of on-site residents could readily be extended to the general population by adding pathways for off-site exposure.

The family-farm scenario used for deriving site-specific soil concentration guidelines is, in most cases, considered credible in the long term. The scenario may be inapplicable in the short term because it is incompatible with currently allowed or feasible use of a site. Soil concentration guidelines derived by the procedures presented here may be unreasonably low for such use. Conversely, there may be situations in which residual radioactivity can be reduced to levels below guideline values at reasonable cost. "Authorized limits" are introduced in the DOE guidelines in order to provide for these situations.

Authorized limits are defined as concentrations of radionuclides and levels of radioactivity that must not be exceeded if the remedial action or decontamination effort is to be considered completed and the site is to be released for use without radiological restrictions. Authorized limits are set equal to guideline values unless (1) variations (supplemental limits or exceptions) specified in Section F of the DOE guidelines apply, in which case an authorized limit may be set above the corresponding guideline value for the specific location or condition to which the exception applies, or (2) it can be clearly established that limits below the guideline values are reasonable and that use of such limits are cost beneficial and comply with appropriate requirements (DOE guidelines, Sections E and F).

In addition to requiring that residual radioactivity be below guideline values, DOE also requires -- as a matter of policy -- that the ALARA process be applied to a site before it is released for use without radiological restrictions. Socioeconomic considerations, as well as technical feasibility, are taken into account in implementing this policy. The ALARA requirements apply to release of FUSRAP and SFMP sites for use with or without restrictions and to management of sites that cannot be released because it is not practicable to reduce the residual radioactivity below authorized limits.

Models for deriving soil concentration guidelines from dose limits are simplified representations of complex processes. It is not feasible to obtain sufficient data to fully or accurately characterize transport and exposure processes. Similarly, it is not possible to predict future conditions with certainty. Hence, there will be uncertainties in the guideline values. The models described in this manual and incorporated into RESRAD have been chosen to be realistic but reasonably conservative, and the calculated doses corresponding to guideline values of the radionuclide concentrations are expected to be reasonably conservative estimates (overestimates) of the actual doses.

The derivation of guideline values for radionuclide concentrations in soil is based on a pathway analysis method known as the concentration factor method (U.S. Nuclear Regulatory Commission [NRC] 1977; ICRP 1979-1982; Till and Meyer 1983; National Council on Radiation Protection and Measurements [NCRP] 1984). With this method, the relation between radionuclide concentrations in soil and the dose to a member of a critical population group is expressed as a pathway sum, which consists of a sum of products of "pathway factors." Pathway factors correspond to pathway segments connecting compartments in the environment between which radionuclides can be transported or radiation transmitted. Most pathway factors are steady-state ratios of concentrations in adjoining compartments. Some are factors for conversion from a radionuclide concentration to a radiation level or radiation dose, and others are use and occupancy factors that affect exposure. Each term in the sum corresponds to a pathway of connected segments. A pathway product or pathway factor can be added, deleted, or replaced without affecting the other pathways or pathway factors. This structuring facilitates the use of alternative models for different conditions or transport processes and the incorporation of additional pathways. Thus, RESRAD can be easily modified or tailored to model any given situation by merely adding or replacing factors or terms in the pathway sum.

This manual covers procedures only for deriving site-specific guidelines for radionuclide concentrations in soil and guidelines for implementing DOE's ALARA process. Problems associated with procedures for collecting and interpreting field measurements of residual radioactivity and protocols for determining whether the guidelines have been met are not covered. Guidance on these topics may be found in the summary protocol for identification, characterization, designation, remedial action, and certification of FUSRAP sites (DOE 1984, 1986a, 1986b) and the procedures manual for remedial action survey and certification activities (Oak Ridge National Laboratory [ORNL] 1982).

The information presented in this manual is organized as follows:

- Pathways and scenarios by which a member of the critical population group can be exposed to radiation -- Chapter 2;
- Derivation and application of soil guidelines -- Chapter 3;
- Description of the RESRAD code and instructions for its use -- Chapter 4;
- ALARA procedures and general guidelines for implementing the ALARA process -- Chapter 5;

- DOE guidelines for residual radioactive material -- Appendix A; and
- Models, formulas, and data used in RESRAD to calculate the pathway factors -- Appendixes B through F.

2 PATHWAY ANALYSIS

The pathway analysis for deriving soil concentration guidelines from a dose limit has four parts: (1) source analysis, (2) environmental transport analysis, (3) dose/exposure analysis, and (4) scenario analysis.

Source analysis addresses the problem of deriving the source terms that determine the rate at which residual radioactivity is released into the environment. This rate is determined by the geometry of the contaminated zone, the concentrations of radionuclides present, the rates of ingrowth and decay of the radionuclides, and the rate of removal by erosion and leaching. Qualitative aspects of these topics are discussed in Section 2.1; quantitative aspects are covered in Chapter 3 and the appendixes.

Environmental transport analysis addresses the problems of (1) identifying environmental pathways by which radionuclides can migrate from the source to a human exposure location and (2) determining the rate of migration along these pathways. The significant environmental pathways are identified and described in Section 2.2. The derivation of environmental transport factors that characterize the rate of migration is covered in Chapter 3 and Appendixes B through E.

Dose/exposure analysis addresses the problem of deriving dose conversion factors for the radiation dose that will be incurred by exposure to ionizing radiation. This problem is discussed in Section 2.3. Appendixes B, C, and D include tabulations of the dose conversion factors used to determine the effective dose equivalent incurred by exposure to external radiation or to internal radiation from inhalation or ingestion of radionuclides.

The parameters that control the rate of radionuclide release into the environment and the severity and duration of human exposure at a given location are determined by patterns of human activity referred to as exposure scenarios. The credible scenarios that are likely to result in the largest exposure to individuals are discussed in Section 2.4.

2.1 SOURCE TERMS

2.1.1 Geometry of the Contaminated Zone

A contaminated zone, defined as a belowground region within which radionuclides are present in above-background concentrations, is the common source term and starting point for all pathways. The derivation of soil guidelines is based on idealized contaminated regions of cylindrical shape, as shown in Figure 2.1, within which radionuclides are assumed to be uniformly distributed. A shape factor, which equals one if the actual contaminated zone is a circular cylinder and less than one if it is irregularly shaped, is used to correct for the difference between dose estimates for the actual and idealized areas. The shape factor is used for the external radiation exposure pathway (see Appendix B). The cover depth (C_d) corresponds to the distance to

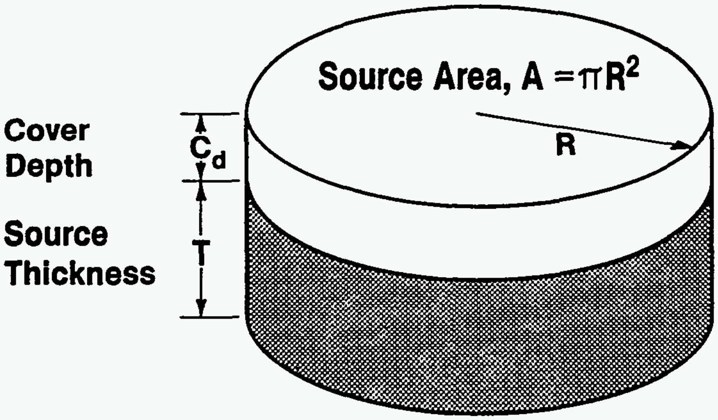

FIGURE 2.1 Geometry of Idealized Contaminated Zone

the uppermost contaminated soil sample, and the cover depth plus contaminated zone thickness (C_d + T) corresponds to the distance to the lowest contaminated soil sample.

If radionuclide distributions are approximately uniform throughout the contaminated region, the source geometry is a single cylinder that specifies a homogeneous contaminated zone. If the distributions are not approximately uniform, the source geometry consists of two or more cylinders that specify an inhomogeneous contaminated zone. Limiting radionuclide concentrations, referred to as single-radionuclide soil guidelines, are derived for each cylindrical volume. The manner in which the cylindrical volumes and soil guidelines are determined is described in Sections 3.1 and 3.3.

2.1.2 Time Dependence

The time dependence of the annual dose incurred by a member of the critical population group is controlled by (1) the rate at which radionuclides are leached from the contaminated zone, (2) the rate of ingrowth and decay of the radionuclides, (3) the rate of erosion of the cover and contaminated soil material, and (4) the rate of contaminant transport through the environmental pathways. The first three of these processes occur within, or primarily within, the contaminated zone; the last process occurs outside the contaminated zone. The models used to account for the time dependence of different transport and erosion processes are described in Appendixes B through E; the models used to account for the rate of ingrowth and decay and leaching are described in Appendix F.

2.1.3 Redistribution

A contaminated zone is treated as a single homogeneous or inhomogeneous source of changing thickness and radionuclide concentrations due to leaching, erosion, and ingrowth and decay. Erosion or human activities (such as excavation for a building erected in the contaminated zone) can result in redistribution of the contaminated soil that creates new contaminated zones. Such zones are not explicitly incorporated into RESRAD. If the topography and circumstances are such that redistribution is likely to occur, the new contaminated zone should be taken into account. This can be done by estimating the initial area and thickness of the new contaminated zone and then deriving its contribution to the soil guidelines in the same manner as for the original contaminated zone (see Section 2.3).

Radionuclides can also be redistributed by use of irrigation water that has been contaminated by radionuclides leached from the original contaminated zone. This contribution is taken into account in the derivation of the contribution from food pathways.

2.2 PATHWAYS

2.2.1 Pathway Identification

Potential pathways are identified in Table 2.1. The three major headings correspond to the three exposure pathways by which radionuclides can enter the body. In the first, exposure is by external radiation from radionuclides outside the body. In the second and third, exposure is by internal radiation from radionuclides that are inhaled or ingested. These three types of exposure correspond to the three kinds of dose conversion factors discussed in Section 2.3.

TABLE 2.1 Potential Pathways[a]

---

1 External Radiation
    1.1 Ground
        1.1.1 Volume Source*
        1.1.2 Surface Source*[b]
    1.2 Air
        1.2.1 Dust
        1.2.2 Radon and Radon Decay Products
        1.2.3 Other Gaseous Airborne Radionuclides
    1.3 Water

2 Inhalation
    2.1 Dust*
    2.2 Radon and Radon Decay Products
    2.3 Other Gaseous Airborne Radionuclides

3 Ingestion
    3.1 Food
        3.1.1 Plant Foods (Vegetables, Grains, and Fruits)*
        3.1.2 Meat*
        3.1.3 Milk*
        3.1.4 Aquatic Foods (Fish, Crustacea, and Mollusks)*
    3.2 Water
        3.2.1 Groundwater (Well)*
        3.2.2 Surface Water*
    3.3 Soil

---

[a] An asterisk indicates the pathways used to derive site-specific soil guidelines.

[b] The surface source can be approximated by assuming a very thin layer of contamination (e.g., 0.1 cm).

For each exposure pathway, radionuclides can migrate from a source to a human exposure location by many environmental pathways. The major categories of environmental pathways are listed in Table 2.1. The items listed should be regarded as environmental pathway categories rather than individual pathways because many of the items can correspond to more than one pathway and some of the items can occur as segments in more than one pathway. For example, there are many different plant food pathways, and contaminated groundwater can contribute to the human drinking water pathway and also to several food pathways if contaminated water is used to irrigate crops or water livestock.

Major pathways used to derive site-specific soil guidelines in the RESRAD code are identified in Table 2.1 by an asterisk and shown diagrammatically in Figure 2.2. Minor pathways for on-site exposure (all remaining pathways except the radon inhalation pathway) are not taken into account in deriving soil guidelines because the dose contribution from these pathways is expected to be insignificant. External radiation from a surface layer formed by redeposition of airborne radionuclides carried by the wind from an exposed contaminated zone is expected to be insignificant compared with external radiation from the residual radioactive material in its original location. External radiation from contaminated water is expected to be insignificant compared with internal exposure from radionuclides ingested in drinking water. The external radiation dose from airborne dust is much smaller than the inhalation dose from dust (by a factor of 100 or more for radionuclides in the U-238 series [Gilbert et al. 1983, Tables 5.6-5.8]). The external radiation dose from airborne radon decay products is negligible compared with (1) the internal inhalation dose to the bronchial epithelium (the critical organ for inhalation of radon decay products), (2) the external radiation dose from the parent radium in the soil, or (3) the internal radiation dose from

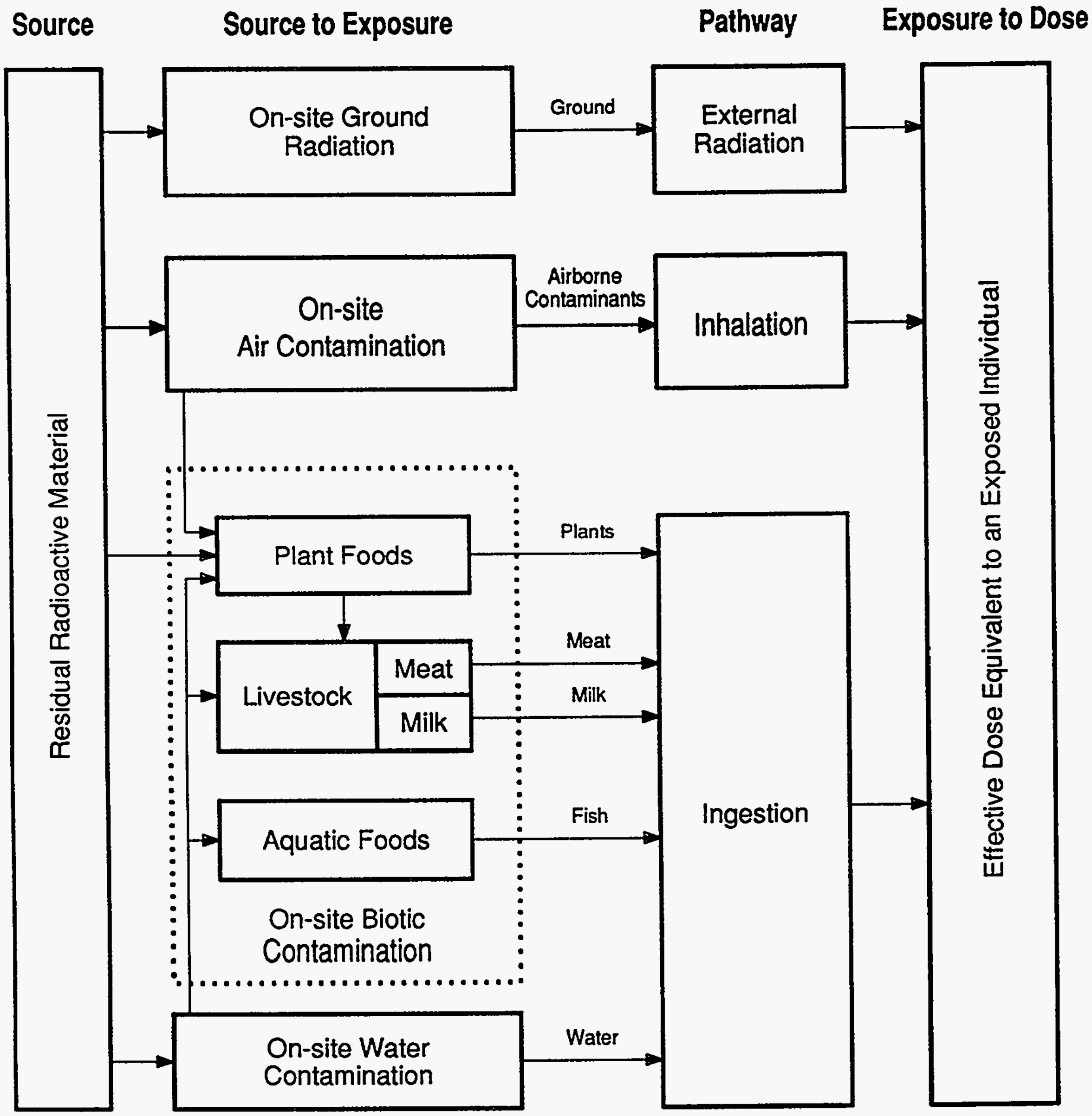

FIGURE 2.2 Exposure Pathway Diagram for Calculating the Dose to an On-site Resident from Residual Radioactive Material at a FUSRAP or SFMP Site (Source: Modified from Gilbert et al. 1983, Figure 2.4)

ingestion of plant foods grown in the radium-contaminated soil (Gilbert et al. 1983). The contributions from gaseous airborne radionuclides other than radon decay products (e.g., from C-14 occurring in CO_2 or from tritium occurring in tritiated water vapor) is insignificant at FUSRAP and SFMP sites. The soil pathway corresponds to direct ingestion of soil (Healy 1977). This pathway is significant only for a child afflicted with pica (a compulsive craving for nonfood objects), which is a rare occurrence limited to a period of about one year in a child's life; thus, it makes only a small contribution to the lifetime dose.

Internal radiation from inhalation of radon decay products is a major -- in many circumstances, the dominant -- dose contributor when radium is present in the soil. The radon inhalation pathway is not included in the current version of RESRAD because generic soil guidelines have been established for radium (see Appendix A). This pathway may be added in a later version to allow guidelines to be derived in a more consistent manner for hot spots and mixtures in which radium occurs.

2.2.2 External Radiation Pathways

Gamma radiation from radionuclides distributed throughout the contaminated zone is the dominant external radiation pathway and the only external radiation pathway taken into account in calculating soil guidelines.* The dose due to external gamma radiation is first calculated for an individual exposed continuously to radiation from an infinite contaminated zone at a distance of one meter from the ground surface. Correction factors are then

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*The dose contribution from electrons (beta particles) is primarily restricted to the skin; the dose contribution from neutron radiation can be significant for some transuranic radionuclides and should be considered if neutron-emitting radionuclides are known to be present.

applied for the finite area and thickness of the contaminated zone, shielding by a cover of uncontaminated soil (if $C_d > 0$; see Figure 2.1), irregular shape, shielding by the floors and walls of a house, and less-than-continuous occupancy. Quantitative details are presented in Chapter 3 and Appendix B.

2.2.3 Inhalation Pathways

Inhalation exposure results primarily from inhalation of radon decay products and contaminated dust. As noted earlier, the radon pathway is not included in the current version of RESRAD because generic soil guidelines have been established for radium, which is the source of all radon (see Appendix A). The following discussion is, therefore, limited to the dust pathway.

An inhalation pathway consists of two segments: (1) an airborne exposure segment linking the source (contaminated zone) with the airborne radionuclides at an exposure location and (2) an inhalation segment linking the airborne radionuclides with the exposed individual. The inhalation segment is characterized by an occupancy factor (equivalent fraction of time during which an individual inhales contaminated air) and a factor for the inhalation rate. Numerical values for these factors may be obtained by well-established procedures (ICRP 1975; Momeni et al. 1979). The airborne exposure pathway segment is the critical segment. It is characterized by the air/soil concentration ratio, defined as the ratio of the airborne concentration of a radionuclide at a human exposure location to the concentration in the soil. The air/soil concentration ratio for contaminated dust depends on the complex processes by which soil particles become airborne by resuspension and are transported to an exposure location. It is used in the food chain pathways (for the foliar deposition subpathways) as well as in the inhalation pathways.

Modeling the airborne exposure pathway segment consists of two steps: (1) modeling the process by which radionuclides become airborne and (2) modeling the process by which the airborne radionuclides are transported to a human exposure location and diluted before inhalation. The first step gives the ratio of the concentration in air near the source before it is dispersed and diluted to the concentration in the resuspendable layer of dust; the second step gives the ratio of the airborne concentration at the point of exposure to the undiluted airborne concentration at the source. Quantitative details are presented in Appendix C.

2.2.4 Ingestion Pathways

2.2.4.1 Food Pathways

Four food pathway categories are taken into account: plant foods, meat, milk, and aquatic foods. The plant food pathway category is divided into four subcategories corresponding to (1) root uptake from crops grown in the contaminated zone, (2) foliar uptake from contaminated dust deposited on the foliage, (3) root uptake from contaminated irrigation water, and (4) foliar uptake from contaminated irrigation water. The plant food pathway subcategories are applicable to livestock fodder; hence, they are applicable to the pathways through which meat and milk become contaminated by ingestion of contaminated fodder. There is a fifth subcategory for the meat and milk pathways corresponding to contamination by ingestion of contaminated livestock water. The aquatic food pathway is for ingestion of fish, crustacea, and mollusks from a nearby pond that has been contaminated by radionuclides that have been leached from the contaminated zone.

The food pathways are activated by scenarios in which crops are grown in or close to the contaminated zone. Plant crops grown in the contaminated zone will be the dominant and most frequent contributor, especially if the crops are irrigated with contaminated water. Contributions from the meat and milk pathways, which involve an additional pathway segment for transfer of radionuclides from fodder or water to the meat or milk, will generally be smaller but not insignificant. Vegetable gardens are common in urban and suburban areas as well as rural areas, whereas raising livestock is generally limited to rural areas. The aquatic food pathway will occur only in areas where the topography and soil characteristics are favorable for building a pond.

The food pathways may be classified as water-independent or water-dependent. The direct root uptake and foliar dust deposition pathways for plant foods, meat, and milk are water-independent (where water refers to the water that has been contaminated by radionuclides leached from the contaminated zone). Water-dependent pathways are the irrigation water pathway for plant foods, meat, and milk; the livestock water pathway for meat and milk; and the aquatic food pathway. In regions where natural rainfall is the only source of water used in raising crops, the only water-dependent pathways will be the livestock water branch of the meat and milk pathways and the aquatic food pathway. If ditch irrigation is used, the contribution from root uptake of contaminated irrigation water by plant foods and fodder will be added. If overhead irrigation is used, the contribution from the subpathways for foliar and root uptake from irrigation water will be added.

The water-independent pathways are assumed to contribute to the dose as soon as a family establishes a residence and garden on the site. The time dependence of these pathways is determined by the time dependence of the cover and contaminated zone thickness and the radionuclide concentrations in the contaminated zone. The contribution from water-dependent pathways will be delayed until radionuclides transported by groundwater reach a point of water withdrawal (i.e., well or pond). The time dependence of these pathways is determined by the time dependence of the radionuclide concentrations in the contaminated water, as determined by the hydrological model used for the groundwater pathway segment. A fraction of a radionuclide will have been leached from the root zone before the radionuclide first reaches a point of water withdrawal in above-background concentrations (the breakthrough time); hence, the contributions to the dose from the water-independent and water-dependent pathways will occur at different times.

After the breakthrough time, the contaminated irrigation water will create a new contaminated zone as it percolates down through the soil. The contribution of this secondary contaminated zone to pathways other than the food pathway is not taken into account because it is assumed to be small compared with the contributions of the food pathway.

Radionuclide transport through the food pathways is determined by the quantities of different foods consumed (dietary factors), the fraction of the diet from foods that are contaminated by radionuclides from the contaminated zone (which is determined by the fraction raised locally and the area of the contaminated zone), the cover depth and contaminated zone thickness relative to the root zone of the plants, the various transfer factors from root or foliage to plants and from fodder or water to meat or milk, and the concentrations of radionuclides in water that has percolated through the contaminated zone. The factors used to take these effects into account are discussed in Chapter 3 and Appendixes D and E.

2.2.4.2 Water Pathway Segments

A water pathway segment connects the contaminated zone with a point of water withdrawal for drinking or irrigation or with a pond where aquatic foods are raised for human consumption. It is characterized by a water/soil concentration ratio for each radionuclide, defined as the ratio of the radionuclide concentration in the water at the point of withdrawal or use to the radionuclide concentration in the contaminated zone. Irrigation and drinking water are assumed to be taken from a well or pond. The well is assumed to be either in the center of or at the downgradient edge of the contaminated zone (see Appendix E). The pond water is assumed to be contaminated by water that seeps to the surface after percolating through the contaminated zone. Figure 2.3 schematically represents the process by which natural precipitation or irrigation water infiltrates the contaminated zone and transports radionuclides through the unsaturated (vadose) zone and saturated zone (aquifer) to a well or point of seepage into surface water.

Groundwater Pathway Segment. Two models are used for calculating the water/soil concentration ratio for the groundwater pathway segment: a mass-balance (MB) model and a nondispersion (ND) model.* The MB model assumes that all of the radionuclides released annually from the contaminated zone are withdrawn through a well located at the center of the contaminated zone. The ND model assumes that the dispersivity is nil, the vadose zone and aquifer are homogeneous, the well is located at the downgradient edge of the contaminated zone, and water withdrawal introduces only a minor perturbation in the water

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*The mass-balance model is an adaptation of a model proposed by staff of the NRC (Neuder 1986).

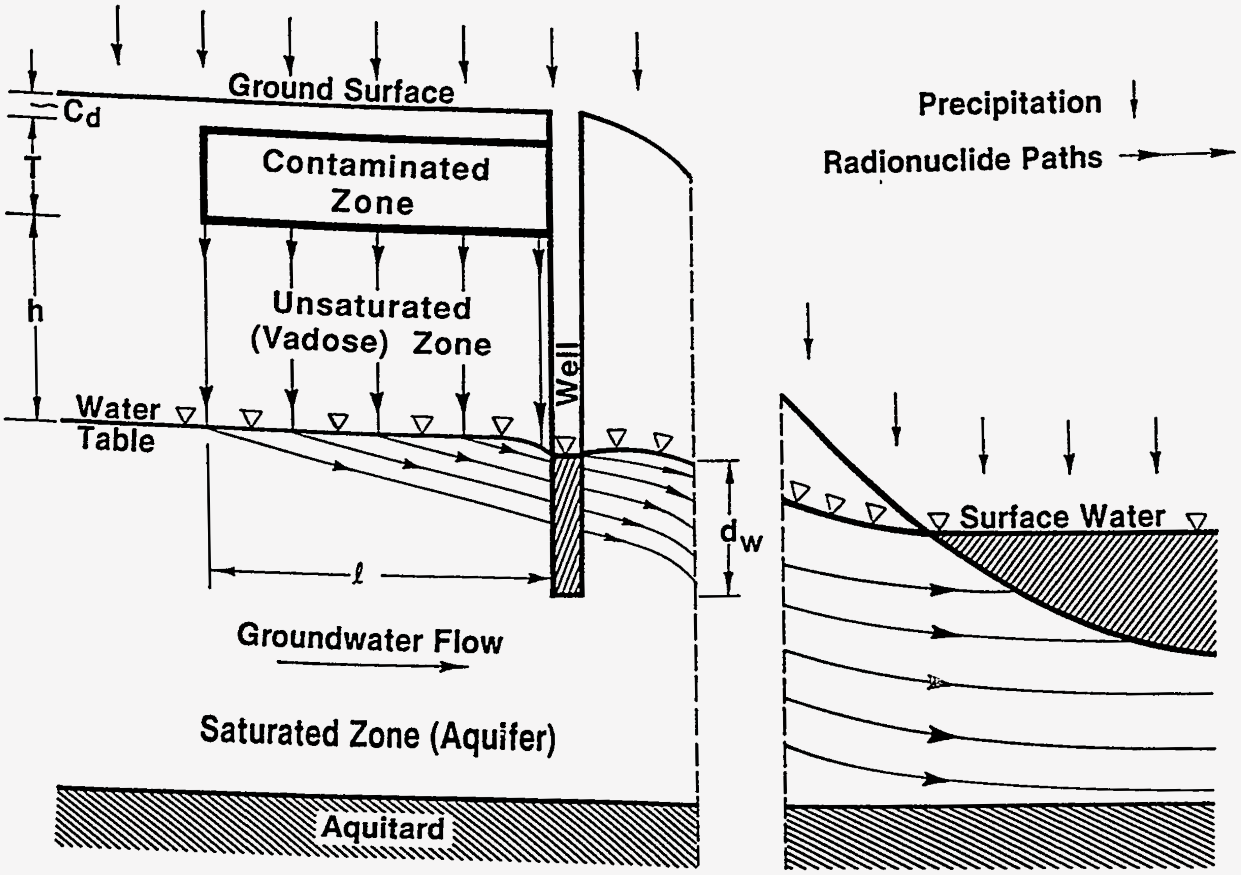

FIGURE 2.3 Schematic Representation of the Water Pathway Segments

flow. These assumptions lead to a flow pattern from which the dilution factor can be estimated by geometric considerations. The MB model is used for smaller contaminated areas (e.g., 1,000 m^2 or less), and the ND model is used for larger contaminated areas. The MB and ND models are discussed in more detail in Appendix E.

The groundwater pathway segment is analyzed in terms of parameters that remain valid for more sophisticated models. These parameters consist of the breakthrough time, rise time, and dilution factor. The breakthrough time is the time from a radionuclide's release into infiltrating water at the contaminated zone until its detection at the point of withdrawal or use. The rise time is the time from initial detection until the concentration reaches a maximum value when the release rate from the contaminated zone is constant after initiation. (A linear rise is assumed; a straight-line approximation can be used when the actual rise has a more complicated time dependence.) The dilution factor is the steady-state ratio of a radionuclide concentration at the point of withdrawal or use to the concentration of the same radionuclide in infiltrating water as it leaves the contaminated zone. Formulas for calculating the breakthrough times, rise times, and dilution factors for the MB and ND models are given in Chapter 3 and Appendix E.

The groundwater pathway models implemented in the RESRAD code apply only to situations for which the hydrological strata can reasonably be approximated by a sequence of uniform, horizontal strata. For sites having more complicated strata such as fracture zones, simple models may be used to provide reasonable estimates if a set of effective hydrogeologic flow parameters are used. However, the accuracy of the results predicted is determined by the accuracy of the effective input parameters used (Yu et al. 1986).

Surface Water Pathway Segment. The surface water is assumed to be a pond for which (1) the water inflow and outflow are in steady-state equilibrium and (2) the annual inflow of radioactivity into the pond equals the annual quantity of radioactivity leached from the contaminated zone. The dilution factor is assumed to be the ratio of the annual volume of water that infiltrates the contaminated zone to the annual total inflow of water into the pond. If, as also assumed, the infiltrating water flow is vertically downward through the contaminated zone, the surface water dilution factor is given by the ratio of the area of the contaminated zone to the area of the watershed that supplies the pond. Breakthrough time and rise time are assumed to be the same as for an on-site well; no credit is taken for the additional time for radionuclides to be transported from the edge of the contaminated zone to the point of seepage. This simplified model will give a conservative estimate of the water/soil concentration ratio for a pond.

2.2.4.3 Drinking Water Pathway

The concentration factor that characterizes the drinking water pathway is obtained by multiplying the water/soil concentration ratio by the annual quantity of contaminated drinking water consumed by an individual. Both well water and surface water can be used for drinking. The fraction of well water balanced from surface water is used to calculate the total contribution from groundwater and surface water. The default value for this fraction is unity, i.e., 100% of the drinking water is drawn from a well.

2.3 DOSE CONVERSION FACTORS

The distribution of dose within the body depends upon the type of radiation involved and the location of the radionuclides emitting the radiation, i.e., within or external to the body. The ICRP has provided a useful quantity that, on a risk scale, can be applied to any radiation pattern (ICRP 1977, 1978, 1979-1982). This quantity -- the effective dose equivalent -- is the weighted sum of the dose equivalent in various organs. The weighting factors for the organs are proportional to the potential risk associated with the irradiation of those organs. All dose factors used for deriving soil concentration guidelines are based on the effective dose equivalent.

Internal radiation doses to organs and tissues of the body are frequently estimated with factors representing the committed dose equivalent for a unit intake of a radionuclide via inhalation or ingestion. In the case of external radiation, the dose rate in organs depends on the concentration of the radionuclide in the environment. These relationships are expressed as dose/exposure ratios called "dose conversion factors." A dose conversion factor is the ratio of the committed effective dose equivalent (for internal exposure) or the effective dose equivalent rate (for external exposure) to the quantity of a radionuclide inhaled or ingested (for internal exposure) or the concentration of a radionuclide in the air, water, or ground (for external exposure).

2.3.1 Ingestion and Inhalation

The radiation dose from inhalation and ingestion of radionuclides has been systematically evaluated by the ICRP in its Publication 30 (ICRP 1979-1982). This effort was undertaken to compute secondary limits for occupational exposures corresponding to the primary radiation protection guidance of Publication 26 (ICRP 1977). Dose equivalents in organs or tissues of the body are calculated with models that (1) describe the entrance of materials into the body (respiratory and gastrointestinal [GI] tract) and the deposition and subsequent retention of the radionuclides in body organs (referred to as metabolic models), and (2) estimate the energy deposition in tissues of the body (ICRP 1979-1982). In applying the results of these calculations, some insight into the details of models for the lung and GI tract is required because these models serve as the interface between humans and the environment.

Inhalation of radionuclides attached to airborne particles is a potential route for intake of radionuclides into the body. The ICRP model of the respiratory tract divides the tract into three regions: nasopharyngeal, tracheobronchial, and pulmonary (ICRP 1966). These regions are connected with one another as well as with body fluids and the GI tract. The fraction of inhaled activity deposited in these regions is a function of the size of the airborne particles. The activity median aerodynamic diameter (AMAD) is the measure most widely used to characterize the aerosol. The rate at which the deposited material is removed from the regions is considered to be independent of particle size; the rate is, however, related to the chemical form of the particles. Chemical compounds are assigned to one of three classes to characterize their removal rate from the lung. The inhalation classes are denoted as D, W, and Y -- corresponding to clearance or removal times from the pulmonary region of the lung on the order of days, weeks, or years, respectively. Details are provided in the ICRP task group's report (ICRP 1966) and subsequent ICRP publications (ICRP 1968, 1979-1982).

A portion of the material initially deposited in the lung enters the GI tract and, of course, ingested radionuclides enter the GI tract directly. The ICRP model of the GI tract divides the tract into four compartments: stomach, small intestine, upper large intestine, and lower large intestine (Eve 1966). Absorption of materials into body fluids is generally considered to occur within the small intestine. The fraction of the ingested material absorbed into body fluids from the tract is denoted as f_1. The numerical value of f_1 depends on the chemical form of the ingested material (ICRP 1979-1982).

Radionuclides that enter body fluids from either the lung or the GI tract may be deposited within the various organs of the body. Metabolic processes and radioactive decay reduce the radioactivity in the body. These removal processes are modeled in a rather simple manner in which the organs are represented by a number of mathematical compartments from which the removal rate is directly proportional to the amount of radionuclide present (ICRP 1979-1982). This approach leads to functions involving a sum of exponentials to describe the time course of activity within the body. An exception to this representation occurs for radium, for which the more-detailed metabolic model of ICRP Publication 20 (ICRP 1972) is used.

In calculating the dose from intake of radionuclides into the body, the occurrence of radioactive decay products must be considered. When an atom undergoes radioactive decay, the new atom formed may also be radioactive and thus contribute to the dose. Although these decay products may be treated as independent radionuclides in external exposures, they must be considered in conjunction with the parent in the evaluation of radionuclides inhaled or ingested because their distribution among the organs of the body depends on the metabolism of the parent (ICRP 1979-1982). Thus, the contributions to dose from decay products formed within the body are included in the dose conversion factor for any radionuclide with radioactive decay products.

Factors representing the committed effective dose equivalent per unit intake of radionuclides are given in Appendix C (Table C.1) for inhalation and Appendix D (Table D.1) for ingestion. These values were taken from a DOE report (DOE 1988a); similar values are given in an EPA report (Eckerman et al. 1988). In many instances, several chemical forms have been considered; that is, more than one clearance class (inhalation) or f_1 (ingestion) value is given for the radionuclide. If the user of this manual has information indicating the chemical forms expected in the particular environment being considered, then the appropriate value should be selected after consulting ICRP Publication 30 (ICRP 1979-1982). If no information on the relevant chemical forms is available, then the most conservative value (i.e., the highest estimate of dose) should be used.

Dose conversion factors identified with "+D" in Tables C.1 and D.1 are the sums of dose conversion factors for a principal radionuclide (a radionuclide with a half-life greater than one year) and its associated decay chain (all short-lived decay products of a principal radionuclide down to, but not including, the next principal radionuclide or the final nonradioactive nuclide in the chain). These aggregated dose conversion factors correspond to ingestion or inhalation of the principal radionuclide together with its associated decay product radionuclides, which are assumed to be in secular equilibrium at the time of intake (see Section 3.1 and Table 3.1).

2.3.2 External Radiation

Organs of the body may be irradiated by radiation emitted from radionuclides present in the environment. Gamma radiation is the only external radiation taken into account in calculating soil guidelines (see Section 2.2.2). Gamma radiation is of particular concern because this radiation is sufficiently penetrating that the dose at a given location depends on the spatial distribution over considerable distances. In addition, the dose distribution pattern within the body is rather uniform. The actual distribution of dose in the body depends somewhat on the distribution pattern of the radionuclide in the environment. An idealized distribution pattern that is often assumed is a uniform distribution of the radionuclide within an infinite or semi-infinite region. By considering such idealized distributions, dose conversion factors relating the effective dose equivalent rate to the radionuclide concentration can be tabulated. For other situations, the details of radionuclide distribution must be included in the numerical calculation of dose.

Kocher (1983) has published extensive tabulations of dose-rate factors for radionuclides distributed in air, in water, and on the ground surface. The methods of Kocher and Sjoreen (1985) were used in this manual to derive dose-rate factors of radionuclides uniformly distributed in the soil volume. Dose conversion factors for exposure from radionuclides in or on the ground are presented in Appendix B (Table B.1). The dose-rate factors for surface contamination were taken from a DOE report (DOE 1988b).

The dose conversion factors for ground contamination are for exposure at a point one meter above the ground. The volume contamination is assumed to be uniformly distributed to infinite depth and infinite lateral extent. Contributions from all associated radionuclides, which are assumed to be in secular equilibrium with the parent principal radionuclide, are included in the dose conversion factors for principal radionuclides. (Note: "infinite" dimensions reflect consideration of radiation transport and may in fact correspond to small physical dimensions. For example, one meter of soil is generally infinite with respect to the dose rate from a photon-emitting radionuclide.)

Dose conversion factors for radionuclides distributed in the ground depend on the bulk density of the soil (ρ_b). Factors for $\rho_b = 1.0$ g/cm^3 and $\rho_b = 1.8$ g/cm^3 are listed in Table B.1. Values for other soil densities may be obtained by interpolation.

2.4 EXPOSURE SCENARIOS

Many parameters that determine the quantity of radionuclides or radiation to which an individual is exposed are determined by exposure scenarios, i.e., patterns of human activity that can affect release of radioactivity from the contaminated zone and the amount of exposure received at the exposure location. Soil guidelines are based on a family-farm exposure scenario. This scenario activates all environmental pathways for on-site or near-site exposure and is expected to result in the highest predicted lifetime dose.

Other scenarios can be taken into account by adjusting the scenario parameters in formulas for calculating transport of radionuclides through the pathways (see Chapters 3 and 4 and Appendixes B through E).

In the family-farm scenario, a family is assumed to move onto the site after it has been released for use without radiological restrictions, build a home, and raise crops and livestock for family consumption. Members of the family can incur a radiation dose by (1) direct radiation from radionuclides in the soil, (2) inhalation of resuspended dust (if the contaminated area is exposed at the ground surface), (3) ingestion of food from crops grown in the contaminated soil, (4) ingestion of milk from livestock raised in the contaminated area, (5) ingestion of meat from livestock raised in the contaminated area, (6) ingestion of fish from a nearby pond contaminated by water percolating through the contaminated zone, and (7) ingestion of water from a well contaminated by water percolating through the contaminated zone. The basis for the choice of a family-farm scenario for the critical population group is summarized below.

Permanent residents, rather than individuals exposed by activities not associated with residential living, have been chosen as the critical population group because the exposure for permanent residents is more likely to be long term and will generally involve exposure by more pathways. The nonresident group most likely to receive significant exposure consists of construction workers. An individual involved in recreational activities (e.g., a baseball field built on the site) will receive a much smaller dose than a permanent resident because the former will spend less time on-site. Scavenging can also occur, although this is less likely considering the lack of economic value of the contaminated material. The exposure of scavengers can reasonably be assumed to be comparable to that of construction workers.

The exposure of construction workers or scavengers is unlikely to last longer than a few months and would generally be limited to working hours. The lifetime exposure for construction workers and scavengers is, therefore, unlikely to exceed the lifetime dose for a permanent on-site resident. (The basic dose limit of 100 mrem/yr is based on the lifetime dose [ICRP 1977]. A dose limit of 500 mrem/yr is allowable for some years if the dose averaged over a lifetime does not exceed the basic dose limit of 100 mrem/yr [DOE 1989].) Exposure of workers in on-site industrial or commercial buildings can also occur, but this exposure will generally be less than that of residents because the exposure will be limited to working hours and will not include contributions from ingestion of foods grown on-site.

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

Exposure scenarios used for establishing soil guidelines should be bounding in the sense that they correspond to actions, events, and processes that will result in the largest exposure likely to occur to individuals and groups. However, they must also be credible, which implies that the probability of occurrence should be above some threshold value. The basis for specifying a credible bounding scenario is ill-defined because a threshold probability for distinguishing between a credible and a noncredible scenario has not been established, and it is usually not possible to assign a meaningful probability of occurrence for a scenario (unless the scenario is physically impossible, in which case a zero probability can be assigned). A family-farm scenario, in which a family constructs a home on the contaminated site and raises an appreciable fraction of its food on this site, is considered to be a credible bounding scenario for the purpose of this manual.* Even though such a scenario may be unlikely in the foreseeable future for a FUSRAP or SFMP site located in an industrial or urban area, it cannot be excluded as noncredible at some time several hundred years in the future.

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

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*This scenario is referred to as the intruder-agriculture scenario when used for analyzing the long-term radiological impacts of a low-level radioactive waste disposal site (NRC 1981). This terminology is inappropriate for FUSRAP and SFMP sites because a resident cannot be regarded as an intruder after a site has been released for use without radiological restrictions.

current conditions. Scenario parameters and parameter values required for the pathway analysis are given in Appendixes B through E. The basis for the choice of key parameter values that require special consideration are discussed below.

One scenario parameter is the fraction of the family diet that consists of contaminated foodstuffs. This will be determined by the fraction of the diet that is raised on-site and the fraction of the on-site crops grown in contaminated soil. The fraction raised on-site will be determined by the living and farming style and the area of land available to a family for gardening.

Farms or residential gardens that provide a significant fraction of the family diet are fairly common, and it is not uncommon for families in rural areas to raise livestock to provide most of their meat and milk; however, a fully self-sufficient farm is a rarity. For a "self-sufficient" scenario to apply, the family would have to raise all of its vegetables on-site -- that is, grow its own potatoes, get all fruit from an on-site fruit orchard, can or freeze enough of the summer crop to provide all food during the winter, and raise all grain used for bread and cereal. A scenario that is considered to be bounding and credible is for a family to have a garden that provides half of the total plant food diet if the area available for gardens and orchards is 0.1 ha or larger. This value is based on the following estimates for the area required for a year's supply of food for an individual: 50 m^2 for a year's supply of leafy and other aboveground vegetables, 200 m^2 for root vegetables and grains, and a somewhat larger area for fruit trees. It is inferred from these figures that 0.1 ha would be sufficient for half of the plant food diet for a family of four. It is also assumed, as noted above, that half the diet would be food purchased from a market even if sufficient land were available for a larger garden.

The area required for livestock, including summer pasture and forage for winter use, is somewhat larger. A single pig requires a food supply from an area of about 2,000 m^2, and a single milk cow needs a forage supply that may require an area of 1 ha or more. It is assumed that an area of 2 ha would be needed to provide sufficient meat and milk, including all forage, for a family of four. Thus, if the contaminated area exceeds 2 ha, the scenario diet factors specify that all of the meat and milk and 50% of the plant foods in the family diet are potentially contaminated. The fraction of the meat and milk diet that is contaminated is assumed to decrease linearly from 1 to 0 as the area decreases from 2 to 0 ha. The fraction of the plant food diet that is contaminated is assumed to decrease linearly from 0.5 to 0 as the area decreases from 0.1 to 0 ha.

If the contaminated material is initially underneath a protective cover of uncontaminated material, one should take into account the dose that might be incurred from radioactive material that is redistributed during excavation for the basement of a residence to form an exposed surface layer. For the purpose of estimating the extent of the contaminated zone caused by redistribution of the excavated radioactive material, it may be assumed that the basement has an area of 200 m^2 and requires excavation to a depth of 3 m. It may also be assumed that the excavated soil is mixed before spreading and is redistributed on the surface to a depth of 0.3 m over an area of 2,000 m^2. Thus, if the contaminated layer was T meters thick and did not extend below 3 m, after excavation there would be a contaminated layer exposed at the surface with a radionuclide concentration that was less than the concentration in the excavated contaminated layer by a factor T/3. No credit for this reduction in concentration should be taken if the undisturbed contaminated layer is exposed at the surface or if the redistributed layer would result in a predicted potential dose that was less than the potential dose predicted for the undisturbed layer.

3 GUIDELINES FOR RADIONUCLIDE CONCENTRATIONS IN SOIL

The basic criterion for releasing a site for use without radiological restrictions is specified as a dose limit (see Appendix A). This dose limit is converted to soil guidelines -- specified as radionuclide concentrations -- by means of dose/source ratios (DSRs) that are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport factors (ETFs), and source factors (SFs). The definitions and use of these factors for deriving soil guidelines are described in this chapter. Tables, detailed models, and formulas for calculating the factors are given in Appendixes B through E.

3.1 RADIOLOGICAL RELEASE CRITERIA

The basic dose limit that must be satisfied before a site can be released for use without radiological restrictions is

$$H_E(t) \le H_{EL}, \qquad t_r \le t \le t_h \tag{3.1}$$

where*

$H_E(t)$ = average annual effective dose equivalent received by a member of the critical population group at time t following the radiological survey of the site (mrem/yr),

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*Units are specified in parentheses following the variable description. Numerical values are given for input variables to which default values are assigned. Default values are assigned to all input variables except radionuclide concentrations. Site-specific values should be substituted for default values unless it is not feasible to determine a site-specific value and the mixture sum is not sensitive to the value used.

H_{EL} = basic dose limit (100 mrem/yr),

t_r = time at which the site is released for use without radiological restrictions following the radiological survey (1 year), and

t_h = time horizon (1,000 years).

The time at which a radiological survey is done is the time of origin, or time 0. The time at which a site is released after the radiological survey is the release time, or time t_r. The default value used in the RESRAD code for t_r is 1 year. A time horizon of 1,000 years is used for FUSRAP and SFMP sites (see Appendix A).

If the radionuclides are uniformly distributed within the contaminated zone, Equation 3.1 may be transformed into the inequality

$$M(t) = \sum_i S_i(0)/G_i(t) \le 1, \qquad t_r \le t \le t_h \tag{3.2}$$

where

$M(t) \equiv H_E(t)/H_{EL}$ = fraction of the basic dose limit received by an average member of the critical population group at time t following the radiological survey (dimensionless),

$S_i(0)$ = initial concentration of the i^{th} principal radionuclide in a uniformly contaminated zone at time 0 (pCi/g), and

$G_i(t)$ = single-radionuclide soil concentration guideline for the i^{th} principal radionuclide in a uniformly contaminated zone at time t (pCi/g).

M(t) is referred to as the mixture sum.* Principal radionuclides are radionuclides with half-lives greater than 1 year. The decay products of any principal radionuclide down to, but not including, the next principal radionuclide in its decay chain are called associated radionuclides and consist of radionuclides with half-lives less than 1 year. It is assumed that a principal radionuclide is in secular equilibrium with its associated radionuclides at the point of exposure. Principal and associated radionuclides included in the current version of RESRAD are listed in Table 3.1.

A contaminated zone is defined as a belowground volume within which the radionuclide concentrations in soil samples clearly exceed the background concentrations. Background concentrations are determined from measurements in soil samples taken at several nearby off-site locations where contamination is very unlikely. The concentration of a radionuclide is considered to clearly exceed the background concentration if it is larger than the mean background concentration plus twice the standard deviation of the background measurements. If the concentrations in the samples used for determining the background concentration are below the lower limit of detection (LLD) of the instrument used, the concentration of that radionuclide is considered to exceed background if it exceeds the LLD of the instrument. The sensitivity of the instrument used must comply with current standards for high-quality commercial instruments.

A distinction should be made between a uniformly contaminated zone and a homogeneously contaminated zone. In a uniformly contaminated zone, radionuclide concentrations are exactly the same at every point. A uniformly

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*The term "sum of fractions" is commonly used in regulatory references.

TABLE 3.1 Principal and Associated Radionuclides

Principal Radionuclide[a]			Terminal Nuclide or Radionuclide[c]	
Species	Half-life (yr)	Associated Decay Chain[b]	Species	Half-life (yr)
H-3	12.33	-	He-3	*
C-14	5730	-	N-14	*
Fe-55	2.685	-	Mn-55	*
Co-60	5.271	-	Ni-60	*
Ni-59	7.5×10^{4}	-	Co-59	*
Ni-63	100	-	Cu-63	*
Sr-90	28.8	Y-90 (64.1 h)	Zr-90	*
Nb-94	2.0×10^{4}	-	Mo-94	*
Tc-99	2.14×10^{5}	-	Ru-99	*
I-129	1.6×10^{7}	-	Xe-129	*
Cs-135	3×10^{6}	-	Ba-135	*
Cs-137	30.17	Ba-137m (2.551 min)	Ba-137	*
Sm-151	90	-	Eu-151	*
Eu-152	13	-	Gd-152 (27%) Sm-152 (73%)	1.1×10^{14} *
Eu-154	8.5	-	Gd-154	*
Pb-210	22.3	Bi-210 (5.01 d) Po-210 (138.38 d)	Pb-206	*
Ra-226	1.60×10^{3}	Rn-222 (3.8235 d) Po-218 (3.05 min) Pb-214 (26.8 min) Bi-214 (19.7 min) Po-214 (164 μs)	Pb-210	22.3
Ra-228	5.76	Ac-228 (6.13 h)	Th-228	1.9131
Ac-227	21.733	[Th-227 (98.6%, 18.71 d) Fr-223 (1.4%, 21.8 min)] Ra-223 (11.435 d) Rn-219 (3.96 s) Po-215 (1.78 ms) Pb-211 (36.1 min) Bi-211 (2.15 min) Tl-207 (4.77 min)	Pb-207	*
Th-228	1.9131	Ra-224 (3.66 d) Rn-220 (55.6 s) Po-216 (0.15 s) Pb-212 (10.64 h) Bi-212 (60.60 min) [Po-212 (64%, 0.30 μs) Tl-208 (36%, 3.053 min)]	Pb-208	*

TABLE 3.1 (Cont'd)

Principal Radionuclide[a]			Terminal Nuclide or Radionuclide[c]	
Species	Half-life (yr)	Associated Decay Chain[b]	Species	Half-life (yr)
Th-229	7.3×10^3	Ra-225 (14.8 d) Ac-225 (10.0 d) Fr-221 (4.8 min) At-217 (32.3 ms) Bi-213 (45.6 min) [Po-213 (97.8%, 4 μs) Tl-209 (2.2%, 2.2 min)] Pb-209 (3.25 h)	Bi-209	*
Th-230	7.7×10^4	-	Ra-226	1.60×10^3
Th-232	1.41×10^{10}	-	Ra-228	5.76
Pa-231	3.28×10^4	-	Ac-227	21.6
U-232	72	-	Th-228	1.9131
U-233	1.592×10^5	-	Th-229	7.3×10^3
U-234	2.45×10^5	-	Th-230	8.0×10^4
U-235	7.038×10^8	Th-231 (25.52 h)	Pa-231	3.28×10^4
U-236	2.342×10^6	-	Th-232	1.41×10^{10}
U-238	4.468×10^9	Th-234 (24.10 d) Pa-234m (1.175 min)	U-234	2.45×10^5
Np-237	2.14×10^6	Pa-233 (27.0 d)	U-233	1.592×10^5
Pu-238	87.74	-	U-234	2.45×10^5
Pu-239	2.41×10^4	-	U-235	7.038×10^8
Pu-240	6.57×10^3	-	U-236	2.342×10^6
Pu-241	14.4	-	Am-241	433
Pu-242	3.76×10^5	-	U-238	4.468×10^9
Am-241	433	-	Np-237	2.14×10^6
Am-243	7.37×10^3	Np-239 (2.35 d)	Pu-239	2.41×10^4
Cm-243	28.5	-	Pu-239	2.41×10^4
Cm-244	18.11	-	Pu-240	6.57×10^3

[a] Radionuclides with half-lives greater than 1 year that might be present at FUSRAP or SFMP sites.

[b] The chain of decay products of a principal radionuclide extending to (but not including) the next principal radionuclide or a stable nuclide. Half-lives are given in parentheses. Branches are indicated by square brackets with branching ratios in parentheses.

[c] The principal radionuclide or stable nuclide that terminates an associated decay chain. Stable nuclides are indicated by an asterisk (*) in place of the half-life.

contaminated zone is a mathematical construct used to calculate soil guidelines. A homogeneously contaminated zone is a volume within which deviations from uniformity of the actual radionuclide concentrations are considered small enough to allow the volume to be treated as if it were uniformly contaminated.

Actual radionuclide distributions are nonuniform. The potential annual individual dose received through a particular pathway is an areal average of the nonuniform residual radioactivity over an area determined by the scenario activities, for example, the area of daily activities for external radiation or the size of the garden for plant food pathways. For the purpose of deriving soil guidelines, it is assumed that this area is 100 m^2 for all pathways. The effect of vertical nonuniformities is taken into account by averaging over the radionuclide concentrations in a 0.15-m-thick layer. Thus, the criterion for releasing a site for use without radiological restrictions is as follows: for any 100-m^2 area and 0.15-m-thick layer within the contaminated zone,

$$\bar{M}(t) \equiv \sum_i \bar{S}_i(0)/G_i(t) \le 1, \qquad t_r \le t \le t_h \tag{3.3}$$

where

$\bar{M}(t)$ = average mixture sum at time t (dimensionless),

$\bar{S}_i(0)$ = initial concentration of the i^{th} principal radionuclide averaged over a 100-m^2 area and 0.15-m-thick layer (pCi/g), and

$G_i(t)$ = single-radionuclide soil concentration guideline for the i^{th} principal radionuclide in a uniformly contaminated zone at time t (pCi/g).

Equation 3.3 is the homogeneous release criterion. It is directly applicable to homogeneous contamination, defined as contamination in a volume within which radionuclide concentrations in individual soil samples do not exceed the average concentrations by a factor larger than three. For a contaminated site, if the number and distribution of soil samples required by characterization and certification protocols result in only one soil sample from a contaminated region that is 100 m^2 in area and 0.15 m thick, then the contamination within the volume is assumed to be homogeneous and the average radionuclide concentrations are assumed to equal the concentrations in that sample. If no soil samples are taken from the volume, the radionuclide concentrations are assumed to be averages of concentrations in soil samples from the nearest neighboring volumes from which samples are taken. (See Ahrends [1987], DOE [1984], and ORNL [1982] for sampling protocols.)

For field applications, the homogeneous criterion as specified by Equation 3.3 may be replaced by the criterion

$$\bar{M} = \sum_i \bar{S}_i(0)/G_i(t_m) \le 1 \tag{3.4}$$

where

$\bar{S}_i(0)$ = as defined for Equation 3.3, and

$G_i(t_m)$ = single-radionuclide soil guideline for the i^{th} principal radionuclide in a homogeneous contaminated zone at the time $t = t_m$ within the interval $t_r \le t \le t_h$ that the time-dependent value $G_i(t)$ is minimum (pCi/g).

$G_i(t_m)$ should be obtained from RESRAD prior to the field actions. Equations 3.3 and 3.4 are equivalent when the minima in $G_i(t)$ for different principal radionuclides all occur at the same time. Equation 3.4 is more restrictive than Equation 3.3 because the minima in $G_i(t)$ usually occur at different times for different principal radionuclides.

For inhomogeneous contamination, defined as contamination in a volume within which the above-background concentration of a radionuclide at one or more sampling locations exceeds three times the average concentration, the average concentration $\bar{S}_i(0)$ in Equation 3.3 may be conservatively replaced by $\hat{S}_i(0)/3$, where $\hat{S}_i(0)$ is the maximum concentration in a soil sample taken from within the area.

Alternatively, when sufficient data are available and conditions warrant, one may apply less conservative, inhomogeneous contamination criteria in place of homogeneous contamination criteria. The purpose of the inhomogeneous contamination criteria is to provide a more realistic guideline for cleanups in cases where the conservatism inherent in the homogeneous assumptions would cause excessive expenditures in comparison to the benefits associated with the more conservative approach. The inhomogeneous contamination criteria, which are discussed in Section 3.3.1, should not be confused with the field criteria or hot spot criteria, which are described in Section 3.3.2.

The purpose of the hot spot criteria is to ensure that applying the homogeneous criteria, in which the concentrations of residual radioactive material are averaged over a 100-m^2 area, does not result in the release of small areas that, due to averaging, contain unacceptably high concentrations of residual radioactive material. Although the inhomogeneous criteria may, under appropriate conditions, be used in place of the general guidelines, the hot spot criteria must be used along with the general guidelines or authorized limits resulting from the homogeneous criteria.

A single-radionuclide soil concentration guideline for a uniformly contaminated zone is defined as

$$G_i(t) \equiv H_{EL}/DSR_i(t) \tag{3.5}$$

where

H_{EL} = basic dose limit (100 mrem/yr),

$DSR_i(t) = \sum_p DSR_{ip}(t)$ = dose/soil-concentration ratio for the i^{th} principal radionuclide in the contaminated zone at time t [(mrem/yr)/(pCi/g)], and

$DSR_{ip}(t)$ = dose/soil-concentration ratio for the i^{th} principal radionuclide and p^{th} environmental pathway [(mrem/yr)/(pCi/g)].

The dose/soil-concentration ratios for individual principal radionuclides and pathways are defined as

$$DSR_{ip}(t) \equiv H_{E,ip}(t)/S_i(0) \tag{3.6}$$

where

$H_{E,ip}(t)$ = average annual effective dose equivalent received at time t by a member of the critical population group from the i^{th} principal radionuclide transported through the p^{th} environmental pathway together with its associated decay products (mrem/yr), and

$S_i(0)$ = initial concentration of the i^{th} principal radionuclide in a uniformly contaminated zone (pCi/g).

The total annual effective dose equivalent to an individual is

$$H_E(t) = \sum_i \sum_p H_{E,ip}(t) \tag{3.7}$$

Substituting Equations 3.5-3.7 into Equation 3.1 and rearranging terms leads to Equation 3.2.

3.2 DOSE/SOURCE CONCENTRATION RATIOS FOR UNIFORM CONTAMINATION

The dose/source (D/S) concentration ratios are calculated by first expressing them as products of dose conversion factors [dose/exposure-parameter (D/E) ratios], environmental transport factors [exposure-parameter/source-concentration (E/S) ratios], and source factors (ratios of the concentration of a radionuclide at a given time to the initial concentration). The factored expression for a D/S ratio is

$$DSR_{ip}(t) = \sum_j DCF_{j,x(p)} \times ETF_{jp}(t) \times SF_{ij}(t) \tag{3.8}$$

where

$DCF_{j,x(p)}$ = dose conversion factor for the j^{th} principal radionuclide and $x(p)^{th}$ exposure pathway [(mrem/yr)/(pCi/cm^3) for external radiation from the contaminated zone; mrem/pCi for internal radiation from ingestion or inhalation of radionuclides],

$ETF_{jp}(t)$ = environmental transport factor for the j^{th} principal radionuclide and p^{th} environmental pathway at time t (g/cm^3 for external radiation from the contaminated zone; g/yr for internal radiation from ingestion or inhalation of radionuclides),

$SF_{ij}(t)$ = factor for ingrowth and decay and leaching of the j^{th} principal radionuclide at time t from the i^{th} principal radionuclide present initially (dimensionless),

$x(p)$ = index label for exposure pathways, which is a function of the environmental pathway p [for $p = 1$ (external radiation from the ground), $x(p) = 1$; for $p = 2$ (inhalation), $x(p) = 2$; and for $p = 3, 4, 5, 6$, and 7 (ingestion of plants, meat, milk, fish, and water, respectively), $x(p) = 3$],

p = index label for environmental pathways, and

i,j = index labels for principal radionuclides.

3.2.1 Dose Conversion Factors

A dose conversion factor is the ratio

$$DCF_{ix} = H_{E,ix}/E_{ix} \tag{3.9}$$

where

$H_{E,ix}$ = annual effective dose equivalent resulting from exposure to external radiation ($x = 1$) from the i^{th} principal radionuclide and its associated radionuclides (mrem/yr) or the annual committed effective dose equivalent resulting from exposure for 50 years to internal radiation from the amount of the i^{th}

principal radionuclide and its associated radionuclides inhaled (x = 2) or ingested (x = 3) in 1 year (mrem/pCi) and

E_{ix} = exposure parameter for the i^{th} principal radionuclide [concentration of the i^{th} principal radionuclide in a standard source (for external radiation pathways) or the annual quantity of the i^{th} principal radionuclide inhaled or ingested (for internal radiation pathways)] (pCi/cm^3 for external radiation [x = 1] from the contaminated zone; pCi/yr for internal radiation from inhalation [x = 2] or ingestion [x = 3]).

An internal dose conversion factor for any radionuclide includes the contribution from ingrowth following ingestion or inhalation. The internal dose conversion factor for a principal radionuclide includes, in addition, the contribution from inhalation or ingestion of associated radionuclides along with the principal radionuclide. The additional contribution is significant only for associated radionuclides with half-lives that are not small compared to the biological half-life. The dose conversion factor for external radiation for a principal radionuclide is defined here to include the dose from all of its associated radionuclides, which are assumed to be in secular equilibrium.

Dose conversion factors for external radiation from the contaminated zone, internal radiation from inhalation, and internal radiation from ingestion are given in Tables B.1, C.1, and D.1, respectively, of Appendixes B, C, and D.

3.2.2 Environmental Transport Factors

An environmental transport factor is the time-dependent ratio

$$\mathrm{ETF}_{ip}(t) = E_{ip}(t)/S_i(t) \tag{3.10}$$

where

$E_{ip}(t)$ = exposure parameter value at time t for the i^{th} principal radionuclide (or radiation therefrom) transported through the p^{th} environmental pathway (pCi/cm^3 for external radiation from the contaminated zone; pCi/yr for internal radiation),

p = index label for environmental pathways, and

$S_i(t)$ = average concentration of the i^{th} principal radionuclide in a uniformly contaminated zone at time t (pCi/g).

The exposure parameter for external radiation from the contaminated zone is the concentration of the i^{th} principal radionuclide in the ground, adjusted for occupancy and the size and depth of the contaminated zone by means of multiplying factors. The exposure parameter for internal radiation pathways is the annual quantity of the i^{th} principal radionuclide that is inhaled or ingested after migrating through the p^{th} environmental pathway. There are only two internal exposure pathways (inhalation and ingestion); several environmental pathways can contribute to each.

Models and formulas for calculating environmental transport factors are given in Appendixes B through E.

3.2.3 Source Factors

A source factor is the time-dependent ratio

$$SF_{ij}(t) = S_{ij}(t)/S_i(0) \tag{3.11}$$

where

$S_{ij}(t)$ = concentration at time t of the j^{th} principal radionuclide remaining in the contaminated zone after leaching and ingrowth from the i^{th} principal radionuclide, if $j \neq i$ (pCi/g); or the concentration at time t of the i^{th} principal radionuclide remaining in the contaminated zone after leaching, excluding contributions from ingrowth from other radionuclides, if $j = i$ (pCi/g), and

$S_i(0)$ = initial concentration of the i^{th} principal radionuclide in the contaminated zone (pCi/g).

Formulas for calculating source factors are given in Appendix F.

3.3 GUIDELINES FOR INHOMOGENEOUS CONTAMINATION

Two separate formulations of inhomogeneous release criteria are developed: (1) the inhomogeneous criteria, intended for use during project planning and review as an alternative to the homogeneous criteria, and (2) the hot spot criteria, intended for field use in conjunction with the homogeneous criteria or for use when determination of compliance must be made immediately.

3.3.1 Inhomogeneous Criteria for Project Planning and Review

A contaminated zone is inhomogeneous if it contains a contaminated region within which the concentration of a radionuclide exceeds three times the average for the contaminated zone. Inhomogeneous release criteria, described below, are generally more realistic and hence less restrictive than the homogeneous release criteria. In general, inhomogeneous contamination should be remediated in order to meet homogeneous contamination limits. However, the inhomogeneous contamination criteria may be used in cases where it is inappropriate to use the homogeneous contamination criteria. For example, homogeneous criteria might be inappropriate if the contamination exists under a roadway, railroad right-of-way, or building. Inhomogeneous criteria can also be used if an area of elevated contamination is found during the verification survey after equipment and crews have left the site. An area of elevated contamination must always be remediated before a site can be released for use without radiological restrictions if that area does not comply with inhomogeneous criteria.

The mixture-sum release criterion for any zone of inhomogeneous contamination is

$$M^*(t) + \bar{M}(t) \le 1, \qquad t_r \le t \le t_h \tag{3.12}$$

where

$M^*(t)$ = mixture sum for area of elevated contamination (dimensionless),
$\bar{M}(t)$ = mixture sum for averaging zone (dimensionless), and
t_r and t_h are as defined for Equation 3.1.

The averaging zone for inhomogeneous contamination is an area of 100 m^2 that encloses the elevated contamination.

The two mixture sums are defined as follows:

$$M^{*}(t) = \sum_{i} [S_{i}^{*}(0) - \bar{S}_{i}(0)]/G_{i}^{*}(t) \tag{3.13}$$

$$\bar{M}(t) = \sum_{i} \bar{S}_{i}(0)/G_{i}(t) \tag{3.14}$$

where

$S_{i}^{*}(0)$ = initial concentration of the ith principal radionuclide in the area of elevated contamination (pCi/g),

$G_{i}^{*}(t)$ = single-radionuclide, time-dependent soil guideline for the ith principal radionuclide in the area of elevated contamination (pCi/g),

$\bar{S}_{i}(0)$ = average initial concentration of the ith principal radionuclide in the averaging zone over a 100-m^2 area and a 0.15-m-thick layer, excluding the area of elevated contamination (pCi/g), and

$G_{i}(t)$ = single-radionuclide, time-dependent soil guideline for the ith principal radionuclide in a uniformly contaminated zone (pCi/g).

If the area of elevated contamination is inhomogeneous, one of two approaches may be used: (1) the area may be treated as if it were homogeneous with a concentration $\hat{S}_{i}(0)/3$, where $\hat{S}_{i}(0)$ is the peak concentration of the ith principal radionuclide in a sample from within the area of elevated contamination, or (2) the area may be divided into subzones using the same procedure that is used for a zone of inhomogeneous contamination.

When inhomogeneous release criteria are used, Equation 3.12 must be satisfied for every area of inhomogeneous contamination and, in addition, Equation 3.3 must be satisfied for any region within the homogeneous portion of the contaminated zone.

3.3.2 Hot Spot Criteria for Field Application

Hot spots are small areas that have levels of residual radioactive material that are considerably above the levels in the surrounding area. The derivation of remedial action criteria generally assumes homogeneous contamination of large areas (several hundred square meters or more), and the derived concentration guide is stated in terms of concentrations averaged over an area of 100 m^2. Because of this averaging process, within these 100-m^2 areas hot spots can exist that contain concentrations of radionuclides that are significantly higher than the authorized limit. Therefore, the presence of hot spots could potentially pose a greater risk of exposure to individuals using the site than the risk associated with homogeneous contamination. In order to ensure that individuals are adequately protected and to ensure that the ALARA process is satisfied, the following hot spot criteria must be applied along with the general criterion for homogeneous contamination. The hot spot criterion for field application is

$$M^{**} \equiv \sum_i S_i^* / G_i^{**} \leq 1 \qquad (3.15)$$

where

M^{**} = hot spot mixture sum for field use (dimensionless),

S_i^* = measured concentration of the i^{th} principal radionuclide in the hot spot (pCi/g), and

G_i^{**} = single-radionuclide soil guideline for the i^{th} principal radionuclide in the hot spot (pCi/g).

The measured hot spot concentrations S_i^* are the peak concentrations if the hot spot area is 1 m^2 or less or the average concentrations if the hot spot area is larger than 1 m^2.

The formula for single-radionuclide, hot spot soil guidelines is

$$G_i^{**} = G_i(t_m) \times (100/A)^{1/2} \qquad (3.16)$$

where

$G_i(t_m)$ = as defined for Equation 3.4,
A = area of hot spot (m^2), and
$(100/A)^{1/2}$ = hot spot multiplication factor.

Equations 3.15 and 3.16 apply to hot spots with areas of 25 m^2 or less. For larger hot spot areas, the homogeneous release criterion is sufficient. An area of $A = 1$ m^2 is used in Equation 3.15 if the actual hot spot area is less than 1 m^2. The average radionuclide concentrations for any 100-m^2 area must always comply with the homogeneous release criterion, irrespective of hot spot criteria.

For general field applications, it is recommended that the ranges of hot spot multiplication factors provided in Table 3.2 be used. The hot spot guideline for radionuclide i is calculated for each specific site by Equation 3.16. The term $G_i(t_m)$ in Equation 3.16 can be substituted by G_i, the authorized limit at a specific site for the i^{th} principal radionuclide.

TABLE 3.2 Ranges for Hot Spot Multiplication Factors

Range	Factor (multiple of authorized limit)
$<1\ m^2$	10[a]
$1 - <3\ m^2$	6
$3 - <10\ m^2$	3
$10 - 25\ m^2$	2

[a] Areas less than 1 m^2 are to be averaged over a 1 m^2 area, and that average shall not exceed 10 times the authorized limit.

The authorized limit is considered adequate to protect the public for areas larger than 25 m^2; hence, no special hot spot limits are required for areas larger than 25 m^2. Averaging of hot spots less than or equal to 25 m^2 shall be done only over the local hot spot area.

Every reasonable effort shall be made to identify and remove any source that has a radionuclide concentration exceeding 30 times the authorized limit, irrespective of area.

4 USER'S GUIDE FOR RESRAD

The analytical method for deriving guidelines for allowable concentrations of residual radioactive material in soil is described in Chapters 2 and 3 and Appendixes B through E. This method has been implemented in a computer code named RESRAD. RESRAD is designed for use on an IBM or IBM-compatible personal computer, with internal help files for information on input and output data. Instructions for installing and using the code are presented in Sections 4.1 through 4.8.

4.1 INSTALLING

An IBM (or IBM-compatible) microcomputer with a hard disk drive and approximately 400K of memory is required. A DOS 3.1 or equivalent operating system is needed; a mathematics coprocessor is optional but highly recommended. A printer capable of 132-column output is desirable. Most PC printers have a condensed print option (17 characters per inch) that is satisfactory. A color monitor and a mouse are optional but recommended. However, a mouse may not work with all monitor and graphics cards. No problems have occurred with Microsoft Bus Mouse, Logitech Bus Mouse, or Mouse Systems PS/2 Mouse. Any hardware problems encountered should be reported to the contact address on the last RESRAD screen.

The code is available either on two 360K 5.25-inch diskettes or on a single 720K 3.5-inch diskette. One 5.25-inch diskette is marked "RESRAD SOURCE CODES." This diskette contains the source code for all RESRAD programs and other supplementary files; it is not necessary for the operation of RESRAD and need not be copied to the hard disk. On the 3.5-inch diskettes, a \SOURCE subdirectory contains the identical material. The steps for installing the code are as follows:

1. Assuming the hard disk is the C disk, move to the C disk drive with the DOS commands

   ```
   C:
   CD\
   ```

2. Issue the DOS command

   ```
   PROMPT $P$G
   ```

   This adds the current subdirectory to the DOS prompt.

3. Create a subdirectory called RESRAD on the hard disk (if an earlier version of RESRAD exists on the hard disk, this version will be replaced by the new version) and move to the new subdirectory using the commands

   ```
   MD\RESRAD
   CD\RESRAD
   ```

   The prompt "C:\RESRAD>" should appear on the monitor.

4. Insert either the 3.5-inch RESRAD distribution diskette or the 5.25-inch diskette labeled "RESRAD SYSTEM DISK" into the A disk drive and issue the command

   ```
   COPY A:*.*
   ```

   to copy all necessary files to the hard disk.

5. The RESRAD system is stored in a special, compacted format. To complete the installation, enter the command

   ```
   INSTALL
   ```

6. At this point, all of the executable modules, forms, data, and files needed to run RESRAD will be on the hard disk. However, successful execution of the code will require a CONFIG.SYS file in the root directory of the hard disk that contains at least the following:

   ```
   FILES=20
   BUFFERS=16
   SHELL=C:\COMMAND.COM /P/E:256
   ```

   A CONFIG.SYS consisting of the above lines will be found in the \RESRAD directory. The existing CONFIG.SYS may be replaced by typing

   ```
   COPY C:\RESRAD\CONFIG.SYS C:\
   ```

   or an existing CONFIG.SYS may be modified with a suitable editor such as EDLIN. Note that the 256 in the SHELL command sets the size of the DOS environment-string table. If an out-of-environment-space error occurs, increase the size of the E parameter. A system reboot (Ctrl-Alt-Del) is needed whenever changes are made to the CONFIG.SYS file.

4.2 RESRAD EXECUTION

The prompts (in boldface) and responses for starting RESRAD are

```
C:\> CD\RESRAD
C:\RESRAD> RESRAD [ARGUMENT 1] [ARGUMENT 2] [ARGUMENT 3]
```

Up to three optional command line arguments may be included. The same information can be supplied (or superseded) later via regular RESRAD form input;

however, command line input, if different from the system defaults, is more efficient. The optional arguments are as follows.

ARGUMENT 1: The name of the initial (template) site-specific data file. The default file for this purpose is RESRAD.DEF. It is supplied on the distribution diskette and contains the default values for all RESRAD parameters. It also serves as a sample test problem. In general, users are advised to specify an initial data file that more closely matches the specific site.

ARGUMENT 2: The name of the final site-specific data file. This is the file that actually serves as input data for RESRAD. In the menu phase of RESRAD (see Section 4.4), any of the parameters supplied by the initial site-specific data file (ARGUMENT 1) may be modified. All changes are saved in the final site-specific data file (ARGUMENT 2). If there are no command line arguments, the default for ARGUMENT 2 is SAMPLE.DAT. If only one argument is supplied, ARGUMENT 2 = ARGUMENT 1 is the default (except if RESRAD.DEF is used, in which case the default for ARGUMENT 2 again is SAMPLE.DAT). *Warning: if the initial site-specific data file is to serve as a template for additional runs, a different name must be supplied for the final site-specific data file.*

ARGUMENT 3: The destination of RESRAD hard copy output. The default is LPT1 for normal printer output. Or the user may specify a disk file name to save all or selected portions of RESRAD output. In the case of an existing disk file, the user can select to either overwrite the file or append to the end of the file.

All of the above arguments may include disk drive and path names up to a maximum of 36 characters each. As a special feature, the DOS wildcard characters "*" or "?" may be included in the file name(s). RESRAD will produce an appropriate directory listing(s) before starting normal output, and the user can then input the desired file name or try another wildcard directory listing. An example using all three possible arguments is

```
C:\RESRAD> RESRAD MYSITE.DAT MYSITE1.DAT A:MYSITE1.PRN
```

In the above example, MYSITE.DAT must exist in the default \RESRAD directory, MYSITE1.DAT will be produced (or overwritten) in the \RESRAD directory, and all hard copy output will be "printed" in MYSITE1.PRN on the A drive.

One final feature is available for starting RESRAD. The standard IBM-PC font, which uses ASCII characters 128-255, is assumed to be available on the printer. If strange characters appear on the printed output, use RESRAD1 instead of RESRAD to start the code, i.e.,

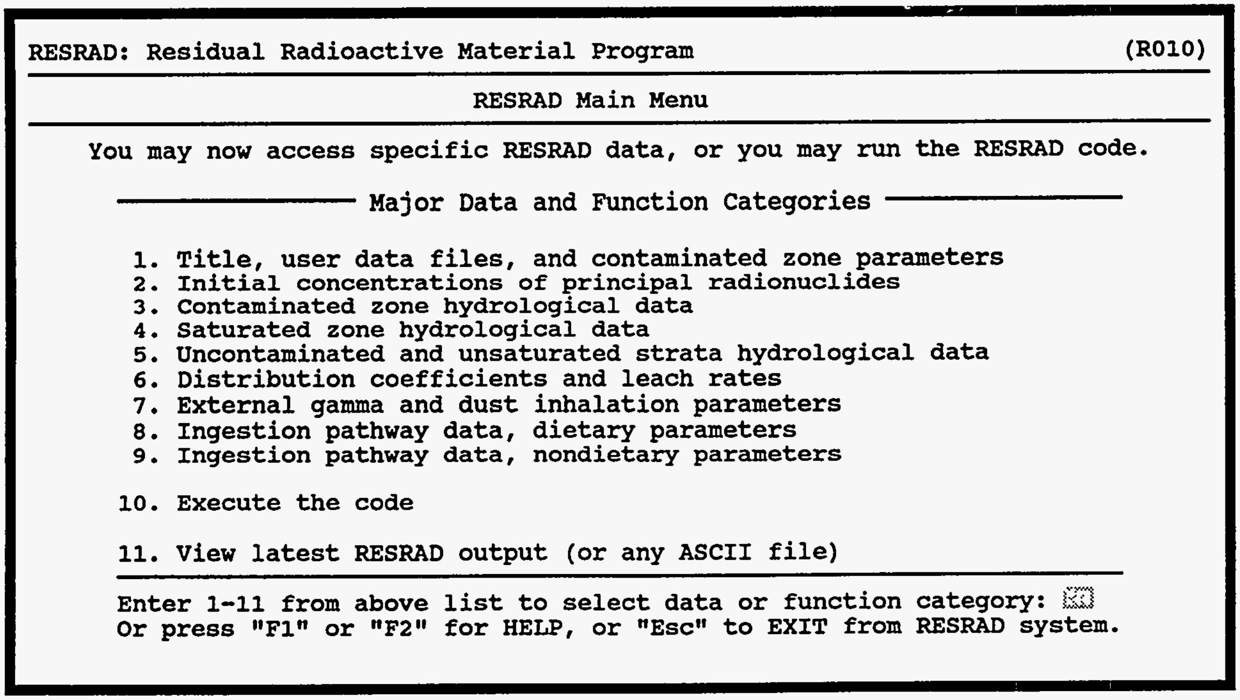
```
C:\RESRAD> RESRAD1 [ARGUMENT 1] [ARGUMENT 2] [ARGUMENT 3]
```

4.3 PRELIMINARY OUTPUT

The initial RESRAD output is a banner page with a brief code definition. This is followed by a printer setup series that allows the user, if desired, to set the printer for output of 132 columns per page. The final preliminary output will occur only if a mouse is available on the PC. In this case, the user is provided with RESRAD-specific instructions on use of the mouse. Although optional, a mouse provides three unique RESRAD advantages: direct access to any menu item, instant review of a parameter's default value, and automatic restoration of a parameter's default value.

4.4 MAIN MENU AND HELP FILES

The true starting point for using RESRAD is the main menu (R010), reproduced in Figure 4.1. This appears as soon as the preliminary output (Section 4.3) is completed. The main menu is also the return point after completion of RESRAD's calculation phase. By selecting the major data and function categories, all input data and output reports are accessible from the main menu. To terminate RESRAD, press "Esc" while the main menu is on screen.



```
RESRAD: Residual Radioactive Material Program                    (R010)
                         RESRAD Main Menu
   You may now access specific RESRAD data, or you may run the RESRAD code.

        ──────────── Major Data and Function Categories ────────────

          1. Title, user data files, and contaminated zone parameters
          2. Initial concentrations of principal radionuclides
          3. Contaminated zone hydrological data
          4. Saturated zone hydrological data
          5. Uncontaminated and unsaturated strata hydrological data
          6. Distribution coefficients and leach rates
          7. External gamma and dust inhalation parameters
          8. Ingestion pathway data, dietary parameters
          9. Ingestion pathway data, nondietary parameters

         10. Execute the code

         11. View latest RESRAD output (or any ASCII file)

         Enter 1-11 from above list to select data or function category:
         Or press "F1" or "F2" for HELP, or "Esc" to EXIT from RESRAD system.
```

FIGURE 4.1 Main Menu for RESRAD

Instructions for interactive use of the code are provided in help files that can be displayed on the screen by pressing the "F1" or "F2" function key. The "F1" help screen contains information for positioning the cursor, scrolling displays, and restoring, deleting, or entering data. This help screen is the same for all RESRAD input forms. Descriptions of the input and output data are given in the "F2" help files. In addition, the last line of every form is a help message for the current active field (cursor position).

Menu items are selected in the main menu (R010) by entering the appropriate item number and pressing "Enter." Items 1-9 display input forms on the screen, item 10 calculates results for the current set of parameters, and item 11 displays the output (summary or detailed report) from the last RESRAD run or the user may view any selected ASCII file.

Input data needed by RESRAD are accessible in a series of input forms. Default input values are provided for all input data except radionuclide concentrations. After an input form has been called for display, its input data can be reviewed and changed from the terminal. Pressing the "F10" function key will record all displayed entries and return control to the main menu. The changes made after an input form has been modified (but before it has been recorded) can be canceled by pressing the escape ("Esc") key. Recorded data are retained until changed again.

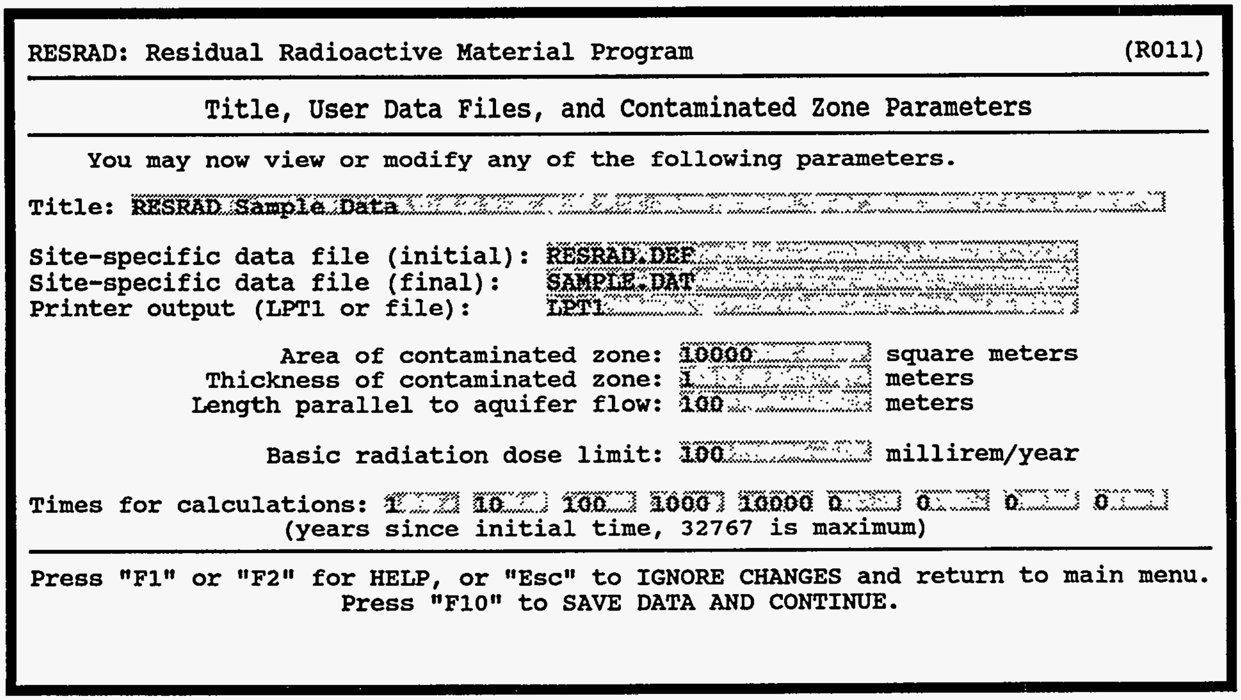
When RESRAD is executed, output from the preceding run is replaced by output from the current run. Thus, output from each run must be reviewed and recorded before executing the next run. However, all input data and all or selected portions of the output can be saved in user-specified disk files. A saved data file can then serve as the default input for a new run, after review and modifications via the input forms.

The output is divided into two parts: (1) the summary report, (SUMMARY.REP), for determining compliance with soil guidelines and examining the relative contributions to the mixture sum from different pathways at different times, and (2) the detailed report, (DETAILED.REP), for examining the effect of different parameters and tracking down the cause of anomalies. Output forms can be viewed page by page and can be printed (or saved) in total or in consecutive page groups.

4.5 INPUT FORMS

4.5.1 Title, User Data Files, and Contaminated Zone Parameters

Input form R011 is used to access the title, user-specified data files, and contaminated zone parameters. Form R011 with default data is shown in Figure 4.2.



```
RESRAD: Residual Radioactive Material Program                            (R011)
          Title, User Data Files, and Contaminated Zone Parameters
    You may now view or modify any of the following parameters.
Title: RESRAD Sample Data

Site-specific data file (initial): RESRAD.DEF
Site-specific data file (final):   SAMPLE.DAT
Printer output (LPT1 or file):     LPT1

                Area of contaminated zone: 10000       square meters
           Thickness of contaminated zone: 1           meters
           Length parallel to aquifer flow: 100        meters

              Basic radiation dose limit: 100          millirem/year

Times for calculations: 1    10   100  1000 10000 0    0    0    0
                 (years since initial time, 32767 is maximum)

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                    Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.2 Input Form R011 for Title, User Data Files, and Contaminated Zone Parameters

The TITLE used to identify the run can be up to 70 alphabetic or numerical characters. It is part of the header for every page of RESRAD output.

The SITE-SPECIFIC DATA FILE (INITIAL) is the name of the data file used for initial site-specific RESRAD input. The default file for this purpose is RESRAD.DEF, as supplied with the system diskette. However, the user will probably have a data file closer to the current need. If so, the file name can be specified here, and the new data will be input as soon as "F10" is pressed. Disk drive and path can be included in the file name (36-character maximum).

If the file name contains the wildcard character * or ?, RESRAD will supply a directory listing instead of attempting to read the file. Thus, A:*.DAT would list all files on the A disk with an extension of DAT. The user can then input the desired file or try another wildcard directory listing.

The SITE-SPECIFIC DATA FILE (FINAL) is the name of a file that contains the actual data used for a run. This "parameter" allows the user an easy method for saving the data used for each RESRAD calculation. The file name, again a 36-character maximum that can include drive and path, is included in the header of each page of RESRAD output. The final data file is updated every time a form is exited by pressing the "F10" function key.

The PRINTER OUTPUT (LPT1 OR FILE) is the destination of RESRAD hard copy output, which is obtained using option 11 from the main menu. The default is LPT1 for normal printer output. Or the user may specify a disk file name, again a 36-character maximum, for the "printer" output. If an existing file is specified, the new output can either overwrite or be appended to the end of the file. The user may also include the wildcard * or ? in the file name, which will produce a directory listing when "F10" is pressed.

The site-specific data file names and the printer output file can also be specified as arguments on the RESRAD command line (see Section 4.2). This is actually the preferred method for the initial data file because otherwise a new data set must be read in. The printer output file can also be changed at any time via main menu option 11 and "F7" (see Section 4.7.3).

After each RESRAD execution (main menu option 10) and return to the main menu, the initial site-specific data file is replaced with the final site-specific data file of the just-completed run. The final site-specific data file and printer output file remain unchanged. This allows the parameter input of the previous run to serve as the template for the next execution. The user, of course, may alter these automatic selections at any time.

The AREA OF CONTAMINATED ZONE is a compact area, specified in square meters (m^2), that contains the locations of all soil samples with radionuclide concentrations that are clearly above background and are separated from the locations of other above-background soil samples by a distance of at least 100 m. The concentration of a radionuclide is clearly above background if it exceeds the background level measurements by at least two standard deviations (see Section 3.1). Credible evidence that the intervening distance between any two contaminated zones is uncontaminated, based on radiological survey data, must be provided in order to justify the use of two or more contaminated zones; otherwise the contaminated zone should be characterized by a single compact area that contains the locations of all soil samples with radionuclide concentrations that are above background.

The THICKNESS OF CONTAMINATED ZONE is the distance, in meters (m), between the uppermost and lowermost soil samples with radionuclide concentrations that are clearly above background.

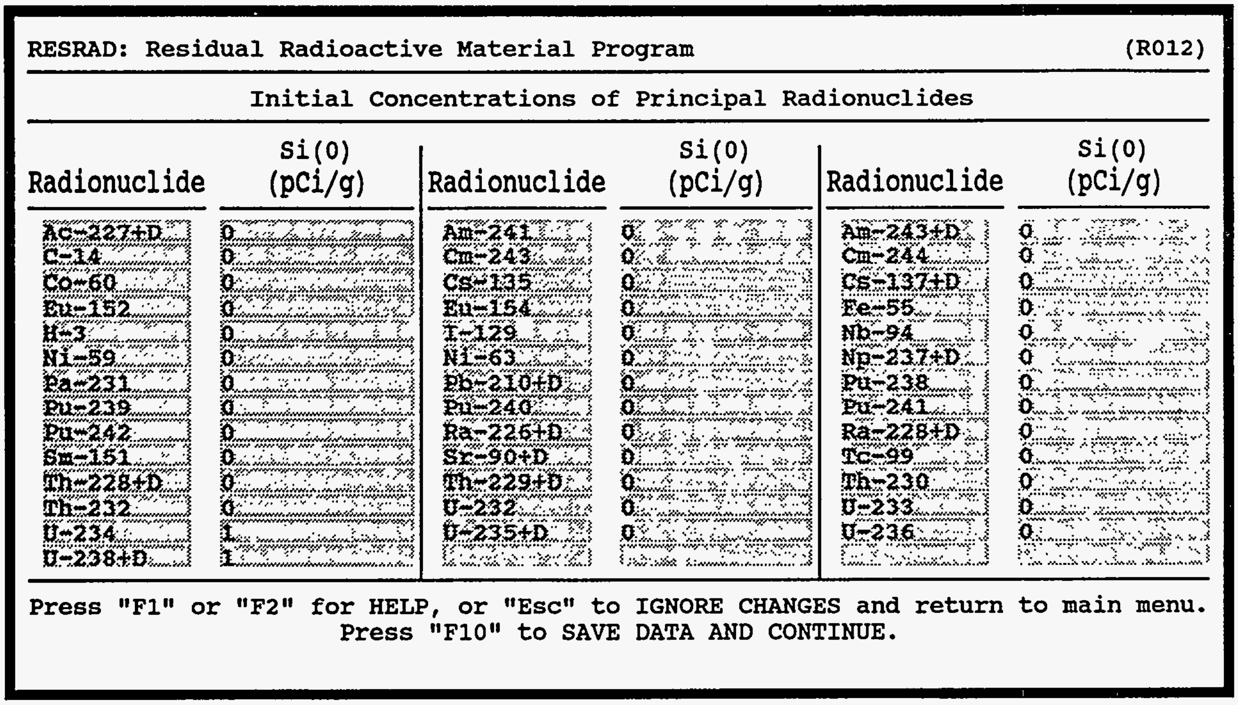
The LENGTH PARALLEL TO AQUIFER FLOW is the distance, in meters (m), between two parallel lines perpendicular to the direction of aquifer flow, one at the upgradient edge of the contaminated zone and the other at the downgradient edge.

The BASIC RADIATION DOSE LIMIT is the annual radiation dose limit, in millirems per year (mrem/yr), used to derive all site-specific soil guidelines.

The TIMES FOR CALCULATIONS are the times, in years, following the radiological survey for which the single radionuclide soil guidelines and mixture sums will be calculated. The default values are 1, 10, 100, 1,000, and 10,000 years. The guidelines require that the mixture sum be less than one at all times out to the time horizon; hence, exploratory calculations at other times should be carried out to ensure that no mixture sum maxima lie between the default times. A time horizon of 1,000 years is used for FUSRAP (see Appendix A); however, calculations can be carried out to greater periods to identify any delayed contributions from the groundwater or other pathways. RESRAD always calculates values for year 0. All years must be input in ascending order. If fewer than 10 time periods are selected, a zero must be input for the time period immediately following the last one desired.

4.5.2 Initial Concentrations of Principal Radionuclides

Input form R012, shown in Figure 4.3, is used to access the initial concentrations of principal radionuclides. The input fields on this form are broken into three parts, each with two columns. All radionuclides for which guidelines can be derived with the current version of RESRAD are listed in the first column of each of the three parts. Soil guidelines are calculated only for those radionuclides for which nonzero concentrations are entered.



```
RESRAD: Residual Radioactive Material Program                          (R012)
                 Initial Concentrations of Principal Radionuclides

                Si(0)                      Si(0)                       Si(0)
Radionuclide   (pCi/g)  | Radionuclide   (pCi/g)  | Radionuclide    (pCi/g)
 Ac-227+D       0       |  Am-241         0       |  Am-243+D        0
 C-14           0       |  Cm-243         0       |  Cm-244          0
 Co-60          0       |  Cs-135         0       |  Cs-137+D        0
 Eu-152         0       |  Eu-154         0       |  Fe-55           0
 H-3            0       |  I-129          0       |  Nb-94           0
 Ni-59          0       |  Ni-63          0       |  Np-237+D        0
 Pa-231         0       |  Pb-210+D       0       |  Pu-238          0
 Pu-239         0       |  Pu-240         0       |  Pu-241          0
 Pu-242         0       |  Ra-226+D       0       |  Ra-228+D        0
 Sm-151         0       |  Sr-90+D        0       |  Tc-99           0
 Th-228+D       0       |  Th-229+D       0       |  Th-230          0
 Th-232         0       |  U-232          0       |  U-233           0
 U-234          1       |  U-235+D        0       |  U-236           0
 U-238+D        1       |                         |

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                     Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.3 Input Form R012 for Initial Concentrations of Principal Radionuclides

A principal radionuclide is a radionuclide with a half-life longer than one year. An associated radionuclide is a decay product with a half-life of one year or less. The radionuclides "associated" with a principal radionuclide consist of all decay products down to, but not including, the next principal radionuclide in the chain. It is assumed that all associated radionuclides are in secular equilibrium with their principal radionuclide in the contaminated zone and also at the location of human exposure.

The single-radionuclide soil guidelines do not depend on the soil concentrations; even if the concentrations are not known, values for these quantities can be obtained by entering any nonzero concentration. The mixture sums, however, depend on the concentrations; hence, calculated mixture sum values are valid only if the concentrations are known.

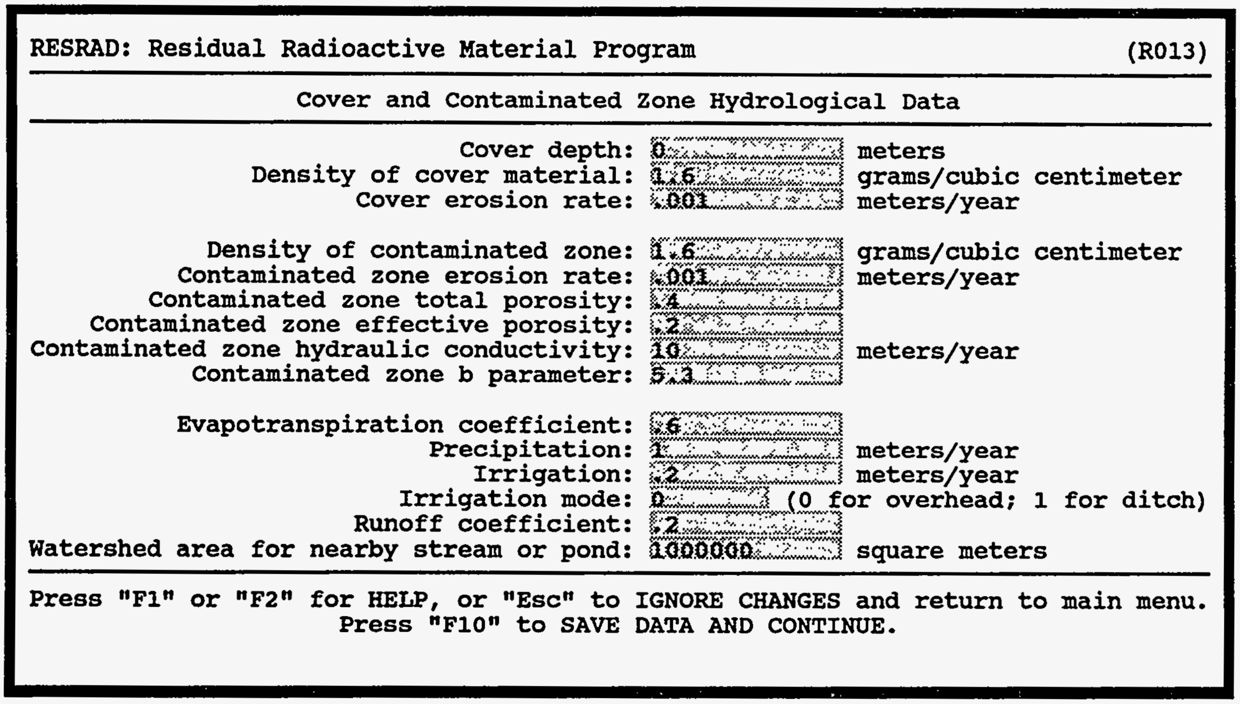
If the contaminated zone is treated as a single homogeneous contaminated zone, the mixture sum should be calculated using the radionuclide concentrations averaged over a compact 100-m^2 area or one-third of the peak radionuclide concentrations within the same area -- whichever gives the largest mixture sum. A 100-m^2 area that gives the largest mixture sum should be used if the area of the contaminated zone is larger than 100 m^2. The entire contaminated zone area should be used if this area is less than 100 m^2 but greater than 1 m^2. If the contaminated zone area is less than 1 m^2, peak radionuclide concentrations should be used.

If the contaminated zone is treated as an inhomogeneous contaminated zone, then the contaminated zone may be divided into subzones within each of which the peak concentration does not exceed the average concentration by a factor larger than three. The mixture sums for these subzones are then calculated as if each subzone were an isolated, homogeneous contaminated zone. The total of the mixture sums for subzones within a 100-m^2 area must be less than 1 for any 100-m^2 area within the contaminated zone.

The current version of RESRAD will calculate the mixture sum only for a single homogeneous zone or subzone. For an inhomogeneous contaminated zone, the subzone contributions must be summed separately according to the procedures described in Section 3.3.

4.5.3 Cover and Contaminated Zone Hydrological Data

Input form R013, shown in Figure 4.4, is used to access cover and contaminated zone hydrological data. The definitions of these data and information for determining appropriate site-specific values are given in Appendix E. The DENSITY OF COVER MATERIAL and COVER EROSION RATE appear on the form only if the cover depth is not zero.



```
RESRAD: Residual Radioactive Material Program                        (R013)
------------------------------------------------------------------------------
                Cover and Contaminated Zone Hydrological Data
------------------------------------------------------------------------------
                            Cover depth: 0           meters
                 Density of cover material: 1.6         grams/cubic centimeter
                     Cover erosion rate: .001        meters/year

           Density of contaminated zone: 1.6         grams/cubic centimeter
          Contaminated zone erosion rate: .001        meters/year
        Contaminated zone total porosity: .4
    Contaminated zone effective porosity: .2
Contaminated zone hydraulic conductivity: 10          meters/year
          Contaminated zone b parameter: 5.3

          Evapotranspiration coefficient: .6
                          Precipitation: 1           meters/year
                             Irrigation: .2          meters/year
                        Irrigation mode: 0      (0 for overhead; 1 for ditch)
                      Runoff coefficient: .2
Watershed area for nearby stream or pond: 1000000     square meters
------------------------------------------------------------------------------
Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                  Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.4 Input Form R013 for Cover and Contaminated Zone Hydrological Data

The COVER DEPTH is the distance, in meters (m), from the ground surface to the location of the uppermost soil sample with radionuclide concentrations that are clearly above background.

The bulk density of dry soil, specified in grams per cubic centimeter (g/cm^3), should be used for the DENSITY OF COVER MATERIAL and the DENSITY OF CONTAMINATED ZONE. A default value of 1.6 g/cm^3 can be used for preliminary estimates.

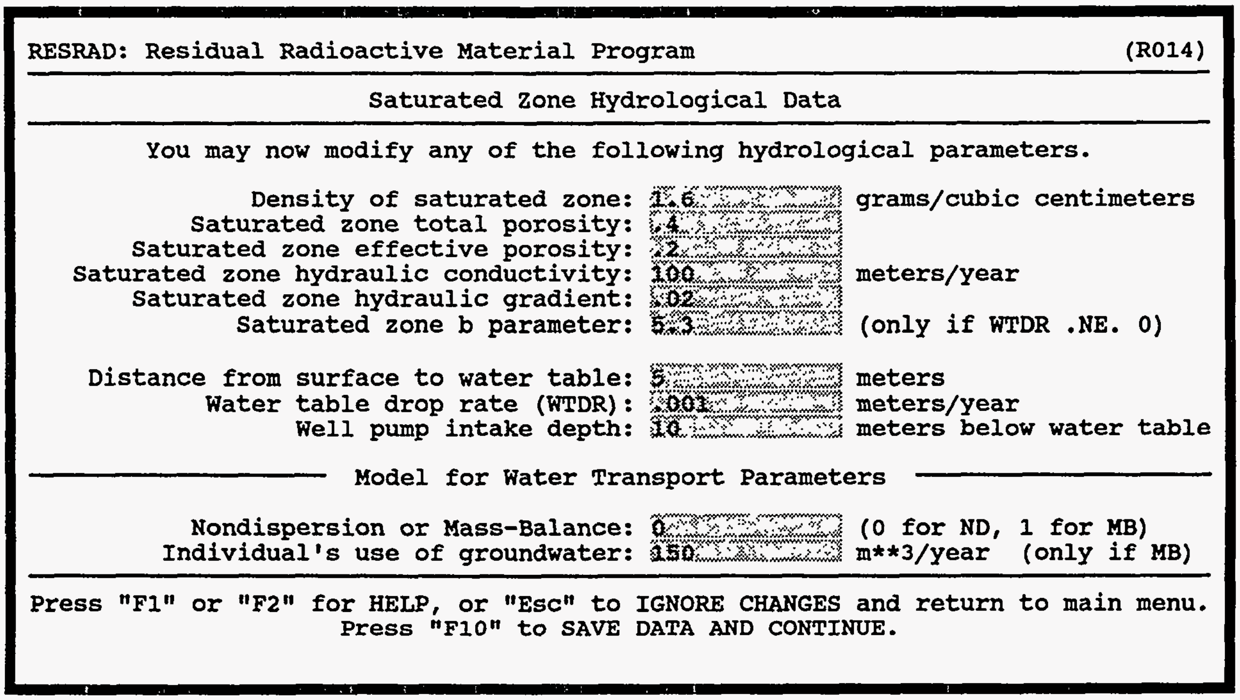
The COVER EROSION RATE and the CONTAMINATED ZONE EROSION RATE are the rates, in meters per year (m/yr), at which soil is removed by erosion. They can be estimated by means of the Universal Soil Loss Equation, as described in Appendix B. A default value of 0.001 m/yr is used for screening estimates. The contaminated zone erosion rate is only significant if and when the cover depth becomes zero. All other parameters are discussed in Appendix E.

Typical parameter values for various soil materials are presented in Tables E.1 through E.7.

4.5.4 Saturated Zone Hydrological Data

Input form R014, shown in Figure 4.5, is used to access saturated zone hydrological data. The definitions and information for determining appropriate values are given in Appendix E. Parameters with special considerations are listed below.

The DISTANCE FROM SURFACE TO WATER TABLE must equal the sum of the cover depth (menu R011), contaminated zone thickness (menu R011), and thicknesses of the unsaturated zone strata below the contaminated zone (menu R015). Immediately prior to the start of calculations (option 10 on the main menu), a consistency check is made to determine that the sum of the above parameters does in fact equal the specified distance to the water table. If the values



```
RESRAD: Residual Radioactive Material Program                        (R014)
                     Saturated Zone Hydrological Data
         You may now modify any of the following hydrological parameters.

               Density of saturated zone: 1.6       grams/cubic centimeters
          Saturated zone total porosity: .4
      Saturated zone effective porosity: .2
  Saturated zone hydraulic conductivity: 100        meters/year
      Saturated zone hydraulic gradient: .02
             Saturated zone b parameter: 5.3        (only if WTDR .NE. 0)

    Distance from surface to water table: 5          meters
              Water table drop rate (WTDR): .001       meters/year
                  Well pump intake depth: 10         meters below water table
 ----------------- Model for Water Transport Parameters -----------------
           Nondispersion or Mass-Balance: 0          (0 for ND, 1 for MB)
         Individual's use of groundwater: 150        m**3/year  (only if MB)

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                    Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.5 Input Form R014 for Saturated Zone Hydrological Data are not in balance, the user is prompted for corrections. The code will not execute until the imbalance is removed.

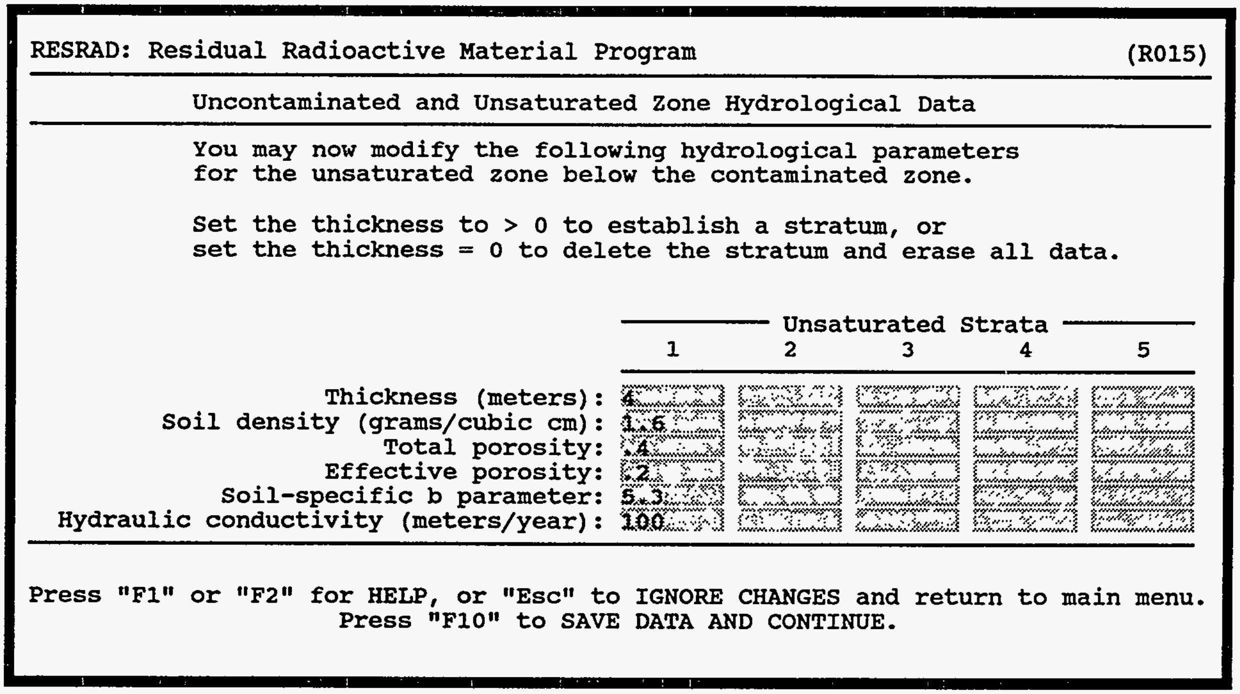
The WATER TABLE DROP RATE is the rate, in meters per year (m/yr), that the depth of the water table decreases. If the water table drop rate is not zero, the unsaturated zone thickness will be created or increased. The saturation of this newly created unsaturated zone is estimated by the hydrological parameters of the saturated zone. The SATURATED ZONE b PARAMETER appears on the form only if the water table drop rate is greater than zero.

The NONDISPERSION or MASS-BALANCE "parameter" selects which of two models will be used for water/soil concentration ratio calculations. A "0" (default) selects the ND model, and "1" selects the MB model. The MB model is not recommended for contaminated zones with an area greater than 1,000 m^2. The ND model can be used for an area of any size.

The INDIVIDUAL'S USE OF GROUNDWATER appears on the form only if the MB model is selected (see above). It is the total volume of well water withdrawn per year, in cubic meters per year (m^3/yr), for use by an individual. The default value is 150 m^3/yr.

4.5.5 Uncontaminated and Unsaturated Zone Hydrological Data

The uncontaminated and unsaturated zone is the portion of the uncontaminated zone that lies below the bottom of the contaminated zone and above the groundwater table. The code has provisions for up to five different horizontal strata within this zone. Each stratum is characterized by six radionuclide-independent parameters: thickness, soil density, total porosity, effective porosity, soil-specific b parameter, and hydraulic conductivity. Input form R015 for these data is shown in Figure 4.6.



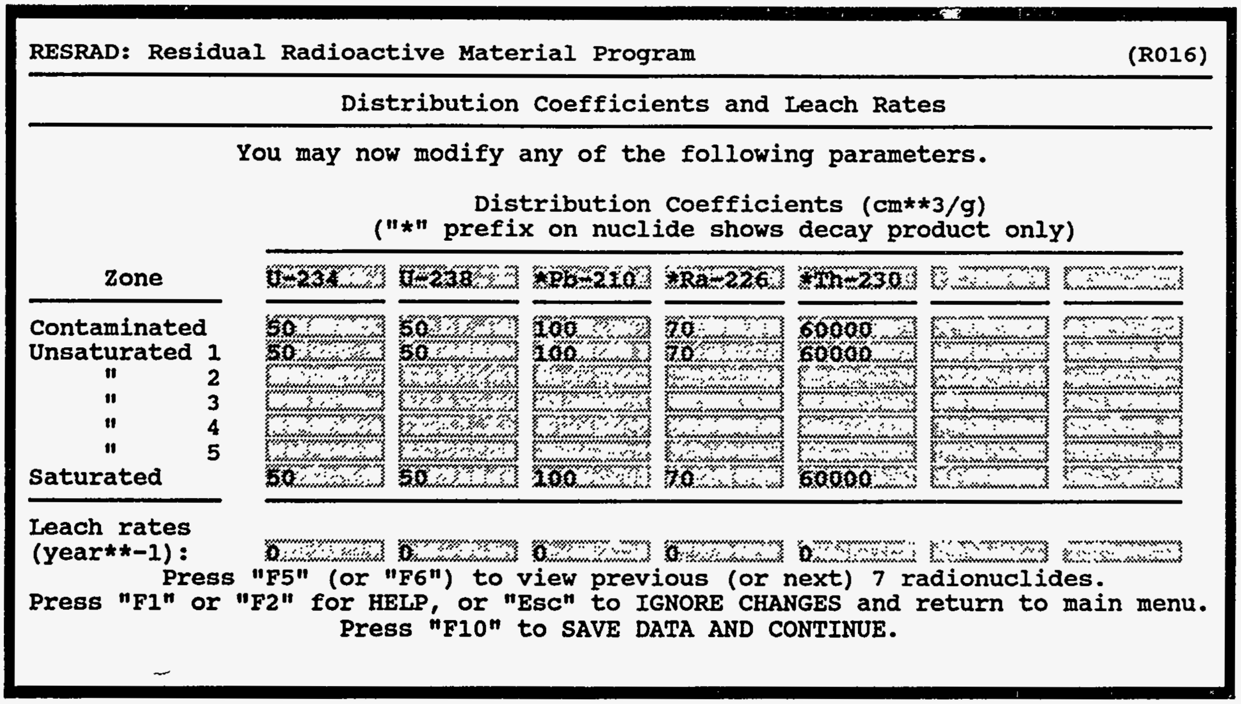
```
RESRAD: Residual Radioactive Material Program                    (R015)

          Uncontaminated and Unsaturated Zone Hydrological Data

          You may now modify the following hydrological parameters
          for the unsaturated zone below the contaminated zone.

          Set the thickness to > 0 to establish a stratum, or
          set the thickness = 0 to delete the stratum and erase all data.

                                       ------- Unsaturated Strata -------
                                         1       2       3       4       5

                     Thickness (meters): 4
         Soil density (grams/cubic cm): 1.6
                        Total porosity: .4
                    Effective porosity: .2
               Soil-specific b parameter: 5.3
   Hydraulic conductivity (meters/year): 100

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                     Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.6 Input Form R015 for Uncontaminated and Unsaturated Zone Hydrological Data

Data must be entered for each stratum used in the calculation. Entering a nonzero thickness for a stratum activates that stratum and, similarly, changing the thickness to zero deletes the stratum. Default values will be supplied by the code for all parameters of an active stratum; however, the use of true site-specific data is strongly recommended. Data for estimating hydrological parameters for different soil types are given in Appendix E.

4.5.6 Distribution Coefficients and Leach Rates

Input form R016, shown in Figure 4.7, is used to access distribution coefficients and leach rates. If the radionuclide leach rates in the contaminated zone are known, these leach rates should be entered in the LEACH RATES fields. If a leach rate is entered (i.e., >0), it will be used to calculate the leaching of radionuclides from the contaminated zone; if a leach



```
RESRAD: Residual Radioactive Material Program                          (R016)
                    Distribution Coefficients and Leach Rates
                  You may now modify any of the following parameters.
                             Distribution Coefficients (cm**3/g)
                        ("*" prefix on nuclide shows decay product only)
     Zone          U-234   U-238   *Pb-210  *Ra-226  *Th-230
Contaminated       50      50      100      70       60000
Unsaturated 1      50      50      100      70       60000
     "      2
     "      3
     "      4
     "      5
Saturated          50      50      100      70       60000
Leach rates
(year**-1):        0       0       0        0        0
        Press "F5" (or "F6") to view previous (or next) 7 radionuclides.
Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                     Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.7 Input Form R016 for Distribution Coefficients and Leach Rates

rate is not entered (i.e., = 0), the program will calculate the leach rate using the distribution coefficient for the contaminated zone.

In addition to the on-site principal radionuclides, form R016 allows parameters to be entered for decay product principal radionuclides. A "*" prefix is added to the symbol of all principal radionuclides present as decay products only.

The input form displays lines for the contaminated and saturated zones and for each unsaturated stratum below the contaminated zone with a nonzero thickness. Default distribution coefficients are provided automatically by the code for most nuclides. However, these values should be used with care because site-specific distribution coefficients can vary over many orders of magnitude depending on soil type, pH, redox potential, and presence of other ions. Replacement of the default values with site-specific data is always recommended. Tables of generic distribution coefficients for various nuclides are given in Appendix E.

Seven radionuclides are displayed at once on the screen, but the user can page through all the radionuclides, seven at a time, by pressing the "F5" (previous set) or "F6" (next set) keys.

The on-site principal radionuclides can be changed by form R012, which is obtained by option 2 on the main menu. The decay product principal radionuclides are added to form R016 automatically. The number of unsaturated strata can be changed by using form R015, which is obtained by option 5 on the main menu.

The most critical groundwater transport data are the distribution coefficients. Site-specific data should be used whenever possible.

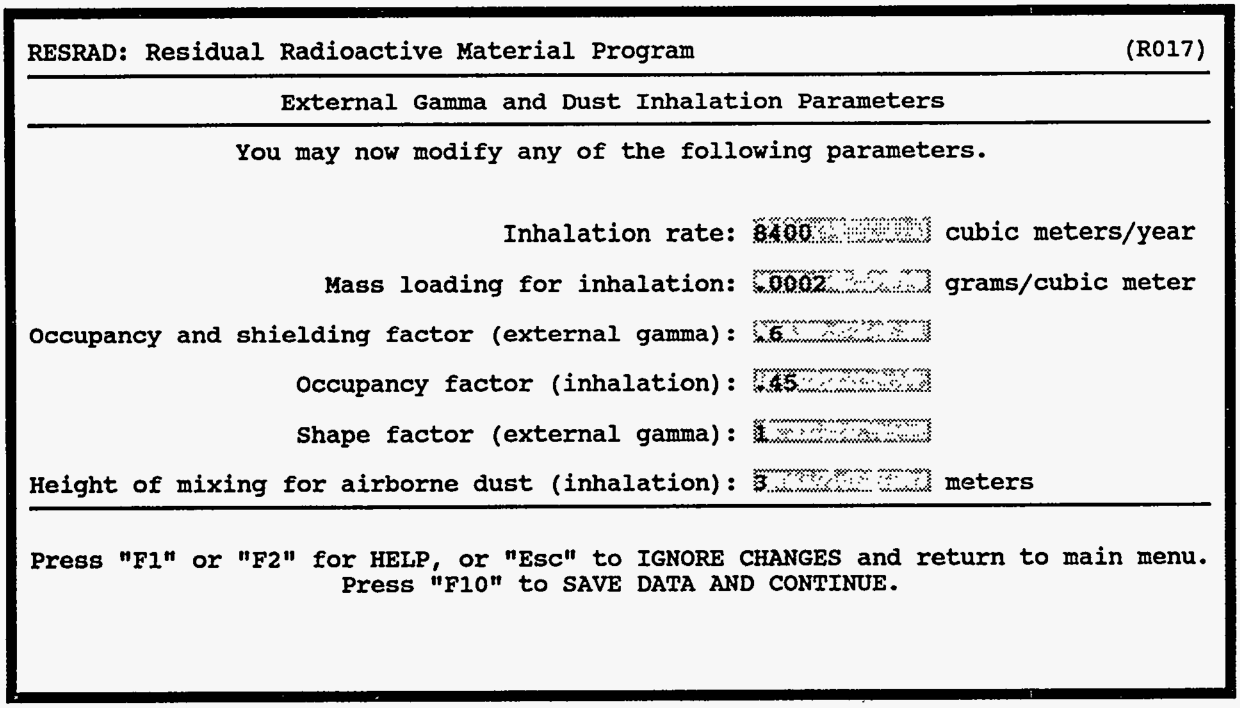
4.5.7 External Gamma and Dust Inhalation Parameters

Input form R017 for external gamma and dust inhalation parameters is shown in Figure 4.8. Values of these parameters applicable in the long term are not strongly site dependent; hence, in most circumstances the generic default values can be used.

4.5.8 Ingestion Pathway Data

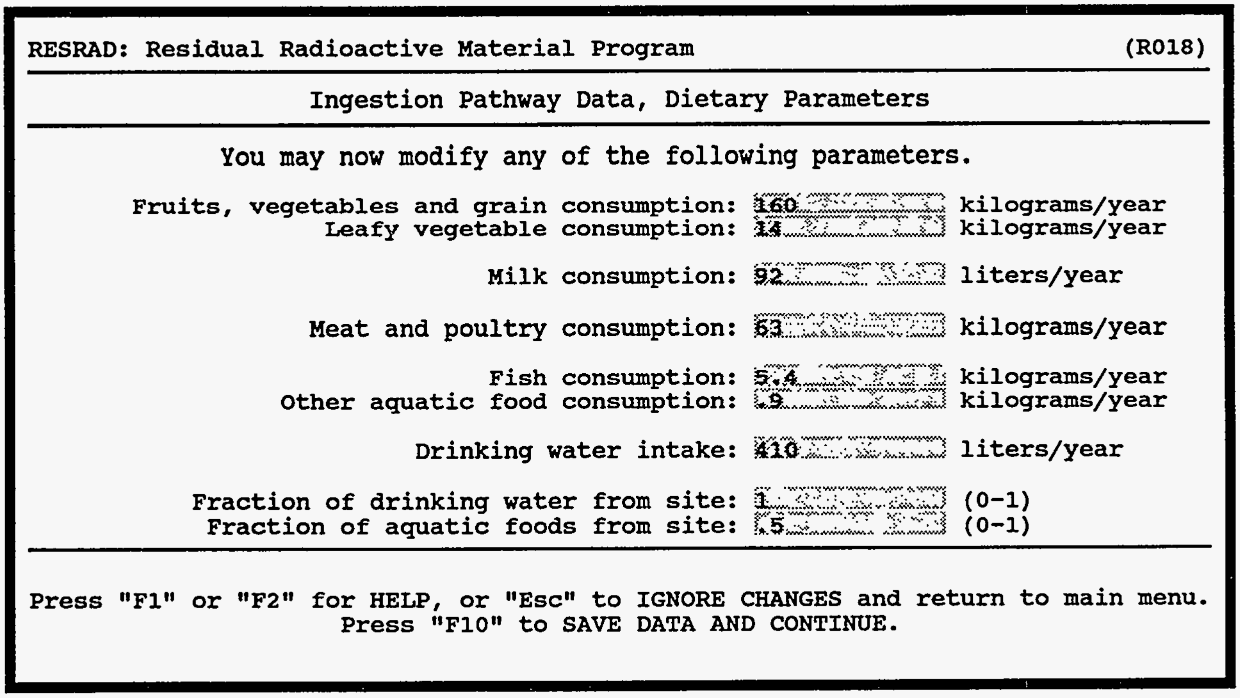
4.5.8.1 Dietary Parameters

Input form R018 for dietary parameters of the ingestion pathway is shown in Figure 4.9. The default parameter values have been chosen to correspond to national averages. The parameters, other than the final two, are not strongly site dependent; hence, use of the generic default values is



```
RESRAD: Residual Radioactive Material Program                              (R017)
                    External Gamma and Dust Inhalation Parameters
                    You may now modify any of the following parameters.

                                       Inhalation rate: 8400       cubic meters/year
                             Mass loading for inhalation: .0002      grams/cubic meter
Occupancy and shielding factor (external gamma): .6
                           Occupancy factor (inhalation): .45
                           Shape factor (external gamma): 1
Height of mixing for airborne dust (inhalation): 3          meters

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                     Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.8 Input Form R017 for External Gamma and Dust Inhalation Parameters



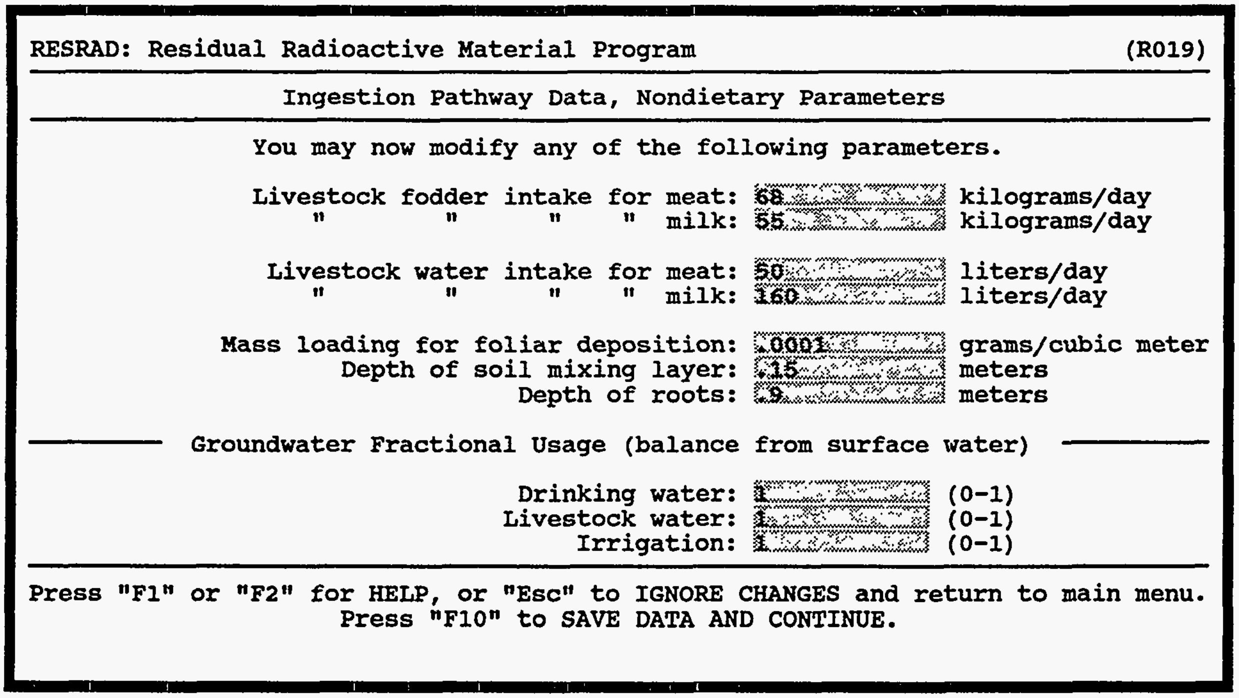
```
RESRAD: Residual Radioactive Material Program                              (R018)
                    Ingestion Pathway Data, Dietary Parameters
                    You may now modify any of the following parameters.
    Fruits, vegetables and grain consumption: 160        kilograms/year
            Leafy vegetable consumption: 14         kilograms/year

                              Milk consumption: 92         liters/year

                     Meat and poultry consumption: 63         kilograms/year

                              Fish consumption: 5.4        kilograms/year
                  Other aquatic food consumption: .9         kilograms/year

                          Drinking water intake: 410        liters/year

          Fraction of drinking water from site: 1          (0-1)
           Fraction of aquatic foods from site: .5         (0-1)

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                     Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.9 Input Form R018 for Ingestion Pathway, Dietary Parameters usually acceptable. Adjustments for regional differences in diet may sometimes be appropriate.

The FRACTION OF DRINKING WATER FROM SITE and FRACTION OF AQUATIC FOOD FROM SITE parameters allow specification of the fraction of contaminated intake for these pathways. The latter value applies to both fish and other aquatic foods. Off-site material is assumed to be uncontaminated. Defaults for the two fractions are 1.0 and 0.5, respectively.

4.5.8.2 Nondietary Parameters

Input form R019 for nondietary parameters of the ingestion pathway is shown in Figure 4.10. The default parameter values have been chosen to correspond to the national averages. The parameters, other than the final three, are not strongly site dependent; hence, use of the generic



```
RESRAD: Residual Radioactive Material Program                       (R019)
                 Ingestion Pathway Data, Nondietary Parameters
               You may now modify any of the following parameters.
               Livestock fodder intake for meat: 68          kilograms/day
                  "        "      "    "  milk: 55          kilograms/day

                Livestock water intake for meat: 50          liters/day
                  "        "      "    "  milk: 160         liters/day

              Mass loading for foliar deposition: .0001       grams/cubic meter
                     Depth of soil mixing layer: .15         meters
                               Depth of roots: .9          meters
 ------- Groundwater Fractional Usage (balance from surface water) -------
                               Drinking water: 1          (0-1)
                              Livestock water: 1          (0-1)
                                  Irrigation: 1          (0-1)
Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
                     Press "F10" to SAVE DATA AND CONTINUE.
```

FIGURE 4.10 Input Form R019 for Ingestion Pathway, Nondietary Parameters default values is usually acceptable. Adjustments for regional differences in farming practices may sometimes be appropriate.

The three groundwater fractional usage parameters -- drinking water, livestock water, and irrigation -- are included primarily to allow groundwater (well) and surface water (pond) scenarios. Hence, the fractions will usually be set at 1 or 0. A value of 1 selects 100% groundwater usage, and 0 selects 100% surface water. The default for all three parameters is 1. For livestock water and irrigation, all usage is assumed to be from the site. The fraction of contaminated drinking water, i.e., from the site, can be varied via a parameter in form R018.

4.6 CONTROL OF RESRAD PATHWAYS

RESRAD always computes the radiation dose resulting from seven potential pathways: (1) direct exposure to external radiation from the contaminated soil material, (2) internal radiation from inhalation, (3) internal radiation from ingestion of plant foods grown on-site and irrigated with water drawn from an on-site well or pond, (4) internal radiation from ingestion of meat from livestock fed with fodder grown on-site and water drawn from an on-site well or pond, (5) internal radiation from ingestion of milk from livestock fed with fodder grown on-site and water drawn from an on-site well or pond, (6) internal radiation from ingestion of aquatic foods from an on-site pond, and (7) internal radiation from drinking water from an on-site well or pond.

In many situations, certain of these pathways are not important or the user may deliberately wish to suppress selected pathways. Table 4.1 is a list of key parameters that, if set to zero, will eliminate the indicated pathway.

TABLE 4.1 Key Parameters to Eliminate Pathways

Pathway	Menu	Parameter[a]
1	R017	Shape factor (external gamma)
2	R017	Occupancy factor (inhalation)
3	R018	Fruits, vegetables, and grain consumption[b]
3	R018	Leafy vegetable consumption[b]
4	R018	Meat and poultry consumption
5	R018	Milk consumption
6	R018	Fraction of aquatic foods from site
7	R018	Fraction of drinking water from site

[a] Set indicated parameter(s) to zero to suppress pathway.

[b] Set both parameters to zero for pathway 3.

However, no savings in computation time will result by eliminating a pathway; only the dose contribution is set to zero.

4.7 RESRAD OUTPUT

When option 10 of the main menu is selected, RESRAD enters its RESMAIN computation and report generation phase. A number of brief progress reports will appear on the display monitor, ending with

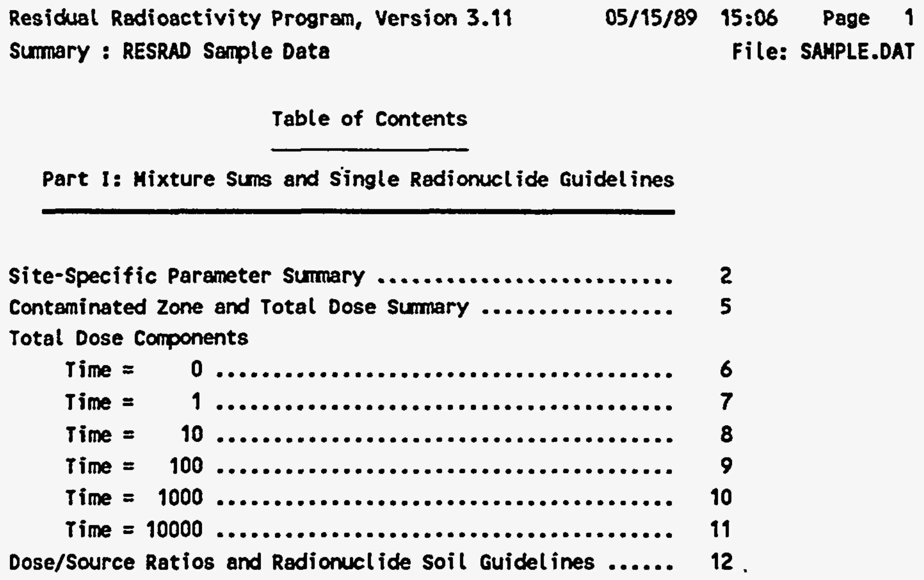
```
RESMAIN program complete, elapsed time =    xxxx.xxxx    seconds.
```

Shortly thereafter, the main menu, R010, will appear on the screen, and the user may continue with any of the options discussed in Section 4.5. However, the customary course will be to examine the output reports just generated via main menu option 11.

When option 11 is selected, the user is prompted to select for viewing the summary or detailed report from the last RESRAD run or any ASCII file. The last option is particularly useful for examining saved output from a prior RESRAD run. It should be noted that it is not necessary to execute RESRAD (or, more strictly, RESMAIN) before using option 11. In general, SUMMARY.REP and DETAILED.REP files from the last RESRAD run will be available and may be examined at any time. However, if appropriate, the user will be warned that the report file may not match the current site-specific data file.

4.7.1 Summary Report

When the summary report option is selected, the first page (table of contents) of a multiple page summary report is displayed on the screen. The table of contents is shown in Figure 4.11. Subsequent report pages can be displayed by entering the page number and pressing either the "Enter" or "F10" function key. Pressing "Esc" will return to the main menu, R010. On-line help, primarily key strokes to aid in the page display, is available via the "F1" function key. Function keys "F7" and "F8" can be used to produce hard copy output (see Section 4.7.3).



```
Residual Radioactivity Program, Version 3.11       05/15/89  15:06    Page   1
Summary : RESRAD Sample Data                                File: SAMPLE.DAT

                              Table of Contents
                              _________________
    Part I: Mixture Sums and Single Radionuclide Guidelines
    _______________________________________________________

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```

FIGURE 4.11 Typical Table of Contents for Summary Report

The summary report starts with a listing of all site-specific parameter values, both as used and default, for the current run. This is followed by a brief summary of the contaminated zone. Summaries of the estimated total dose, TDOSE(t), and the total mixture sum, M(t), for the user-selected time periods, t, are listed next [TDOSE(t) in mrem/yr and t in yr]. If a total dose maximum occurred within the time frame selected, this maximum and its time of occurrence is determined by a standard iterative procedure (Press et al. 1986, p. 283). Convergence is ensured but caution is advised because more than one local maximum may exist within the time frame specified. Repeat runs with different time periods is the only check on the solution. The total dose maximum and time of occurrence (within the listed plus or minus range) will not change if the maximum is unique.

The total mixture sum, M(t), is the estimated effective dose equivalent -- expressed as a multiple of the basic dose limit -- that a member of the critical population group might receive at time t following the radiological survey as a consequence of the residual radioactivity. A site may be certified in compliance with guidelines only if the mixture sum does not exceed the value of one at any time within the time horizon.

The summary report continues with the total dose components for all individual pathways at different times. The results are presented both as actual dose (mrem/yr) and as percent contribution to the total.

The final table series of the summary report presents:

- Total dose/source ratios, DSR(i,t) in (mrem/yr)/(pCi/g), summed over all pathways for radionuclide i and time t;
- Single-radionuclide soil guidelines, G(i,t) in pCi/g, for radionuclide i and time t; and

- Values of DSR(i,t) and G(i,t) for t equals the minimum G(i,t) for radionuclide i and for t equals the maximum total dose.

The single-radionuclide soil guidelines are the concentration guidelines that would apply if only one radionuclide were present. A single-radionuclide soil guideline, G(i,t), is the magnitude of the initial concentration of the i^{th} principal radionuclide that would result in a potential radiation dose equal to the basic radiation limit to a member of the critical population group at time t. Thus, if only the i^{th} radionuclide were present, the initial concentration S(i,0) would have to satisfy the inequality $S(i,0)/G(i,t) \leq 1$ for all times up to the time horizon. G(i,t) is readily obtained by dividing the basic radiation dose limit by the total dose/source ratio, DSR(i,t). The minimum G(i,t) values, or more correctly the corresponding maximum DSR(i,t), are obtained for each radionuclide i with the same iterative procedure used for the maximum total dose.

The total mixture sum enables the user to determine whether the concentrations of residual radioactive material are in compliance with guidelines. The total dose components and single-radionuclide soil guidelines enable the user to identify the critical pathways and radionuclides.

4.7.2 Detailed Report

When the detailed report option is selected, the first page (table of contents) of a multipage detailed report is displayed on the screen. A typical table of contents is shown in Figure 4.12. Individual report pages can be displayed and printed (or saved) in the same manner as for the summary output displays. The detailed displays present all of the intermediate results used to evaluate the formulas in Appendixes B through E for the

```
Residual Radioactivity Program, Version 3.11       05/15/89  15:06    Page   1
Detailed: RESRAD Sample Data                                 File: SAMPLE.DAT

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                             _________________

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======================================================================

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```

FIGURE 4.12 Typical Table of Contents for Detailed Report different pathway contributions. Users will not normally make use of these tables. The detailed data are used for verifying the code and can be useful for gaining insight into the transport mechanisms by enabling a more detailed investigation of the effect of parameter changes on pathway factors, environmental transport factors, and dose/source ratios for the different pathways.

4.7.3 Hard Copy

At any time while viewing RESRAD output (or any other ASCII file) via main menu option 11, hard copy can be produced (if the printer is turned on) by pressing the "F7" or "F8" function keys. The "F8" key produces an immediate copy of the current screen page only.

The "F7" function is a more versatile but complicated option. The user is first informed of the current hard copy destination (printer or disk file name) and allowed to make a change, if desired. If an existing disk file is selected, the user can specify to overwrite or append. The following series of options can then be exercised repeatedly (until "Esc"):

- Enter the first and last page numbers, separated by a space or comma, to print (or save). Enter a single page number to print that page only.
- Press "Enter" key only to print current page (current page number will be displayed on screen).
- Press "D" or "d" to print entire document (file).
- Press "P" or "p" to pass ASCII control characters to the printer.
- Press "Esc" to resume normal RESRAD viewing of the file.

To preserve an option of an earlier RESRAD version, the "*" key is identical to the "F7" key.

4.8 TECHNICAL SUMMARY

This manual is not intended to be a programmer's guide, but a brief technical summary should be useful. For more information, the user is referred to RESRAD.DOC, which is included among the supplementary files in the distribution diskette. The following material is selected from that file.

RESRAD consists of two main programs: RESPC and RESMAIN. RESPC is a compiled Basic program (Microsoft QuickBASIC 4.5) that handles all user interaction with RESRAD, and RESMAIN is the Fortran code (Lahey F77L, Ver. 3.0) that does the actual computations and generates the output tables.

RESPC is loaded first (via RESRAD.BAT, NEXT.ORI, and NEXT.BAT). Within RESPC, the user may input selected site-specific data files, review and/or modify the parameters, save the data in a selected file, view and/or print selected results from the last RESMAIN computation, and run RESMAIN for a new computation. If RESMAIN is called, RESPC is reloaded automatically when RESMAIN completes, and the user may continue with any of the RESPC options.

Most of the tasks accomplished by RESPC are actually performed by FORM.BAS and PAGER.BAS, a library of subroutines comprising the FORMPACK package developed by the Energy and Environmental Systems Division of Argonne National Laboratory. FORMPACK provides a standard system for menus, data entry, and output report display for microcomputer application programs. RESPC is the driving program.

To conserve memory, RESMAIN is organized with an overlay structure. The code is highly optimal in that no overlay is called a second time. PLINK86plus, Ver. 2.24, Phoenix Technologies Ltd., is the overlay linkage editor used. Object modules are produced as usual via the Lahey Fortran compiler, and the file RESMAIN.LNK automates the link process by the command

```
PLINK86 @RESMAIN
```

5 APPLICATION OF THE AS LOW AS REASONABLY ACHIEVABLE PROCESS

Application of the as low as reasonably achievable (ALARA) process is required in DOE environmental protection and health and safety orders and in the DOE residual radioactive material guidelines. The objective of the ALARA process is the attainment of dose levels that are as far below applicable limits as is practicable and reasonably achievable, taking into account many factors -- including technical, economic, safety, and social. Unlike the "below regulatory concern" or "de minimis" concepts, which can define a lower limit of cleanup that should be carried out before remedial action is taken, no set of defined dose levels exists for determining when ALARA is achieved. The ALARA process must be applied throughout the project, from planning to field work. Application of the ALARA process through planning activities occurs both in the development of guidelines and in the site-specific application of the guidelines. This does not necessarily require a significant level of additional effort.

Application of the ALARA process to any radiation protection project is necessary but somewhat subjective. The success of the process depends on good judgment of the health physicists and managers who are responsible for its application. Applying the ALARA process to remedial actions is, in many cases, more complex than applying it to operating situations. In operating facilities, one can identify the waste streams, pathways, potential exposed individuals, and likely time periods for the operation of the facility; also, the dose reductions from specific control actions having specific costs over the expected time period can be estimated and compared. In the case of contaminated facilities requiring remedial action, it is more difficult to define all of these elements, particularly if potential effects must be projected for many years into the future.

For sites to be certified in compliance with the guidelines, the intent is to reduce the concentrations of residual radioactive materials to as low as reasonably achievable considering technical, economic, and social factors. At sites where the residual materials are reduced to levels requiring that restrictions be placed on the use of the facility, the ALARA process includes the establishment of institutional controls to reduce exposure.

In remedial action or decontamination and decommissioning work under DOE jurisdiction, the concentration limit or guideline for a particular radionuclide in soil or on surfaces -- as derived from the basic dose limit by pathway analysis -- is generally assumed to be the upper limit of that nuclide for remediation at a site. Each remedial action will be different from another in some respect. In one situation, the contamination might be spread uniformly over the surface whereas, in others, hot spots of radioactive material might be buried at various depths below the surface. Also, a portion of the radioactive material might have been eroded to another area by wind or water or, in buildings, the contamination might be buried beneath paint or a covering wall. Nonuniform distribution of the contamination is usually the rule rather than the exception. In applying the ALARA process, the first task is to ensure that the area of concern is at or below the chosen limit and the second task is to determine that the remaining contamination is ALARA.

5.1 DETERMINING ALARA

Two approaches are used for determining ALARA: (1) qualitative, or judgmental, procedures and (2) quantitative, or optimization, procedures. Both procedures involve consideration of economic, social, and technical factors to ultimately determine a limit for the site under consideration. The level of detail and documentation involved in a qualitative comparison can vary significantly. The effort should be commensurate with risk and cost. If overall risks are very low and costs for further reduction in potential doses are very high, the decision is obvious and minimal analysis and documentation are required. However, as potential doses approach levels that are significant in comparison to the dose limit, more detail is warranted. The quantitative procedure involves a cost-benefit analysis, as proposed by the ICRP (1973, 1977, 1983), to quantify the costs of improved radiological protection and the costs associated with health detriment from radiation and from other factors not related to radiation.

5.1.1 Qualitative Analysis

The more traditional method for determining ALARA consists of making individual decisions for each situation encountered. A number of such decisions may be made for different parts of the overall area as work progresses; that is, it is not necessary to make ALARA decisions only after all of the work has been completed. Frequently, there are subareas with difficult problems and, before moving to the next subarea, the work can be concentrated on these difficult areas until the ALARA process is satisfied. The temptation to set an "ALARA limit" should be avoided because ALARA is a process rather than a limit and, furthermore, unexpected developments may result in greatly increased costs to meet the derived limit or in even the inability to meet the limit. If an area cannot be decontaminated to the derived concentration guideline, a decision must then be made as to whether the land can be used without radiologically based restrictions or whether controls will be required. A key factor in determining ALARA is the individual judgment of the responsible person, based on that person's understanding of the relevant economic, social, and technical factors.

Economic factors are primarily the concern of those responsible for the remedial action. The most important factor is, of course, the cost of doing the work. The cost of remedial action typically includes the initial planning cost as well as the cost of operation and associated labor, materials, equipment, energy, and services over the period of remediation. The initial planning cost includes all costs relative to planning and engineering tasks -- such as performance of radiation surveys; calculation of contamination inventories; performance of engineering studies; preparation of a remedial action plan, with descriptions and specifications; and preparation of detailed cleanup and removal procedures. The operating cost includes all costs associated with physical tasks such as removal of contamination; removal of equipment and structures; storage, packaging, shipping, and burial of wastes; and final site and facility restoration or preservation. In addition to the cost of doing the work, economic factors should also include the potential impact on current facilities, operations, and the environment. The impact and associated cost of either the action or no action may have a positive or negative effect on current operations or the environment, and such cost may be significant in comparison with the cost of performing the remedial action.

Social factors involve the risk to the people exposed, i.e., the risk to persons carrying out the operations, the risk to persons in the vicinity of the area during operations, and the perceived risk to those persons in the surrounding area after operations. It is easy to consider only the potential exposure scenarios and the risk to those persons who might occupy the area immediately following cleanup; however, many of the sites are contaminated with long-lived radioactive materials, and cleanup will affect the potential risks received over many years and perhaps over areas away from the site. Therefore, in evaluating risks, these temporal and spatial factors must be taken into account. In carrying out remedial actions on contaminated areas and vicinity properties, occupational exposures are likely to occur. Controlling the radiation exposure of the work force should be based on DOE guidance for occupational exposure, and all unnecessary doses should be eliminated. In applying the ALARA process, the reductions in risks to users of the site and to individuals in the area surrounding the disposal site following the remedial action should be compared with the incremental risks to individuals in the same area and to workers during remedial action activities. It is most desirable that such a comparison would result in a beneficial balance in overall risk.

Technical factors are primarily related to technological alternatives for treatment and disposal of the contaminated materials. Also, the technique used to determine the level and extent of contamination is important. The number of soil samples that can be taken might be limited, and the methods of measurement might have limitations with regard to sensitivity. Increasing the number of samples taken and using state-of-the-art instruments or methods for all samples in order to accurately determine the above-background distribution of all radionuclides would be prohibitively expensive. A decision must be made regarding the number and location of samples and the sensitivity of the instruments used for establishing compliance with concentration guidelines and for implementing the ALARA process.

5.1.2 Cost-Benefit Analysis

The ICRP has recommended the use of cost-benefit analysis to determine the levels of population exposure that are reasonably achievable. This quantitative technique compares the cost of health detriment and other factors relative to radiation with the cost of radiation dose reduction.

To apply cost-benefit analysis to radiation protection, a policy decision is often made that assumes the action is already justified (a net positive benefit); this decision may be based on a policy decision or on broad political, economic, or social considerations. Under this assumption, a simplified form of differential cost-benefit analysis can be used. The objective is to ensure that the resultant exposures are kept ALARA and below the dose limit. In this differential analysis, consideration shifts from the total benefit to the change in net benefit that might result from requiring the action to be performed at one level of exposure rather than another. The benefit of a reduction in exposure is compared with the cost of achieving the reduction. The theoretical optimum is achieved when a marginal increase in the cost of protection is exactly balanced by a marginal decrease in the cost of detriment, i.e.,

$$\left.\frac{dX}{dS}\right|_{S^*} = -\left.\frac{dY}{dS}\right|_{S^*} \tag{5.1}$$

where

X = cost of achieving a given level of protection and

Y = cost of the radiological detriment at the level of protection.

S* is the optimum level of collective dose equivalent, where the reduction of detriment per unit dose equivalent balances the increase in cost of protection per unit dose equivalent.

Such a cost-benefit analysis is a helpful procedure for quantifying both the costs of improved protection and the costs associated with radiological detriment from alternative courses of action. This technique is particularly useful when extensive remedial action activities for radiological protection are being considered, when individuals are being exposed to levels close to the dose limit, or when potential collective doses are large. For small-scale problems, simplified analyses are sufficient. However, because a cost-benefit analysis does not encompass all judgments that might be involved in a specific decision concerning radiological protection, such an analysis is only one procedure for quantitatively determining some of the input to that decision.

In order to implement the ALARA process using cost-benefit analysis, the costs of radiological protection and radiological detriment must be assessed. The degree of sophistication and effort given to a cost-benefit assessment should reflect the scale of the radiological problem being considered. For a large-scale problem, the assessment might be an evaluation combining engineering designs, control technologies, accounting techniques, and the use of mathematical models for pathway analyses and dose calculations. For a small-scale problem, the assessment might require only simple, intuitive estimates. The estimation of protection costs is generally straightforward.

The assignment of costs to health detriment requires both scientific and other judgment. For example, the NRC established ALARA guidelines for radionuclide emissions from light-water reactors after several years of intensive study of the emissions and the proper levels to which exposures should be limited based on ALARA (NRC 1974). This was possible because the emissions from most light-water reactors are similar and the costs to control the emissions are similar. The cost/risk ratio for deriving ALARA guidelines was assumed to be $1,000 per person-rem. This same cost/risk ratio was also used by NRC in its proposed safety goals for nuclear power plants (NRC 1982); these safety goals were intended to set design objectives for the reliability of safety systems. The EPA has also used an ALARA approach when deriving many of its regulations. Table 5.1 summarizes some examples of expenditures to limit cancer risk, derived from criteria and guidelines issued by the EPA and NRC. The costs range from \$1 to \$200 million per cancer averted. Using a lifetime cancer fatality risk estimate of 1.25×10^{-4} per person-rem, the cost/risk ratios in Table 5.1 are equivalent to economic values of about \$125 to \$25,000 per person-rem of radiological detriment. However, the applicability of these cost/risk ratios to remedial actions is limited at best. Long time periods and uncertainties in property use make them very difficult to use.

TABLE 5.1 Examples of Expenditures to Limit Cancer Risk

Example	Agency	Cost per Cancer Averted[a] (10^6 \$)	Lifetime Risk Level	Comments
Routine radioactive releases from light-water reactor effluents	NRC	10	6×10^{-5}	1975 dollars; no correction for inflation; only fatal cancers
Dioxin contamination at Times Beach, Missouri	EPA	2-160	1×10^{-2}	Includes nonfatal cancers
Drinking water criteria	EPA	20-200	1×10^{-5}	Includes nonfatal cancers
Safety goals for nuclear power plants	NRC	10	1×10^{-4}	1982 dollars; inflation correction included; only fatal cancers
Proposed asbestos ban	EPA	1	4×10^{-5}	Fatal cancers

[a] Estimated cancers, not actual incidence.

Source: McKone (1986).

5.1.3 Summary

In applying the ALARA process, based on either qualitative or quantitative analysis, the social risks incurred from implementing remedial action must first be justified by the reduction in risk that will result. The ALARA process requires that the responsible persons use judgment with respect to what is "reasonably achievable." The economic, social, and technical factors influencing this judgment are highly variable and site specific. At a minimum, the following parameters should be evaluated to the extent practicable before making a decision:

- Maximum dose to an individual member of the public;
- Collective dose to the population;
- Time and duration of exposure of the affected individual or population;
- Likelihood of a specific use scenario occurring at a site;
- Technological alternatives, such as alternative methods for treatment and disposal of the contaminated materials, alternative operating methods for conducting cleanup activities, or alternative institutional controls for reducing exposure;
- Demographic data;
- Occupational doses associated with each technological alternative;
- Costs of each technological alternative; and
- Variations in social impact associated with the various alternatives.

In allocating resources relative to ALARA considerations, the total value should depend on the size of the affected population, the level of risk already experienced from background radiation sources, and the magnitude of risk for each individual. More cost should be assigned to collective doses made up of individual doses approaching the dose limit than to doses made up of individual doses far below the limit.

Because most radionuclides considered for FUSRAP/SFMP sites have long half-lives, the potential radiation risk must be calculated for populations that might exist in hundreds or thousands of years. This calculation becomes increasingly uncertain as the time period of radiological dose assessment increases. To realistically account for these uncertainties, it is reasonable to attach more weight to doses predicted for the present or the near future than to doses predicted for the far future, especially when use scenarios appear unlikely.

5.2 DOCUMENTING ALARA

The documentation of any decision regarding the ALARA process in remedial action provides an invaluable record to show that the process was applied. Because DOE is responsible for the work being done, any judgment regarding the ALARA process is ultimately the responsibility of DOE, and DOE personnel should be involved in the decisions or alternatively in plans that document how the process will be applied for the project and in the field. It is, therefore, essential that ALARA decisions be well documented, including those made in the field and those made prior to or following field work.

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APPENDIX A

DOE GUIDELINES FOR RESIDUAL RADIOACTIVE MATERIAL

APPENDIX A: DOE GUIDELINES FOR RESIDUAL RADIOACTIVE MATERIAL

[reproduced from U.S. Department of Energy, 1987, *U.S. Department of Energy Guidelines for Residual Radioactive Material at Formerly Utilized Sites Remedial Action Program and Remote Surplus Facilities Management Program Sites (Revision 2, March 1987)*]

A. INTRODUCTION

This document presents U.S. Department of Energy (DOE) radiological protection guidelines for cleanup of residual radioactive material and management of the resulting wastes and residues. It is applicable to sites identified by the Formerly Utilized Sites Remedial Action Program (FUSRAP) and remote sites identified by the Surplus Facilities Management Program (SFMP).* The topics covered are basic dose limits, guidelines and authorized limits for allowable levels of residual radioactive material, and requirements for control of the radioactive wastes and residues.

Protocols for identification, characterization, and designation of FUSRAP sites for remedial action; for implementation of the remedial action; and for certification of a FUSRAP site for release for unrestricted use are given in a separate document (U.S. Department of Energy 1986) and subsequent guidance. More detailed information on applications of the guidelines presented herein, including procedures for deriving site-specific guidelines for allowable levels of residual radioactive material from basic dose limits, is contained in "A Manual for Implementing Residual Radioactive Material Guidelines" (U.S. Department of Energy 1987), referred to herein as the "supplement".

"Residual radioactive material" is used in these guidelines to describe radioactive material derived from operations or sites over which DOE has authority. Guidelines or guidance to limit the levels of radioactive material and to protect the public and the environment are provided for (1) residual concentrations of radionuclides in soil,** (2) concentrations of airborne

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*A remote SFMP site is one that is excess to DOE programmatic needs and is located outside a major operating DOE research and development or production area.

**"Soil" is defined herein as unconsolidated earth material, including rubble and debris that may be present in earth material.

radon decay products, (3) external gamma radiation levels, (4) surface contamination levels, and (5) radionuclide concentrations in air or water resulting from or associated with any of the above.

A "basic dose limit" is a prescribed standard from which limits for quantities that can be monitored and controlled are derived; it is specified in terms of the effective dose equivalent as defined by the International Commission on Radiological Protection (ICRP 1977, 1978). The basic dose limits are used for deriving guidelines for residual concentrations of radionuclides in soil. Guidelines for residual concentrations of thorium and radium in soil, concentrations of airborne radon decay products, allowable indoor external gamma radiation levels, and residual surface contamination concentrations are based on existing radiological protection standards (U.S. Environmental Protection Agency 1983; U.S. Nuclear Regulatory Commission 1982; and DOE Departmental Orders). Derived guidelines or limits based on the basic dose limits for those quantities are used only when the guidelines provided in the existing standards cited above are shown to be inappropriate.

A "guideline" for residual radioactive material is a level of radioactivity or radioactive material that is acceptable if use of the site is to be unrestricted. Guidelines for residual radioactive material presented herein are of two kinds: (1) generic, site-independent guidelines taken from existing radiation protection standards and (2) site-specific guidelines derived from basic dose limits using site-specific models and data. Generic guideline values are presented in this document. Procedures and data for deriving site-specific guideline values are given in the supplement. The basis for the guidelines is generally a presumed worst-case plausible-use scenario for the site.

An "authorized limit" is a level of residual radioactive material or radioactivity that must not be exceeded if the remedial action is to be considered completed and the site is to be released for unrestricted use. The authorized limits for a site will include (1) limits for each radionuclide or group of radionuclides, as appropriate, associated with residual radioactive material in soil or in surface contamination of structures and equipment, (2) limits for each radionuclide or group of radionuclides, as appropriate, in air or water, and, (3) where appropriate, a limit on external gamma radiation resulting from the residual material. Under normal circumstances, expected to occur at most sites, authorized limits for residual radioactive material or radioactivity are set equal to guideline values. Exceptional conditions for which authorized limits might differ from guideline values are specified in Sections D and F of this document. A site may be released for unrestricted use only if site conditions do not exceed the authorized limits or approved supplemental limits, as defined in Section F.1, at the time remedial action is completed. Restrictions and controls on use of the site must be established and enforced if site conditions exceed the approved limits, or if there is potential to exceed the basic dose limit if use of the site is not restricted (Section F.2). The applicable controls and restrictions are specified in Section E.

DOE policy requires that all exposures to radiation be limited to levels that are as low as reasonably achievable (ALARA). For sites to be released for unrestricted use, the intent is to reduce residual radioactive material to levels that are as far below authorized limits as reasonable considering technical, economic, and social factors. At sites where the residual material is not reduced to levels that permit release for unrestricted use, ALARA policy is implemented by establishing controls to reduce exposure to levels that are as low as reasonably achievable. Procedures for implementing ALARA policy are discussed in the supplement. ALARA policies, procedures, and actions shall be documented and filed as a permanent record upon completion of remedial action at a site.

B. BASIC DOSE LIMITS

The basic limit for the annual radiation dose received by an individual member of the general public is 100 mrem/yr. The internal committed effective dose equivalent, as defined in ICRP Publication 26 (ICRP 1977) and calculated by dosimetry models described in ICRP Publication 30 (ICRP 1978), plus the dose from penetrating radiation sources external to the body, shall be used for determining the dose. This dose shall be described as the "effective dose equivalent". Every effort shall be made to ensure that actual doses to the public are as far below the basic dose limit as is reasonably achievable.

Under unusual circumstances, it will be permissible to allow potential doses to exceed 100 mrem/yr where such exposures are based upon scenarios that do not persist for long periods and where the annual lifetime exposure to an individual from the subject residual radioactive material would be expected to be less than 100 mrem/yr. Examples of such situations include conditions that might exist at a site scheduled for remediation in the near future or a possible, but improbable, one-time scenario that might occur following remedial action. These levels should represent doses that are as low as reasonably achievable for the site. Further, no annual exposure should exceed 500 mrem.

C. GUIDELINES FOR RESIDUAL RADIOACTIVE MATERIAL

C.1 Residual Radionuclides in Soil

Residual concentrations of radionuclides in soil shall be specified as above-background concentrations averaged over an area of 100 m^2. Generic guidelines for thorium and radium are specified below. Guidelines for residual concentrations of other radionuclides shall be derived from the basic dose limits by means of an environmental pathway analysis using site-specific data where available. Procedures for these derivations are given in the supplement.

If the average concentration in any surface or below-surface area less than or equal to 25 m^2 exceeds the authorized limit or guideline by a factor of $(100/A)^{1/2}$, where A is the area of the elevated region in square meters, limits for "hot spots" shall also be applicable. Procedures for calculating these hot spot limits, which depend on the extent of the elevated local concentrations, are given in the supplement. In addition, every reasonable effort shall be made to remove any source of radionuclide that exceeds 30 times the appropriate limit for soil, irrespective of the average concentration in the soil.

Two types of guidelines are provided, generic and derived. The generic guidelines for residual concentrations of Ra-226, Ra-228, Th-230, and Th-232 are:

- 5 pCi/g, averaged over the first 15 cm of soil below the surface
- 15 pCi/g, averaged over 15-cm-thick layers of soil more than 15 cm below the surface

These guidelines take into account ingrowth of Ra-226 from Th-230 and of Ra-228 from Th-232, and assume secular equilibrium. If either Th-230 and Ra-226 or Th-232 and Ra-228 are both present, not in secular equilibrium, the appropriate guideline is applied as a limit to the radionuclide with the higher concentration. If other mixtures of radionuclides occur, the concentrations of individual radionuclides shall be reduced so that (1) the dose for the mixtures will not exceed the basic dose limit or (2) the sum of the ratios of the soil concentration of each radionuclide to the allowable limit for that radionuclide will not exceed 1 ("unity"). Explicit formulas for calculating residual concentration guidelines for mixtures are given in the supplement.

C.2 Airborne Radon Decay Products

Generic guidelines for concentrations of airborne radon decay products shall apply to existing occupied or habitable structures on private property that are intended for unrestricted use; structures that will be demolished or buried are excluded. The applicable generic guideline (40 CFR Part 192) is: In any occupied or habitable building, the objective of remedial action shall be, and a reasonable effort shall be made to achieve, an annual average (or equivalent) radon decay product concentration (including background) not to exceed 0.02 WL.* In any case, the radon decay product concentration (including background) shall not exceed 0.03 WL. Remedial actions by DOE are not required in order to comply with this guideline when there is reasonable assurance that residual radioactive material is not the cause.

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*A working level (WL) is any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy.

C.3 External Gamma Radiation

The average level of gamma radiation inside a building or habitable structure on a site to be released for unrestricted use shall not exceed the background level by more than 20 μR/h and shall comply with the basic dose limit when an appropriate-use scenario is considered. This requirement shall not necessarily apply to structures scheduled for demolition or to buried foundations. External gamma radiation levels on open lands shall also comply with the basic dose limit, considering an appropriate-use scenario for the area.

C.4 Surface Contamination

The generic surface contamination guidelines provided in Table 1 are applicable to existing structures and equipment. These guidelines are adapted from standards of the U.S. Nuclear Regulatory Commission (NRC 1982)* and will be applied in a manner that provides a level of protection consistent with the Commission's guidance. These limits apply to both interior and exterior surfaces. They are not directly intended for use on structures to be demolished or buried, but should be applied to equipment or building components that are potentially salvageable or recoverable scrap. If a building is demolished, the guidelines in Section C.1 are applicable to the resulting contamination in the ground.

C.5 Residual Radionuclides in Air and Water

Residual concentrations of radionuclides in air and water shall be controlled to levels required by DOE Environmental Protection Guidance and Orders, specifically DOE Order 5480.1A and subsequent guidance. Other Federal and/or state standards shall apply when they are determined to be appropriate.

D. AUTHORIZED LIMITS FOR RESIDUAL RADIOACTIVE MATERIAL

Authorized limits shall be established to (1) ensure that, as a minimum, the basic dose limits specified in Section B will not be exceeded under the worst-case plausible-use scenario consistent with the procedures and guidance provided or (2) be consistent with applicable generic guidelines, where such guidelines are provided. The authorized limits for each site and its vicinity properties shall be set equal to the generic or derived guidelines except where it can be clearly established on the basis of site-specific data -- including health, safety, and socioeconomic considerations -- that the guidelines are not appropriate for use at the specific site. Consideration should also be given to ensure that the limits comply with or provide a level of protection equivalent to other appropriate limits and guidelines (i.e., state or

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*These guidelines are functionally equivalent to Section 4 -- Decontamination for Release for Unrestricted Use -- of NRC Regulatory Guide 1.86 (U.S. Atomic Energy Commission 1974), but they are applicable to non-reactor facilities.

TABLE 1 SURFACE CONTAMINATION GUIDELINES

Radionuclides[b]	Allowable Total Residual Surface Contamination (dpm/100 cm^2)[a] Average[c,d]	Maximum[d,e]	Removable[d,f]
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	100	300	20
Th-Natural, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	1,000	3,000	200
U-Natural, U-235, U-238, and associated decay products	5,000 α	15,000 α	1,000 α
Beta-gamma emitters (radionuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	5,000 β-γ	15,000 β-γ	1,000 β-γ

[a] As used in this table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by correcting the counts per minute measured by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[b] Where surface contamination by both alpha- and beta-gamma-emitting radionuclides exists, the limits established for alpha- and beta-gamma-emitting radionuclides should apply independently.

[c] Measurements of average contamination should not be averaged over an area of more than 1 m^2. For objects of less surface area, the average should be derived for each such object.

[d] The average and maximum dose rates associated with surface contamination resulting from beta-gamma emitters should not exceed 0.2 mrad/h and 1.0 mrad/h, respectively, at 1 cm.

[e] The maximum contamination level applies to an area of not more than 100 cm^2.

[f] The amount of removable radioactive material per 100 cm^2 of surface area should be determined by wiping that area with dry filter or soft absorbent paper, applying moderate pressure, and measuring the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removable contamination on objects of surface area less than 100 cm^2 is determined, the activity per unit area should be based on the actual area and the entire surface should be wiped. The numbers in this column are maximum amounts.

other Federal). Documentation supporting such a decision should be similar to that required for supplemental limits and exceptions (Section F), but should be generally more detailed because the documentation covers the entire site.

Remedial action shall not be considered complete unless the residual radioactive material levels comply with the authorized limits. The only exception to this requirement will be for those special situations where the supplemental limits or exceptions are applicable and approved as specified in Section F. However, the use of supplemental limits and exceptions should be considered only if it is clearly demonstrated that it is not reasonable to decontaminate the area to the authorized limit or guideline value. The authorized limits are developed through the project offices in the field and are approved by the headquarters program office.

E. CONTROL OF RESIDUAL RADIOACTIVE MATERIAL AT FUSRAP AND REMOTE SFMP SITES

Residual radioactive material above the guidelines at FUSRAP and remote SFMP sites must be managed in accordance with applicable DOE Orders. The DOE Order 5480.1A and subsequent guidance or superceding Orders require compliance with applicable Federal and state environmental protection standards.

The operational and control requirements specified in the following DOE Orders shall apply to interim storage, interim management, and long-term management.

a. 5000.3, Unusual Occurrence Reporting System

b. 5440.1C, Implementation of the National Environmental Policy Act

c. 5480.1A, Environmental Protection, Safety, and Health Protection Program for DOE Operations, as revised by DOE 5480.1 change orders and the 5 August 1985 memorandum from Vaughan to Distribution

d. 5480.2, Hazardous and Radioactive Mixed Waste Management

e. 5480.4, Environmental Protection, Safety, and Health Protection Standards

f. 5482.1A, Environmental, Safety, and Health Appraisal Program

g. 5483.1A, Occupational Safety and Health Program for Government-Owned Contractor-Operated Facilities

h. 5484.1, Environmental Protection, Safety, and Health Protection Information Reporting Requirements

i. 5820.2, Radioactive Waste Management

E.1 Interim Storage

a. Control and stabilization features shall be designed to ensure, to the extent reasonably achievable, an effective life of 50 years and, in any case, at least 25 years.

b. Above-background Rn-222 concentrations in the atmosphere above facility surfaces or openings shall not exceed (1) 100 pCi/L at any given point, (2) an annual average concentration of 30 pCi/L over the facility site, and (3) an annual average concentration of 3 pCi/L at or above any location outside the facility site (DOE Order 5480.1A, Attachment XI-1).

c. Concentrations of radionuclides in the groundwater or quantities of residual radioactive material shall not exceed existing Federal or state standards.

d. Access to a site shall be controlled and misuse of on-site material contaminated by residual radioactive material shall be prevented through appropriate administrative controls and physical barriers -- active and passive controls as described by the U.S. Environmental Protection Agency (1983--p. 595). These control features should be designed to ensure, to the extent reasonable, an effective life of at least 25 years. The Federal government shall have title to the property or shall have a long-term lease for exclusive use.

E.2 Interim Management

a. A site may be released under interim management when the residual radioactive material exceeds guideline values if the residual radioactive material is in inaccessible locations and would be unreasonably costly to remove, provided that administrative controls are established to ensure that no member of the public shall receive a radiation dose exceeding the basic dose limit.

b. The administrative controls, as approved by DOE, shall include but not be limited to periodic monitoring as appropriate, appropriate shielding, physical barriers to prevent access, and appropriate radiological safety measures during maintenance, renovation, demolition, or other activities that might disturb the residual radioactive material or cause it to migrate.

c. The owner of the site or appropriate Federal, state, or local authorities shall be responsible for enforcing the administrative controls.

E.3 Long-Term Management

Uranium, Thorium, and Their Decay Products

a. Control and stabilization features shall be designed to ensure, to the extent reasonably achievable, an effective life of 1,000 years and, in any case, at least 200 years.

b. Control and stabilization features shall be designed to ensure that Rn-222 emanation to the atmosphere from the wastes shall not (1) exceed an annual average release rate of 20 pCi/m^2/s and (2) increase the annual average Rn-222 concentration at or above any location outside the boundary of the contaminated area by more than 0.5 pCi/L. Field verification of emanation rates is not required.

c. Prior to placement of any potentially biodegradable contaminated wastes in a long-term management facility, such wastes shall be properly conditioned to ensure that (1) the generation and escape of biogenic gases will not cause the requirement in paragraph b. of this section (E.3) to be exceeded and (2) biodegradation within the facility will not result in premature structural failure in violation of the requirements in paragraph a. of this section (E.3).

d. Groundwater shall be protected in accordance with appropriate Departmental Orders and Federal and state standards, as applicable to FUSRAP and remote SFMP sites.

e. Access to a site should be controlled and misuse of on-site material contaminated by residual radioactivity should be prevented through appropriate administrative controls and physical barriers -- active and passive controls as described by the U.S. Environmental Protection Agency (1983--p. 595). These controls should be designed to be effective to the extent reasonable for at least 200 years. The Federal government shall have title to the property.

Other Radionuclides

f. Long-term management of other radionuclides shall be in accordance with Chapters 2, 3, and 5 of DOE Order 5820.2, as applicable.

F. SUPPLEMENTAL LIMITS AND EXCEPTIONS

If special site-specific circumstances indicate that the guidelines or authorized limits established for a given site are not appropriate for a portion of that site or for a vicinity property, then the field office may request that supplemental limits or an exception be applied. In either case, the field office must justify that the subject guidelines or authorized limits are not appropriate and that the alternative action will provide adequate protection, giving due consideration to health and safety, the environment, and costs. The field office shall obtain approval for specific supplemental limits or exceptions from headquarters as specified in Section D of these guidelines and shall provide to headquarters those materials required for the justification as specified in this section (F) and in the FUSRAP and SFMP protocols and subsequent guidance documents. The field office shall also be responsible for coordination with the state or local government of the limits or exceptions and associated restrictions as appropriate. In the case of exceptions, the field office shall also work with the state and/or local governments to ensure that restrictions or conditions of release are adequate and mechanisms are in place for their enforcement.

F.1 Supplemental Limits

The supplemental limits must achieve the basic dose limits set forth in this guideline document for both current and potential unrestricted uses of a site and/or vicinity property. Supplemental limits may be applied to a vicinity property or a portion of a site if, on the basis of a site-specific analysis, it is determined that (1) certain aspects of the vicinity property or portion of the site were not considered in the development of the established authorized limits and associated guidelines for that vicinity property or site and, (2) as a result of these unique characteristics, the established limits or guidelines either do not provide adequate protection or are unnecessarily restrictive and costly.

F.2 Exceptions

Exceptions to the authorized limits defined for unrestricted use of a site or vicinity property may be applied to a vicinity property or a portion of a site when it is established that the authorized limits cannot be achieved and restrictions on use of the vicinity property or portion of the site are necessary to provide adequate protection of the public and the environment. The field office must clearly demonstrate that the exception is necessary and that the restrictions will provide the necessary degree of protection and will comply with the requirements for control of residual radioactive material as set forth in Section E of these guidelines.

F.3 Justification for Supplemental Limits and Exceptions

Supplemental limits and exceptions must be justified by the field office on a case-by-case basis using site-specific data. Every effort should be made to minimize use of the supplemental limits and exceptions. Examples of specific situations that warrant use of the supplemental standards and exceptions are:

a. Where remedial action would pose a clear and present risk of injury to workers or members of the general public, notwithstanding reasonable measures to avoid or reduce risk.

b. Where remedial action -- even after all reasonable mitigative measures have been taken -- would produce environmental harm that is clearly excessive compared to the health benefits to persons living on or near affected sites, now or in the future. A clear excess of environmental harm is harm that is long-term, manifest, and grossly disproportionate to health benefits that may reasonably be anticipated.

c. Where it is clear that the scenarios or assumptions used to establish the authorized limits do not, under plausible current or future conditions, apply to the property or portion of the site identified and where more appropriate scenarios or assumptions indicate that other limits are applicable or necessary for protection of the public and the environment.

d. Where the cost of remedial action for contaminated soil is unreasonably high relative to long-term benefits and where the residual radioactive material does not pose a clear present or future risk after taking necessary control measures. The likelihood that buildings will be erected or that people will spend long periods of time at such a site should be considered in evaluating this risk. Remedial action will generally not be necessary where only minor quantities of residual radioactive material are involved or where residual radioactive material occurs in an inaccessible location at which site-specific factors limit their hazard and from which they are costly or difficult to remove. Examples include residual radioactive material under hard-surface public roads and sidewalks, around public sewer lines, or in fence-post foundations. A site-specific analysis must be provided to establish that it would not cause an individual to receive a radiation dose in excess of the basic dose limits stated in Section B, and a statement specifying the level of residual radioactive material must be included in the appropriate state and local records.

e. Where there is no feasible remedial action.

G. SOURCES

Limit or Guideline	Source
Basic Dose Limits	
Dosimetry model and dose limits	International Commission on Radiological Protection (1977, 1978)
Generic Guidelines for Residual Radioactivity	
Residual concentrations of radium and thorium in soil	40 CFR Part 192
Airborne radon decay products	40 CFR Part 192
External gamma radiation	40 CFR Part 192
Surface contamination	Adapted from U.S. Nuclear Regulatory Commission (1982)
Control of Radioactive Wastes and Residues	
Interim storage	DOE Order 5480.1A and subsequent guidance
Long-term management	DOE Order 5480.1A and subsequent guidance; 40 CFR Part 192; DOE Order 5820.2

H. REFERENCES

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APPENDIX B

EXTERNAL GROUND RADIATION PATHWAY FACTORS

APPENDIX B: EXTERNAL GROUND RADIATION PATHWAY FACTORS

Models, formulas, and data for calculating pathway factors for the external ground radiation pathway are presented in this appendix. Exposure to external radiation occurs primarily as a result of radiation emanating from radionuclides in a contaminated zone. Exposure can also occur from radiation emanating from radionuclides in the air, water, or ground surface that have been transported from their original location in the contaminated zone. In general, the radiation dose resulting from these secondary sources is negligibly small compared with the dose resulting from direct exposure to the primary source. Therefore, these secondary sources are not taken into account in deriving soil concentration guidelines.

The contribution to the effective dose equivalent from the external ground radiation pathway for the i^{th} principal radionuclide at time t following the radiological survey is given by the dose/source ratio $DSR_{i1}(t)$. This ratio may be expressed as a sum of products of dose conversion factors, environmental transport factors, and source factors (see Equation 3.8). Tables of dose conversion factors for the external ground radiation pathway are given in Section B.1. Models and formulas for calculating the environmental transport factors are given in Section B.2. Formulas for calculating the source factors are given in Section 3.2.3 and Appendix F.

B.1 DOSE CONVERSION FACTORS

The dose conversion factor DCF_{i1} for the external ground radiation pathway is the annual effective dose equivalent received from exposure to radiation from the i^{th} principal radionuclide present at unit concentration in a uniformly contaminated zone of infinite depth and lateral extent. The radiation field is assumed to be equal to the radiation level at a distance of 1 m above the ground surface. The DCFs for surface contamination (infinite thinness and lateral extent) were taken from a DOE report (DOE 1988). The DCFs for volume contamination (infinite depth and lateral extent) were calculated using the methods of Kocher and Sjoreen (1985). The results are given in Table B.1. In the RESRAD code, the volume contamination dose conversion factors are used. Values for densities other than 1.0 and 1.8 g/cm^3 are obtained by linear interpolation or extrapolation of log(DCF).

B.2 ENVIRONMENTAL TRANSPORT FACTORS

The environmental transport factor ETF_{i1} for the external ground radiation pathway is the ratio of the effective dose equivalent for the actual source to the effective dose equivalent for the standard source, multiplied by an occupancy and shielding factor. The standard source is a contaminated zone of infinite depth and lateral extent with no cover. The actual source is approximated by a cylindrical contaminated zone of radius R and depth T located at distance C_d below the ground surface (see Figure 2.1).

Calculations by Napier et al. (1984) have indicated that the dependence on source size can be approximated reasonably well by an area factor. The ETF for the external ground radiation pathway is expressed as the product

$$ETF_{i1}(t) = \rho_b^{(cz)} \times FO_1 \times FS_1 \times FA_1 \times FD_{i1}(t) \times FC_{i1}(t) \qquad (B.1)$$

TABLE B.1 Effective Dose Equivalent Conversion Factors (DCF_{il}) for External Gamma Radiation from Contaminated Ground

Radionuclide i	Surface Factors[a] (mrem/yr)/(pCi/cm^2)	Volume Factors[a] (mrem/yr)/(pCi/cm^3)	
		ρ_b = 1.0 g/cm^3	ρ_b = 1.8 g/cm^3
H-3	0	0	0
C-14	0	0	0
Fe-55	2.21×10^{-4}	0	0
Co-60	2.27	2.27×10^{1}	1.25×10^{1}
Ni-59	4.16×10^{-4}	0	0
Ni-63	0	0	0
Sr-90+D	0	0	0
Nb-94	1.59	1.42×10^{1}	7.83
Tc-99	6.26×10^{-7}	1.68×10^{-6}	9.32×10^{-7}
I-129	2.20×10^{-2}	3.24×10^{-2}	1.75×10^{-2}
Cs-135	0	0	0
Cs-137+D	6.11×10^{-1}	5.03	2.77
Eu-152	1.11	9.91	5.47
Eu-154	1.21	1.10×10^{1}	6.06
Pb-210+D	3.00×10^{-3}	4.87×10^{-3}	2.31×10^{-3}
Ra-226+D	1.69	1.55×10^{1}	8.56
Ra-228+D	9.10×10^{-1}	8.18	4.51
Ac-227+D	4.70×10^{-1}	2.76	1.52
Th-228+D	1.45	1.33×10^{1}	7.36
Th-229+D	3.44×10^{-1}	2.20	1.21
Th-230	9.07×10^{-4}	2.11×10^{-3}	1.03×10^{-3}
Th-232	6.66×10^{-4}	1.35×10^{-3}	6.04×10^{-4}
Pa-231	3.58×10^{-2}	2.21×10^{-1}	1.21×10^{-1}
U-232	1.03×10^{-3}	2.19×10^{-3}	1.01×10^{-3}
U-233	5.00×10^{-4}	1.40×10^{-3}	7.12×10^{-4}
U-234	8.07×10^{-4}	1.58×10^{-3}	6.97×10^{-4}
U-235+D	1.90×10^{-1}	8.94×10^{-1}	4.90×10^{-1}
U-236	7.33×10^{-4}	1.35×10^{-3}	5.80×10^{-4}
U-238+D	2.46×10^{-2}	1.27×10^{-1}	6.97×10^{-2}

TABLE B.1 (Cont'd)

Radionuclide i	Surface Factors[a] (mrem/yr)/(pCi/cm^2)	Volume Factors[a] (mrem/yr)/(pCi/cm^3) ρ_b = 1.0 g/cm^3	Volume Factors[a] (mrem/yr)/(pCi/cm^3) ρ_b = 1.8 g/cm^3
Np-237+D	2.68×10^{-1}	1.61	8.90×10^{-1}
Pu-238	8.58×10^{-4}	1.56×10^{-3}	6.65×10^{-4}
Pu-239	3.78×10^{-4}	8.14×10^{-4}	3.76×10^{-4}
Pu-240	8.20×10^{-4}	1.48×10^{-3}	6.35×10^{-4}
Pu-241	0	0	0
Pu-242	6.82×10^{-4}	1.24×10^{-3}	5.29×10^{-4}
Am-241	2.99×10^{-2}	4.79×10^{-2}	2.58×10^{-2}
Am-243+D	2.58×10^{-1}	1.08	5.95×10^{-1}
Cm-243	1.46×10^{-1}	7.26×10^{-1}	4.01×10^{-1}
Cm-244	8.29×10^{-4}	1.51×10^{-3}	6.67×10^{-4}

[a] Surface factors represent infinite thinness; volume factors represent infinite depth.

where*

$\rho_b^{(cz)}$ = bulk density of soil material in the contaminated zone (1.6 g/cm^3),

FO_1 = occupancy and shielding factor (0.6, dimensionless),

FS_1 = shape factor (1.0, dimensionless),

FA_1 = area factor (dimensionless),

$FD_{i1}[\rho_b^{(cz)}, T(t)]$ = depth factor for radionuclide i (dimensionless),

$FC_{i1}[\rho_b^{(cv)}, C_d(t)]$ = cover factor for radionuclide i at time t (dimensionless),

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*Numbers preceding the units in parentheses are default values, given only for parameters for which site-specific input values can be provided by the user. If the units are not preceded by a number, the parameter is a derived quantity.

$T(t)$ = thickness of contaminated zone at time t (m),

$\rho_b^{(cv)}$ = bulk density of cover material (1.6 g/cm^3), and

$C_d(t)$ = thickness of cover at time t (m).

The area factor is calculated in the RESRAD code by linear interpolation using the contaminated zone area (as input parameter) and the values listed in Table B.2. The area factor calculated is for a circular-area-equivalent contaminated zone. A shape factor (input parameter) is used to correct for the noncircular-shape area factor. The shape factor for a circular contaminated area is 1.0. For an irregularly shaped contaminated area, the shape factor may be obtained by enclosing the irregularly shaped contaminated area in a circle, multiplying the area factor of each annulus by the fraction of the annulus area that is contaminated, summing the products, and dividing by the area factor of a circular-area-equivalent contaminated zone. The area

TABLE B.2 Area Factors for External Gamma Radiation from Contaminated Ground[a]

Contaminated Area (m^2)	Radius[b] (m)	Area Factor,[c] FA_1
1	0.56	0.016
25	2.8	0.4
100	5.6	0.55
500	13	0.8
1,200	20	1.0

[a] Napier et al. (1984).

[b] Radius for a circular contaminated area.

[c] Intermediate values may be obtained by linear interpolation.

factor of an annulus is the area factor from an annular zone bounded by the radii tabulated in Table B.2. For example, the area factor is 0.2 for the annulus with inner and outer radii of 13 m and 20 m, respectively; 0.25 for the annulus with radii of 5.6 and 13 m; and so forth.

B.2.1. Depth Factor

The depth factor FD_{i1} for a specified contaminated zone thickness is obtained by interpolation or extrapolation from Table B.3. It is assumed that the depth factor can be approximated by the equation

$$FD_{i1}[\rho_b^{(cz)}, T(t)] = 1 - \exp[-k_i \rho_b^{(cz)} T(t)] \tag{B.2}$$

where

k_i = an empirical constant (m^2/kg), and

$\rho_b^{(cz)}$ = bulk density of soil material in the contaminated zone (1,600 kg/m^3),

and the other parameters are as defined for Equation B.1. Note that the units for $\rho_b^{(cz)}$ in Equations B.1 and B.2 are different. The empirical constant k_i for radionuclide i is a function of soil material density; it is determined from the tabulated values of the quantity $FD_{i1}[\rho_b^{(cz)}, T(t)]$ in Table B.3. The equation used to calculate k_i for $\rho_b^{(cz)}$ equals 1,000 and 1,800 kg/m^3 is

$$k_i(\rho_b^{(cz)}) = -\log_e[1 - FD_{i1}(\rho_b^{(cz)}, 0.15)]/(0.15\rho_b^{(cz)}) \tag{B.3}$$

TABLE B.3 Depth Factors (FD_{i1}) for External Gamma Radiation from Contaminated Ground as a Function of Thickness (T) of a Contaminated Layer Exposed at the Ground Surface and Soil Density (ρ_b) for Principal and Associated Radionuclides

Radionuclide i^a	$\rho_b = 1.0$ g/cm^3			$\rho_b = 1.8$ g/cm^3		
	T = 0.15 m	T = 0.5 m	T = 1.0 m	T = 0.15 m	T = 0.5 m	T = 1.0 m
H-3	1.0	1.0	1.0	1.0	1.0	1.0
C-14	9.6×10^{-1}	1.0	1.0	1.0	1.0	1.0
Fe-55	1.0	1.0	1.0	1.0	1.0	1.0
Co-60	6.8×10^{-1}	1.0	1.0	8.6×10^{-1}	1.0	1.0
Ni-59	1.0	1.0	1.0	1.0	1.0	1.0
Ni-63	1.0	1.0	1.0	1.0	1.0	1.0
Sr-90+D	8.1×10^{-1}	9.8×10^{-1}	1.0	9.0×10^{-1}	1.0	1.0
Nb-94	7.2×10^{-1}	1.0	1.0	8.9×10^{-1}	1.0	1.0
Tc-99	9.6×10^{-1}	1.0	1.0	1.0	1.0	1.0
I-129	1.0	1.0	1.0	1.0	1.0	1.0
Cs-135	9.6×10^{-1}	1.0	1.0	1.0	1.0	1.0
Cs-137+D	7.2×10^{-1}	9.8×10^{-1}	1.0	9.1×10^{-1}	1.0	1.0
Eu-152	6.8×10^{-1}	9.6×10^{-1}	1.0	8.5×10^{-1}	1.0	1.0
Eu-154	6.9×10^{-1}	9.8×10^{-1}	1.0	8.6×10^{-1}	1.0	1.0
Pb-210+D	8.8×10^{-1}	1.0	1.0	9.7×10^{-1}	1.0	1.0
Ra-226+D	6.3×10^{-1}	9.2×10^{-1}	1.0	8.5×10^{-1}	1.0	1.0
Ra-228+D	6.8×10^{-1}	9.7×10^{-1}	1.0	8.5×10^{-1}	1.0	1.0
Ac-227+D	7.9×10^{-1}	9.7×10^{-1}	1.0	9.1×10^{-1}	1.0	1.0
Th-228+D	6.1×10^{-1}	9.4×10^{-1}	1.0	7.5×10^{-1}	1.0	1.0
Th-229+D	6.5×10^{-1}	9.5×10^{-1}	1.0	8.5×10^{-1}	9.9×10^{-1}	1.0

TABLE B.3 (Cont'd)

Radionuclide i^a	ρ_b = 1.0 g/cm^3			ρ_b = 1.8 g/cm^3		
	T = 0.15 m	T = 0.5 m	T = 1.0 m	T = 0.15 m	T = 0.5 m	T = 1.0 m
Th-230+D	9.3×10^{-1}	1.0	1.0	1.0	1.0	1.0
Th-232+D	9.5×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pa-231	7.9×10^{-1}	1.0	1.0	9.2×10^{-1}	1.0	1.0
U-232	8.8×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-233	9.6×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-234	9.0×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-235+D	8.7×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-236	9.4×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-238+D	7.8×10^{-1}	1.0	1.0	8.8×10^{-1}	1.0	1.0
Np-237+D	8.2×10^{-1}	1.0	1.0	9.3×10^{-1}	1.0	1.0
Pu-238	9.3×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-239	9.2×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-240	9.2×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-241+D	9.4×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-242	9.6×10^{-1}	1.0	1.0	1.0	1.0	1.0
Am-241	9.4×10^{-1}	1.0	1.0	1.0	1.0	1.0
Am-243+D	9.0×10^{-1}	1.0	1.0	9.7×10^{-1}	1.0	1.0
Cm-243	8.7×10^{-1}	1.0	1.0	9.6×10^{-1}	1.0	1.0
Cm-244	9.6×10^{-1}	1.0	1.0	1.0	1.0	1.0

[a] A "+D" signifies that the contributions from the associated decay chain are included; radionuclides in the associated decay chain are identified in Table 3.1.

Linear interpolation is then used to obtain $k_i(\rho_b^{(cz)})$ for the actual soil density. If $FD_{i1}(\rho_b^{(cz)}, 0.15) = 1.0$, then the tabulated value is replaced by $FD_{i1}(\rho_b^{(cz)}, 0.15) = 0.995$.

The time dependence of the contaminated zone thickness is given by

$$\begin{aligned} T(t) &= T(0), && 0 \le t \le t_c \\ &= T(0) - v^{(cz)} (t - t_c), && t_c < t \end{aligned} \tag{B.4}$$

where

$T(t)$ = thickness of the contaminated zone at time t (m),

$T(0)$ = initial thickness of the contaminated zone (1 m),

$t_c = C_d(0)/v^{(cv)}$ = time for the cover to be removed by erosion (yr),

$v^{(cv)}$ = erosion rate of cover material (0.001 m/yr), and

$v^{(cz)}$ = erosion rate of contaminated zone (0 m/yr).

Erosion rates for both the cover and the contaminated zone may be estimated by means of the Universal Soil Loss Equation (USLE), an empirical model that has been developed for predicting the rate of soil loss by sheet and rill erosion. If sufficient site-specific data are available, a site-specific erosion rate can be calculated. Details are discussed in Wischmeier and Smith (1978) and Foster (1979). Estimates based on the range of erosion rates for typical sites in humid areas east of the Mississippi River (based on model site calculations for locations in New York, New Jersey, Ohio, and Missouri) may also be used (Knight 1983). For a site with a 2% slope, these model calculations predict a range of 8×10^{-7} to 3×10^{-6} m/yr for natural succession vegetation, 1×10^{-5} to 6×10^{-5} m/yr for permanent pasture, and 9×10^{-5} to 6×10^{-4} m/yr for row-crop agriculture. The rate increases by a factor of about 3 for a 5% slope, 7 for a 10% slope, and 15 for a 15% slope. If these generic values are used for a farm/garden scenario, in which the dose contribution from food ingestion pathways is expected to be significant, an erosion rate of 0.06 cm/yr should be assumed for a site with a 2% slope. This would lead to erosion of 0.6 m of soil in 1,000 years. A proportionately higher erosion rate must be used if the slope exceeds 2%. An erosion rate of 6×10^{-5} m/yr, leading to erosion of 0.006 m of soil in 1,000 years, may be used for a site with a 2% slope if it can be reasonably shown that the farm/garden scenario is unreasonable, e.g., because the site is, and will likely continue to be, unsuitable for agricultural use.

The erosion rates are more difficult to estimate for arid sites in the West than for humid sites in the East. Although water erosion is generally more important than wind erosion, the latter can also be significant. Water erosion in the West is more difficult to estimate because it is likely to be due to infrequent heavy rainfalls for which the empirical constants used in the USLE may not be applicable. Long-term erosion rates are generally less for sites in arid locations than for sites in humid locations; hence, values estimated in the manner described above for humid sites can be used because they can be expected to provide conservative values. The cover factors and the formula for time dependence of the cover depth are described in Section B.2.2.

B.2.2 Cover Factor

The cover factor for radionuclide i in the contaminated zone with a cover thickness of $C_d(t)$ and a cover density of $\rho_b^{(cv)}$ is approximated by the formula

$$FC_{i1}[\rho_b^{(cv)}, C_d(t)] = \exp[-k_i \rho_b^{(cv)} C_d(t)] \qquad (B.5)$$

where

k_i = empirical constant (m^2/kg),
$\rho_b^{(cv)}$ = bulk density of the cover material ($1{,}600\ kg/m^3$), and
$C_d(t)$ = cover depth at time t (m).

The empirical constant k_i for radionuclide i is a function of soil material density. Linear interpolation is used to obtain $k_i(\rho_b^{(cv)})$ for the actual cover density (see Section B.2.1).

The time dependence of the cover depth is given by

$$\begin{aligned} C_d(t) &= C_d(0) - v^{(cv)}t, & 0 \le t < t_c \\ &= 0, & t_c \le t \end{aligned} \qquad (B.6)$$

where

$C_d(t)$ = cover depth at time t (m),
$C_d(0)$ = initial cover depth (0 m),
$v^{(cv)}$ = erosion rate of the cover material (0.001 m/yr), and
t_c = time for the cover to be removed by erosion (yr).

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APPENDIX C

INHALATION PATHWAY FACTORS

APPENDIX C: INHALATION PATHWAY FACTORS

Models, formulas, and data for calculating pathway factors for the inhalation pathway are presented in this appendix. Inhalation exposure can occur from inhalation of dust, radon and radon decay products, and other gaseous airborne radionuclides. The radon pathway is not included in the current version of the RESRAD code because generic soil guidelines have been established for radium (Ra-226 and Ra-228), which is the source of all radon (see Appendix A). The other gaseous airborne decay products are primarily tritium (in tritiated water vapor) and C-14 (in CO_2); these are not included in the current version because they constitute only a small, usually negligible, fraction of the residual radioactivity at FUSRAP and SFMP sites and are unlikely to contribute significantly to the dose received by any individual.

The contribution to the committed effective dose equivalent from the dust inhalation pathway for the i^{th} principal radionuclide at time t following the radiological survey is given by the dose/source ratio $DSR_{i2}(t)$. This ratio may be expressed as a sum of products of dose conversion factors, environmental transport factors, and source factors (see Equation 3.8). A tabulation of dose conversion factors for dust inhalation is presented in Section C.1. Models and formulas for calculating the environmental transport factors are given in Section C.2. Formulas for calculating the source factors are given in Section 3.2.3 and Appendix F.

C.1 DOSE CONVERSION FACTORS

A dose conversion factor for inhalation is the dose/exposure ratio $DCF_{i2} = H_{E,i2}/E_{i2}$ for the committed effective dose equivalent $H_{E,i2}$ that is incurred by an individual from exposure by inhalation of a quantity E_{i2} of the i^{th} principal radionuclide in contaminated dust. Values of dose conversion factors for inhalation were taken from a DOE report (DOE 1988) and are listed in Table C.1. Similar values are given in an EPA report (Eckerman et al. 1988). The values listed in Table C.1 are for dust particles with an activity median aerodynamic diameter (AMAD) of 1 micron. Values for different inhalation classes are also listed in Table C.1. The inhalation class for inhaled radioactive material is defined according to its rate of clearance from the lung. The three inhalation classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days, respectively. If the inhalation class for a radionuclide is not known, the largest dose conversion factor for that radionuclide should be used. The default value for a radionuclide used in the RESRAD code is the largest dose conversion factor for that radionuclide.

C.2 ENVIRONMENTAL TRANSPORT FACTORS

An environmental transport factor for dust inhalation is the ratio $ETF_{i2}(t) = E_{i2}(t)/S_i(t)$ of the annual intake $E_{i2}(t)$ of the i^{th} principal radionuclide by dust inhalation to the concentration $S_i(t)$ of that radionuclide in the soil for the t^{th} year following the radiological survey. It can be expressed as the product

$$ETF_{i2}(t) = ASR_2 \times FA_2 \times FCD_2(t) \times FO_2 \times FI_2 \qquad (C.1)$$

where

$ETF_{i2}(t)$ = environmental transport factor at time t for dust inhalation for the i^{th} principal radionuclide (g/yr),

TABLE C.1 Committed Effective Dose Equivalent Conversion Factors (DCF_{i2}) for Inhalation[a]

Radionuclide i[b]	Inhalation Class[c]	DCF_{i2} (mrem/pCi)	Radionuclide i[b]	Inhalation Class[c]	DCF_{i2} (mrem/pCi)
H-3	* (H_2O)	6.3×10^{-8}	Eu-152	W	2.2×10^{-4}
C-14	* (organic)	2.1×10^{-6}	Eu-154	W	2.6×10^{-4}
	* (CO)	2.9×10^{-9}			
	* (CO_2)	2.4×10^{-8}	Pb-210+D	D	2.1×10^{-2}
Fe-55	D	2.6×10^{-6}	Ra-226+D	W	7.9×10^{-3}
	W	1.2×10^{-6}			
			Ra-228+D	W	4.5×10^{-3}
Co-60	W	3.0×10^{-5}			
	Y	1.5×10^{-4}	Ac-227+D	D	6.7
				W	1.7
Ni-59	D	1.3×10^{-6}		Y	1.2
	W	7.0×10^{-7}			
	* (vapor)	2.7×10^{-6}	Th-228+D	W	2.5×10^{-1}
				Y	3.1×10^{-1}
Ni-63	D	3.0×10^{-6}			
	W	1.9×10^{-6}	Th-229+D	W	2.0
	* (vapor)	6.3×10^{-6}		Y	1.7
Sr-90+D	D	2.3×10^{-4}	Th-230	W	3.2×10^{-1}
	Y	1.3×10^{-3}		Y	2.6×10^{-1}
Nb-94	W	2.6×10^{-5}	Th-232	W	1.6
	Y	3.3×10^{-4}		Y	1.1
Tc-99	D	8.4×10^{-7}	Pa-231	W	1.3
	W	7.5×10^{-6}		Y	8.6×10^{-1}
I-129	D	1.8×10^{-4}	U-232	D	1.2×10^{-2}
				W	1.3×10^{-2}
Cs-135	D	4.5×10^{-6}		Y	6.7×10^{-1}
Cs-137+D	D	3.2×10^{-5}	U-233	D	2.7×10^{-3}
				W	7.1×10^{-3}
				Y	1.3×10^{-1}

TABLE C.1 (Cont'd)

Radionuclide i^b	Inhalation Class^c	DCF_{i2} (mrem/pCi)	Radionuclide i^b	Inhalation Class^c	DCF_{i2} (mrem/pCi)
U-234	D	2.7×10^{-3}	Pu-239	W	5.1×10^{-1}
	W	7.1×10^{-3}		Y	3.3×10^{-1}
	Y	1.3×10^{-1}			
			Pu-240	W	5.1×10^{-1}
U-235+D	D	2.5×10^{-3}		Y	3.3×10^{-1}
	W	6.7×10^{-3}			
	Y	1.2×10^{-1}	Pu-241	W	1.0×10^{-2}
				Y	5.7×10^{-3}
U-236	D	2.5×10^{-3}			
	W	6.7×10^{-3}	Pu-242	W	4.8×10^{-1}
	Y	1.2×10^{-1}		Y	3.1×10^{-1}
U-238+D	D	2.4×10^{-3}	Am-241	W	5.2×10^{-1}
	W	6.2×10^{-3}			
	Y	1.2×10^{-1}	Am-243+D	W	5.2×10^{-1}
Np-237+D	W	4.9×10^{-1}	Cm-243	W	3.5×10^{-1}
Pu-238	W	4.6×10^{-1}	Cm-244	W	2.7×10^{-1}
	Y	3.0×10^{-1}			

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[a] Inhalation factors are for an AMAD of 1 micron.

[b] Dose conversion factors for entries labeled by "+D" are aggregated dose conversion factors for intake of a principal radionuclide together with radionuclides of the associated decay chain in secular equilibrium (see Section 3.1 and Table 3.1).

[c] An asterisk (*) indicates a gaseous material. The three inhalation classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days, respectively.

ASR_2 = air/soil concentration ratio = average mass loading of airborne contaminated soil particles (2×10^{-4} g/m^3),

FA_2 = area factor (dimensionless),

$FCD_2(t)$ = cover and depth factor (dimensionless),

FO_2 = occupancy factor (0.45, dimensionless), and

FI_2 = annual intake of air (8,400 m^3/yr).

The mass loading is a conservative estimate that takes into account short periods of high mass loading and sustained periods of normal activity on a typical farm (Gilbert et al. 1983, Appendix A).

Three models are commonly used for the process by which dust becomes airborne (Healy and Rodgers 1979, Appendix E; Oztunali et al. 1981, Appendix A; Gilbert et al. 1983, Appendix A). One is a resuspension factor model in which the airborne dust concentration (C_{dust}) is given as a function of an empirically determined resuspension factor (R_f), the effective depth of the layer of dust from which resuspension occurs (d_r), and the bulk soil density (ρ_b). The formula relating these variables is

$$C_{dust} = R_f \, d_r \, \rho_b \tag{C.2}$$

The second is a resuspension rate model in which the airborne dust concentration is given as a function of an empirically determined resuspension rate (R_r), surface dust concentration ($\sigma_s = \rho_b \, d_r$), and average deposition velocity (v_d). The formula is

$$C_{dust} = R_r \, \sigma_s / v_d \tag{C.3}$$

The third is a mass loading model in which an average value of the airborne dust concentration is specified on the basis of empirical data.

The resuspension factor and resuspension rate are related by the equality $R_r = v_d R_f$; hence, the resuspension factor and resuspension rate models are not independent. Both resuspension models require two parameters that must be determined empirically and can vary over a wide range: (1) a resuspension factor or rate and (2) the thickness of the resuspendable layer. (The deposition velocity can also vary because of dependence on particle size, but the uncertainty in assigning a value is somewhat smaller.) The mass loading model uses a single parameter that is more directly measurable and for which empirical data are more readily available. The mass loading model has, therefore, been used in RESRAD for estimating the airborne dust concentration near the source.

For on-site exposure, the transport process may be regarded as a dilution process in which the resuspended contaminated dust is mixed with uncontaminated dust blown in from off-site. This dilution can be modeled by a Gaussian plume model (using an area distribution of point sources with zero release height) or by a simple mixing model that assumes perfect mixing of resuspended on-site contaminated dust with off-site uncontaminated dust within a volume defined by a mixing height and the area of the exposed contaminated zone. The Gaussian plume model, as applied to annual average meteorological data, using sector averages, is generally regarded as applicable over distances from one hundred meters to several thousand meters; it has not been validated for on-site exposure in which the exposure occurs immediately above the source. There are uncertainties regarding exposure in the immediate area, primarily because of possible air turbulence or downdrafts created by buildings and structures. Considering these uncertainties regarding the

Gaussian plume model for on-site exposure and the large increase in the size of the code that incorporation of an area-source Gaussian plume model would entail, a simple mixing model has been used in the current version of RESRAD.

The area factor represents the fraction of airborne dust that is contaminated. It is calculated using a mixing model for estimating the dilution of contaminated dust that is resuspended on-site by uncontaminated dust blown in from off-site and is given by the formula

$$FA_2 = A^{1/2}/[A^{1/2} + DL] \tag{C.4}$$

where

A = area of contaminated zone (10,000 m^2) and
DL = dilution length (3 m).

The dilution length depends on the wind speed, mixing height, resuspension rate, and thickness of the resuspendable dust layer (Gilbert et al. 1983, Appendix A). Estimates of lower and upper bounds of DL for bounding values of the independent variables are 0.03 m and 250 m, respectively. The geometric mean of the bounds, DL = 3 m, is used as the default value. The model has not been tested experimentally; hence, the accuracy and range of values of A and DL for which the model is applicable are not known.

The cover and depth factor is the fraction of resuspendable soil particles at the ground surface that are contaminated. It is calculated by assuming that mixing of the soil will occur within a layer of thickness d_m at the surface. The cover and depth factor $FCD_{i2}(t)$ is calculated by the formula

$$FCD_{i2}(t) = \begin{cases} 1, & C_d(t) = 0,\ T(t) \geq d_m \\ T(t)/d_m, & C_d(t) + T(t) < d_m \\ 1 - C_d(t)/d_m, & C_d(t) < d_m,\ C_d(t) + T(t) \geq d_m \\ 0, & C_d(t) \geq d_m \end{cases} \qquad (C.5)$$

where

d_m = depth of soil mixing layer (0.15 m),
$C_d(t)$ = cover depth at time t (m), and
$T(t)$ = thickness of contaminated zone at time t (m).

The default occupancy factor of $FO_2 = 0.45$ used in the RESRAD code is based on the assumption that 50% of a person's time is spent indoors [where the dust level is 40% of the outdoor level (Alzona et al. 1979)], 25% is spent outdoors in the contaminated area, and 25% is spent in uncontaminated areas.

The annual air intake of 8,400 m^3/yr used in the RESRAD code is the value recommended by the International Commission on Radiological Protection (1975).

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APPENDIX D

INGESTION PATHWAY FACTORS

APPENDIX D: INGESTION PATHWAY FACTORS

Ingestion pathways consist of five environmental pathways and the common exposure pathway to which they contribute (see Table 2.1). The doses from these pathways are specified by the dose/source ratios described in Chapter 3. Dose/source ratios may be analyzed into sums of products of dose conversion factors (which characterize the exposure pathways), environmental transport factors (which characterize the environmental pathways), and source factors (which characterize ingrowth and decay and leaching of the radionuclides) (see Equation 3.8). Dose conversion factors for ingestion are described in Section D.1. Environmental transport factors and the models and formulas used to calculate them are presented in Sections D.2-D.4. Formulas for calculating the source factors are given in Section 3.2.3 and Appendix F.

D.1 DOSE CONVERSION FACTORS

A dose conversion factor for ingestion is the dose/exposure ratio $DCF_{i3} = H_{E,i3}/E_i$, where $H_{E,i3}$ is the committed effective dose equivalent incurred by an individual from intake by ingestion of a quantity E_i of the i^{th} principal radionuclide. Values of dose conversion factors for ingestion were taken from a DOE report (DOE 1988) and are tabulated in Table D.1. Similar values are given in an EPA report (Eckerman et al. 1988). Dose conversion factors depend on the chemical form, which determines the fraction f_1 of a radionuclide entering the gastrointestinal (GI) tract that reaches body fluids. Data on the appropriate fractions for different chemical forms are given in Publication No. 30 of the International Commission on Radiological Protection (ICRP 1979-1982). The dose conversion factors used in RESRAD are the values corresponding to the largest values of f_1 in Table D.1. If the chemical form of a radionuclide is known and a different value of DCF_{i3} is

TABLE D.1 Committed Effective Dose Equivalent Conversion Factors (DCF_{i3}) for Internal Radiation from Ingestion

Radio-nuclide i^a	$f_1{}^b$	DCF_{i3} (mrem/pCi)	Radio-nuclide i^a	$f_1{}^b$	DCF_{i3} (mrem/pCi)
H-3	1.0	6.3×10^{-8}	U-232	5×10^{-2}	1.3×10^{-3}
C-14	1.0	2.1×10^{-6}		2×10^{-3}	6.8×10^{-5}
Fe-55	1×10^{-1}	5.8×10^{-7}	U-233	5×10^{-2}	2.7×10^{-4}
Co-60	3×10^{-1}	2.6×10^{-5}		2×10^{-3}	2.5×10^{-5}
	5×10^{-2}	1.0×10^{-5}	U-234	5×10^{-2}	2.6×10^{-4}
Ni-59	5×10^{-2}	2.0×10^{-7}		2×10^{-3}	2.5×10^{-5}
Ni-63	5×10^{-2}	5.4×10^{-7}	U-235+D	5×10^{-2}	2.5×10^{-4}
Sr-90+D	3×10^{-1}	1.4×10^{-4}		2×10^{-3}	2.6×10^{-5}
	1×10^{-2}	1.2×10^{-5}	U-236	5×10^{-2}	2.5×10^{-4}
Nb-94	1×10^{-2}	5.1×10^{-6}		2×10^{-3}	2.4×10^{-5}
Tc-99	8×10^{-1}	1.3×10^{-6}	U-238+D	5×10^{-2}	2.5×10^{-4}
I-129	1.0	2.8×10^{-4}		2×10^{-3}	3.8×10^{-5}
Cs-135	1.0	7.1×10^{-6}	Np-237+D	1×10^{-3}	3.9×10^{-3}
Cs-137+D	1.0	5.0×10^{-5}	Pu-238	1×10^{-3}	3.8×10^{-3}
Eu-152	1×10^{-3}	6.0×10^{-6}		1×10^{-5}	5.4×10^{-5}
Eu-154	1×10^{-3}	9.1×10^{-6}	Pu-239	1×10^{-3}	4.3×10^{-3}
Pb-210+D	2×10^{-1}	6.7×10^{-3}		1×10^{-5}	5.8×10^{-5}
Ra-226+D	2×10^{-1}	1.1×10^{-3}	Pu-240	1×10^{-3}	4.3×10^{-3}
Ra-228+D	2×10^{-1}	1.2×10^{-3}		1×10^{-5}	5.8×10^{-5}
Ac-227+D	1×10^{-3}	1.5×10^{-2}	Pu-241	1×10^{-3}	8.6×10^{-5}
Th-228+D	2×10^{-4}	7.5×10^{-4}		1×10^{-5}	9.2×10^{-7}
Th-229+D	2×10^{-4}	4.3×10^{-3}	Pu-242	1×10^{-3}	4.1×10^{-3}
Th-230	2×10^{-4}	5.3×10^{-4}		1×10^{-5}	5.6×10^{-5}
Th-232	2×10^{-4}	2.8×10^{-3}	Am-241	1×10^{-3}	4.5×10^{-3}
Pa-231	1×10^{-3}	1.1×10^{-2}	Am-243+D	1×10^{-3}	4.5×10^{-3}
			Cm-243	1×10^{-3}	2.9×10^{-3}
			Cm-244	1×10^{-3}	2.3×10^{-3}

[a] Dose conversion factors for entries labeled by "+D" are aggregated dose conversion factors for intake of a principal radionuclide together with radionuclides of the associated decay chain in secular equilibrium (see Section 3.1).

[b] Fraction of a stable element entering the GI tract that reaches body fluids.

needed, the value can be entered by modifying the DCF_{i3} data file contained in the RESRAD package.

D.2 ENVIRONMENTAL TRANSPORT FACTORS

D.2.1 Plant, Meat, and Milk Pathways

D.2.1.1 Environmental Transport Factor Components

Environmental transport factors for the plant, meat, and milk pathways can be factored into the product

$$ETF_{ipq}(t) = FA_p \times FCD_{ipq}(t) \times \sum_k DF_{pk} \times FSR_{ipqk}(t) \qquad (D.1)$$

where

$ETF_{ipq}(t)$ = environmental transport factor for the i^{th} principal radionuclide and pq^{th} environmental pathway at time t (g/yr),

p = primary pathway index for the plant ($p = 3$), meat ($p = 4$), and milk ($p = 5$) pathways,

q = secondary index for root uptake ($q = 1$), foliar deposition ($q = 2$), ditch irrigation ($q = 3$), overhead irrigation ($q = 4$), and livestock water ($q = 5$),

FA_p = area factor for p^{th} primary pathway (dimensionless),

$FCD_{ipq}(t)$ = cover and depth factor for the i^{th} principal radionuclide and pq^{th} ingestion pathway at time t (dimensionless),

DF_{pk} = dietary factor = annual consumption of the k^{th} food class for the p^{th} food pathway (g/yr),

k = food class index, and

$FSR_{ipqk}(t)$ = food/soil concentration ratio for the i^{th} principal radionuclide, pq^{th} ingestion pathway, and k^{th} food class at time t (dimensionless).

The sum is over the applicable food classes. The plant pathway consists of two food classes: (1) fruit, nonleafy vegetables, and grain (k = 1) and (2) leafy vegetables (k = 2). For the meat and milk pathways, only a single food class is used in the current version of RESRAD. Dietary factors are commonly given in kg/yr; they must be converted to g/yr before substitution into Equation D.1 in order for FSR = C/S to be a dimensionless quantity when the soil concentration S is specified in pCi/g.

For water-dependent pathways (pathways with q = 3, 4, or 5 -- which include a groundwater or surface water pathway segment), the food/soil concentration ratios can be factored into the products

$$FSR_{ipqk}(t) = FWR_{ipqk} \times WSR_{ir}(t) \qquad (D.2)$$

where

FWR_{ipqk} = food/water concentration ratio for the i^{th} principal radionuclide, pq^{th} water-dependent pathway, and k^{th} food class (L/g),

$WSR_{ir}(t)$ = water/soil concentration ratio for the r^{th} water pathway segment (g/L), and

r = water pathway segment index for groundwater (r = 1) or surface water (r = 2).

Substituting Equation D.2 into Equation D.1, one obtains

$$ETF_{ipqr}(t) = WEF_{ipq}(t) \times WSR_{ir}(t) \qquad (D.3)$$

where

$$WEF_{ipq}(t) = FA_p \times FCD_{ipq}(t) \times \sum_k DF_{pk} \times FWR_{ipqk} \tag{D.4}$$

is the water exposure factor for the pqth pathway in units of L/yr, and the quantities on the right are as defined for Equations D.1 and D.2. A water exposure factor is equal to the ratio of the annual intake of the ith principal radionuclide in food contaminated through the pqth water-dependent pathway to the concentration of the radionuclide in the contaminated water. Water/soil concentration ratios are defined and discussed in Appendix E.

D.2.1.2 Area Factors

The area factor for the plant (FA_3), meat (FA_4), and milk (FA_5) pathways is given by

$$\begin{aligned} FA_3 &= A/2{,}000, && 0 \le A \le 1{,}000\ m^2 \\ &= 0.5, && A > 1{,}000\ m^2 \\ FA_4 = FA_5 &= A/20{,}000, && 0 \le A \le 20{,}000\ m^2 \\ &= 1, && A > 20{,}000\ m^2 \end{aligned} \tag{D.5}$$

where A = area of contaminated zone (10,000 m^2).* An area of 10,000 m^2 = 1 hectare (ha).

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*If a number is included with the unit identification, the variable is an input variable and the number is the default value.

D.2.1.3 Cover and Depth Factors

The cover and depth factors FCD_{ipq} for $q = 1$ through $q = 4$ are applicable to the plant ($p = 3$), meat ($p = 4$), and milk ($p = 5$) pathways. The cover and depth factor FCD_{ip5} for the livestock water pathway is applicable only to the meat and milk pathways.

Root Uptake. The cover and depth factor for root uptake ($q = 1$) is

$$\begin{aligned} FCD_{ip1}(t) &= 1, && C_d(t) = 0,\ T(t) \geq d_r \\ &= T(t)/d_r, && C_d(t) + T(t) < d_r \\ &= 1 - C_d(t)/d_r, && C_d(t) < d_r,\ C_d(t) + T(t) \geq d_r \\ &= 0, && C_d(t) \geq d_r \end{aligned} \tag{D.6}$$

where

$C_d(t)$ = cover depth at time t (m),

$T(t)$ = thickness of contaminated zone at time t (m), and

d_r = maximum root depth (0.9 m).

The cover depth is given by Equation B.6. Equation D.6 is based on the assumption of a sharp boundary between the bottom of any uncontaminated cover and the top of the contaminated zone. The effect of mixing uncontaminated and contaminated soil in a surface layer by plowing or other disturbance of the soil close to the ground surface is not taken into account.

Foliar Deposition. The cover and depth factor $FCD_{ip2}(t)$ for foliar deposition for the ingestion pathways is the same as the cover and depth factor $FCD_{i2}(t)$ for the inhalation pathway (see Equation C.5).

Ditch Irrigation, Overhead Irrigation, and Livestock Water. The contributions from ditch irrigation ($q = 3$), overhead irrigation ($q = 4$), and livestock water ($q = 5$) are independent of the depth of the contaminated zone in the models used because the infiltrating water will carry the contamination to the aquifer and contaminate the water regardless of the depth, and the subsequent contamination mechanisms do not depend on depth. Hence, the cover and depth factors for these subpathways are

$$FCD_{ip3}(t) = FCD_{ip4}(t) = FCD_{ip5}(t) = 1 \qquad (D.7)$$

D.2.1.4 Dietary Factors

The dietary factor for human food consumption is a tabulated quantity. The values used are given in Table D.2.

TABLE D.2 Dietary Factors (DF_{pk}) for Human Food Consumption

Primary Pathway Index, p	Ingestion Pathway	Food Class Index, k	Class Description	Dietary Factor, DF_{pk}
3	Plant foods	1	Fruits, vegetables, and grain	160 kg/yr
3	Plant foods	2	Leafy vegetables	14 kg/yr
4	Meat	1	Meat and poultry	63 kg/yr
5	Milk	1	Milk	92 L/yr
6	Aquatic foods	1	Fish	5.4 kg/yr
6	Aquatic foods	2	Crustacea and mollusks	0.9 kg/yr
7	Drinking water	1	Drinking water	410 L/yr

D.2.1.5 Food/Soil Concentration Ratios for Plant Foods

Root Uptake. The plant-food/soil concentration ratios for root uptake are given by

$$FSR_{i31k} = B_{iv} \tag{D.8}$$

where B_{iv} are the vegetable/soil transfer factors listed in Table D.3. It is assumed that the same root uptake transfer factors can be used for nonleafy vegetables (k = 1) and leafy vegetables (k = 2).

Foliar Deposition. The plant-food/soil concentration ratio for uptake from airborne contaminants that deposit on foliage is given by

$$FSR_{i32k} = FA_2 \times FAR_{i32k} \times ASR_3 \tag{D.9}$$

where

FSR_{i32k} = plant-food/soil concentration ratio for foliar deposition for the i^{th} principal radionuclide and k^{th} food class (dimensionless),

FA_2 = area factor for dilution of resuspended contaminated dust (dimensionless),

FAR_{i32k} = plant-food/air concentration ratio for radionuclide transfer by airborne foliar deposition for the i^{th} principal radionuclide and k^{th} food class (m^3/g), and

TABLE D.3 Vegetable/Soil Transfer Factors (B_{iv}) for Root Uptake

Element	B_{iv}	Element	B_{iv}	Element	B_{iv}
H	0	Sr	2.0×10^{-1}	Pm	2.5×10^{-3}
Be	4.7×10^{-4}	Y	2.5×10^{-3}	Sm	2.5×10^{-3}
C	0	Zr	1.7×10^{-4}	Eu	2.5×10^{-3}
N	7.5	Nb	9.4×10^{-3}	Tb	2.6×10^{-3}
F	2.0×10^{-2}	Mo	1.3×10^{-1}	Ho	2.6×10^{-3}
Na	5.0×10^{-2}	Tc	2.5×10^{-1}	W	1.8×10^{-2}
P	5.0×10^{-1}	Ru	1.0×10^{-2}	Ir	9.9×10^{-4}
Ar	0	Rh	1.3×10^{-1}	Hg	3.8×10^{-1}
Ca	4.0×10^{-2}	Pd	5.0	Pb	6.8×10^{-2}
Sc	1.1×10^{-3}	Ag	1.5×10^{-1}	Bi	1.5×10^{-1}
Cr	2.5×10^{-4}	Cd	3.0×10^{-1}	Po	9.0×10^{-3}
Mn	3.0×10^{-2}	Sn	2.5×10^{-3}	Rn	0
Fe	4.0×10^{-4}	Sb	1.1×10^{-2}	Ra	1.4×10^{-3}
Co	9.4×10^{-3}	Te	1.3	Ac	2.5×10^{-3}
Ni	1.9×10^{-2}	I	2.0×10^{-2}	Th	4.2×10^{-3}
Cu	1.3×10^{-1}	Xe	0	Pa	2.5×10^{-3}
Zn	4.0×10^{-1}	Cs	2.0×10^{-3}	U	2.5×10^{-3}
As	1.0×10^{-2}	Ba	5.0×10^{-3}	Np	2.5×10^{-3}
Se	1.3	La	2.5×10^{-3}	Pu	2.5×10^{-4}
Br	7.6×10^{-1}	Ce	5.0×10^{-4}	Am	2.5×10^{-4}
Kr	0	Pr	2.5×10^{-3}	Cm	2.5×10^{-3}
Rb	1.3×10^{-1}	Nd	2.4×10^{-3}	Cf	2.5×10^{-3}

ASR_3 = air/soil concentration ratio, specified as the average mass loading of airborne contaminated soil particles in a garden during the growing season (1×10^{-4} g/m^3).

The area factor for dilution of resuspended contaminated dust by mixing with uncontaminated dust blown in from off-site is given by Equation C.2. The formula for the plant-food/air concentration ratio is

$$FAR_{i32k} = 3.16 \times 10^4 \frac{[V_{di} \times f_r \times T_{ivk}][1 - \exp(-\lambda_w t_{ek})]}{Y_{vk} \times \lambda_w} \qquad (D.10)$$

where

V_{di} = deposition velocity of contaminated dust (0 m/s for H, C, Ar, Kr, and Xe; 1×10^{-2} m/s for F, Br, I, and Cl; and 1×10^{-3} m/s for all remaining elements listed in Table D.3),

f_r = fraction of deposited radionuclides retained on the vegetation (0.25, dimensionless),

T_{ivk} = foliage-to-food radionuclide transfer coefficient for the i^{th} principal radionuclide and k^{th} food class ($T_{iv1} = 0.1$, $T_{iv2} = 1.0$, and $T_{iv3} = 1.0$, dimensionless),

Y_{vk} = wet-weight crop yield for the k^{th} food class ($Y_{v1} = 0.7$ kg/m^2, $Y_{v2} = 1.5$ kg/m^2, and $Y_{v3} = 1.1$ kg/m^2),

λ_w = weathering removal constant for vegetation (20 yr^{-1}), and

t_{ek} = time of exposure of the k^{th} food class to contamination during the growing season ($t_{e1} = 0.17$ yr, $t_{e2} = 0.25$ yr, and $t_{e3} = 0.08$ yr).

The numerical factor 3.16×10^4 (kg/g)(s/yr) is used to convert FAR_{i32k} to units of m^3/g. The foliage-to-food transfer coefficient T_{ivk} is assumed to be radionuclide independent in the current version of the code. The weathering removal constant corresponds to a contaminant removal half-time of two weeks. The values for k = 3 are for fodder; they are not included in the sum over k in Equation D.1.

Ditch Irrigation. The plant-food/soil concentration ratio for ditch irrigation is given by

$$FSR_{i33k}(t) = FWR_{i33k} \times \left[WSR_{i1}(t) \times FI1 + WSR_{i2}(t) \times (1 - FI1)\right] \quad (D.11)$$

where

$FSR_{i33k}(t)$ = plant-food/soil concentration ratio for ditch irrigation for the i^{th} principal radionuclide and k^{th} food class at time t (dimensionless),

FWR_{i33k} = plant-food/water concentration ratio for ditch irrigation for the i^{th} principal radionuclide and the k^{th} food class (L/g),

$WSR_{i1}(t)$ = well-water/soil concentration ratio for the i^{th} principal radionuclide (g/L),

$FI1$ = fraction of well water used for irrigation (balanced from surface water; 1.0, dimensionless), and

$WSR_{i2}(t)$ = surface-water/soil concentration ratio for the i^{th} principal radionuclide (g/L).

Plant-food/soil concentration ratios for root uptake are assumed to be the same for all food classes. The formula for the plant-food/water concentration ratio, FWR_{i33k}, for ditch irrigation is

$$FWR_{i33k} = \frac{I_{rr}\ B_{iv}\ \left[1 - \exp(- L_i t_{ek})\right]}{Y_{vk} \times L_i} \qquad (D.12)$$

where

I_{rr} = irrigation rate (0 m/yr), and

L_i = leach rate constant for radionuclide i (yr^{-1}).

FWR_{i33k} is in dimensions of L/g (m^3/kg), B_{iv} is as defined for Equation D.8, and t_{ek} and Y_{vk} are as defined for Equation D.10. The leach rate constant L_i is discussed in Appendix E. The default value used in the RESRAD code for fraction of well water used for irrigation is 1.0, i.e., 100% of irrigation water is well water. A value of 0.5 means 50% of irrigation water is well water and 50% is surface (pond) water. The water/soil concentration ratios are discussed in Appendix E.

Overhead Irrigation. The factoring of the plant-food/soil concentration ratio for overhead irrigation, FSR_{i34k}, is the same as the factoring for ditch irrigation in Equation D.11. That is,

$$FSR_{i34k}(t) = FWR_{i34k} \times \left[WSR_{i1}(t) \times FI1 + WSR_{i2}(t) \times (1 - FI1)\right] \qquad (D.13)$$

The only difference is that, for overhead irrigation, the plant-food/water concentration ratio is given by

$$FWR_{i34k} = \frac{[I_{rr} \times f_r \times T_{ivk}][1 - \exp(-\lambda_w t_{ek})]}{Y_{vk} \times \lambda_w} + FWR_{i33k} \qquad (D.14)$$

where FWR_{i34k} is in units of L/g (m^3/kg), I_{rr} is as defined for Equation D.12, and the remaining quantities are as defined for Equation D.10.

D.2.1.6 Food/Soil Concentration Ratios for Meat and Milk

The food/soil concentration ratios $FSR_{ipq}(t)$ for meat and milk can be factored into the product

$$FSR_{ipq}(t) = FQR_{ip} \times FI_{pq} \times QSR_{ipq}(t) \qquad (D.15)$$

where

FQR_{ip} = radionuclide transfer factor for meat ($p = 4$) or milk ($p = 5$) = ratio of the concentration of the i^{th} principal radionuclide in meat or milk in pCi/kg to the rate of intake in fodder or water by livestock of the i^{th} principal radionuclide in pCi/d (d/kg),

FI_{pq} = daily intake of fodder ($q = 1$, 2, 3, and 4) or water ($q = 5$) by livestock (kg/d -- see below for default values), and

$QSR_{ipq}(t)$ = fodder/soil or livestock-water/soil concentration ratio for meat ($p = 3$) or milk ($p = 5$) for the i^{th} principal radionuclide and q^{th} subpathway (dimensionless).

The radionuclide transfer factors FQR_{ip} are listed in Table D.4. The livestock fodder intake rates are FI_{4q} = 68 kg/d and FI_{5q} = 55 kg/d for q = 1, 2, 3, and 4 for meat and milk, respectively, and the livestock water intake rates are FI_{45} = 50 L/d and FI_{55} = 160 L/d for q = 5. (Note that 1 L of water weighs 1 kg; hence, units of kg/d may be used for all intakes.)

The expressions for the fodder/soil concentration ratios are the same as the expressions for the food/soil concentration ratios given earlier; the only difference is in a few parameter values. QSR_{ipq} is time independent for the water-independent pathways (q = 1, 2) and depends on time only through the water/soil concentration ratio $WSR_{i1}(t)$ for the water-dependent pathways (q = 3, 4 and 5). The formulas for the fodder/soil concentration ratios are as follows.

$$QSR_{i41} = QSR_{i51} = B_{iv} \tag{D.16}$$

is the ratio for root uptake by fodder, where B_{iv} is the vegetable/soil transfer factor for root uptake, tabulated in Table D.3.

$$QSR_{i42} = QSR_{i52} = FA_2 \times FAR_{i323} \times ASR_3 \tag{D.17}$$

is the ratio for foliar deposition on fodder, where FA_2 is an area factor and ASR_3 is the air/soil concentration ratio, both defined for Equation D.9, and FAR_{i323} is the plant-food/air concentration ratio defined by Equation D.10.

$$\begin{aligned} QSR_{i43}(t) &= QSR_{i53}(t) \\ &= FWR_{i333} \times \left[WSR_{i1}(t) \times FI1 + WSR_{i2} \times (1 - FI1)\right] \end{aligned} \tag{D.18}$$

TABLE D.4 Meat (FQR_{i4}) and Milk (FQR_{i5}) Transfer Factors for Root Uptake

Element	Beef (FQR_{i4}) (d/kg)	Milk (FQR_{i5}) (d/L)	Element	Beef (FQR_{i4}) (d/kg)	Milk (FQR_{i5}) (d/L)
H	0	0	Sn	9.9×10^{-4}	1.3×10^{-3}
Be	8.0×10^{-4}	2.0×10^{-6}	Sb	3.0×10^{-3}	7.5×10^{-4}
C	0	0	Te	5.0×10^{-2}	5.0×10^{-4}
N	9.9×10^{-4}	1.0×10^{-2}	I	2.0×10^{-2}	1.0×10^{-2}
F	2.0×10^{-2}	7.0×10^{-3}	Xe	0	0
Na	5.0×10^{-2}	4.0×10^{-2}	Cs	3.0×10^{-2}	5.0×10^{-3}
P	5.0×10^{-2}	1.2×10^{-2}	Ba	5.0×10^{-4}	4.0×10^{-4}
Ar	0	0	La	5.0×10^{-3}	2.5×10^{-6}
Ca	3.3×10^{-3}	8.0×10^{-3}	Ce	1.0×10^{-3}	1.0×10^{-5}
Sc	6.0×10^{-3}	2.5×10^{-6}	Pr	5.0×10^{-3}	2.5×10^{-6}
Cr	9.9×10^{-4}	1.1×10^{-3}	Nd	5.0×10^{-3}	2.5×10^{-6}
Mn	5.0×10^{-3}	1.0×10^{-4}	Pm	5.0×10^{-3}	2.5×10^{-6}
Fe	2.0×10^{-2}	6.0×10^{-4}	Sm	5.0×10^{-3}	2.5×10^{-6}
Co	1.0×10^{-3}	5.0×10^{-4}	Eu	5.0×10^{-3}	2.5×10^{-6}
Ni	1.0×10^{-3}	3.4×10^{-3}	Tb	5.0×10^{-3}	2.5×10^{-6}
Cu	1.0×10^{-2}	7.0×10^{-3}	Ho	5.0×10^{-3}	2.5×10^{-6}
Zn	5.0×10^{-2}	6.0×10^{-3}	W	9.9×10^{-4}	2.5×10^{-4}
As	1.5×10^{-3}	3.0×10^{-3}	Ir	9.9×10^{-4}	9.9×10^{-4}
Se	1.0	2.3×10^{-2}	Hg	1.0×10^{-1}	1.9×10^{-2}
Br	2.0×10^{-2}	2.5×10^{-2}	Pb	9.9×10^{-4}	1.0×10^{-5}
Kr	0	0	Bi	9.9×10^{-4}	2.5×10^{-4}
Rb	1.5×10^{-1}	1.0×10^{-2}	Po	9.9×10^{-4}	1.2×10^{-4}
Sr	3.0×10^{-4}	1.5×10^{-3}	Rn	0	0
Y	5.0×10^{-3}	5.0×10^{-6}	Ra	9.9×10^{-4}	2.0×10^{-4}
Zr	5.0×10^{-4}	2.5×10^{-6}	Ac	5.0×10^{-3}	2.5×10^{-6}
Nb	5.0×10^{-4}	1.2×10^{-3}	Th	5.0×10^{-3}	2.5×10^{-6}
Mo	1.0×10^{-2}	4.0×10^{-3}	Pa	5.0×10^{-3}	2.5×10^{-6}
Tc	9.9×10^{-4}	1.2×10^{-2}	U	5.0×10^{-3}	6.0×10^{-4}
Ru	1.0×10^{-3}	5.0×10^{-7}	Np	5.0×10^{-3}	2.5×10^{-6}
Rh	1.0×10^{-3}	5.0×10^{-3}	Pu	5.0×10^{-3}	2.5×10^{-8}
Pd	1.0×10^{-3}	5.0×10^{-3}	Am	5.0×10^{-3}	2.5×10^{-6}
Ag	9.9×10^{-4}	2.5×10^{-2}	Cm	5.0×10^{-3}	2.5×10^{-6}
Cd	1.6×10^{-2}	6.2×10^{-5}	Cf	5.0×10^{-3}	7.5×10^{-7}

is the ratio for ditch irrigation of fodder, where FWR_{i333} is the plant-food/water concentration ratio given by Equation D.12; $WSR_{i1}(t)$ and WSR_{i2} are the water/soil concentration ratios for well water and surface water, respectively, as derived in Appendix E; and FI1 is as defined for Equation D.11.

$$\begin{aligned} QSR_{i44}(t) &= QSR_{i54}(t) \\ &= FWR_{i343} \times \left[WSR_{i1}(t) \times FI1 + WSR_{i2}\ (1 - FI1)\right] \end{aligned} \tag{D.19}$$

is the ratio for overhead irrigation of fodder, where FWR_{i343} is the fodder/water concentration ratio for overhead irrigation given by Equation D.14.

$$QSR_{i45}(t) = QSR_{i55}(t) = WSR_{i1}(t) \times FL1 + WSR_{i2}\ (1 - FL1) \tag{D.20}$$

is the ratio for intake of contaminated livestock water, where FL1 is the fraction of well water used for feeding livestock (balanced from surface water; 1.0, dimensionless).

D.2.2 Aquatic Food Pathway

The environmental transport factor for the aquatic food pathway (p = 6) can be factored into the product

$$ETF_{i6}(t) = FR_6 \times \left[\sum_k DF_{6k} \times FWR_{i6k}\right] \times WSR_{i2}(t) \tag{D.21}$$

where the summation is over the aquatic food classes (see Table D.2) and

$ETF_{i6}(t)$ = environmental transport factor for the aquatic food pathway (fish, crustacea, and mollusks) (g/yr),

DF_{6k} = dietary factors for annual consumption of fish (k = 1) and crustacea and mollusks (k = 2) (kg/yr),

FR_6 = fraction of aquatic food consumed that is contaminated (0.5, dimensionless),

FWR_{i6k} = fish/water (k = 1) and crustacea-mollusk/water (k = 2) concentration ratios (bioaccumulation factors) (L/kg), and

$WSR_{i2}(t)$ = water/soil concentration ratio for surface water (g/L).

Dietary factors are given in Table D.2. Bioaccumulation factors are given in Table D.5. The water/soil concentration ratio for surface water is calculated using the surface-water model described in Appendix E.

The environmental transport factors may also be written as products of a water exposure factor and a water/soil concentration ratio

$$ETF_{i6}(t) = WEF_{i6} \times WSR_{i2}(t) \tag{D.22}$$

where

$$WEF_{i6}(t) = FR_6 \times \left[\sum_k DF_{6k} \times FWR_{i6k}\right] \tag{D.23}$$

D.2.3 Drinking Water Pathway

The formula for the environmental transport factors for the drinking water pathway is

$$ETF_{i7}(t) = DF_7 \times FDW \times \left[WSR_{i1}(t) \times FD1 + WSR_{i2}(t) \times (1 - FD1)\right] \tag{D.24}$$

TABLE D.5 Aquatic Bioaccumulation Factors (FWR_{i6k}) for Fresh Water

Element	Fish (k=1) (L/kg)	Crustacea and Mollusks (k=2) (L/kg)	Element	Fish (k=1) (L/kg)	Crustacea and Mollusks (k=2) (L/kg)
H	9.0×10^{-1}	9.0×10^{-1}	Sn	3.0×10^{3}	1.0×10^{3}
Be	2.0	1.0×10^{1}	Sb	1.0	1.0×10^{1}
C	4.6×10^{3}	9.1×10^{3}	Te	4.0×10^{2}	7.5×10^{1}
N	0	0	I	1.5×10^{1}	5.0
F	1.0×10^{1}	1.0×10^{2}	Xe	1.0	1.0
Na	1.0×10^{2}	2.0×10^{2}	Cs	2.0×10^{3}	1.0×10^{2}
P	1.0×10^{5}	2.0×10^{4}	Ba	4.0	2.0×10^{2}
Ar	1.0	1.0	La	2.5×10^{1}	1.0×10^{3}
Ca	4.0×10^{1}	3.3×10^{2}	Ce	1.0	1.0×10^{3}
Sc	2.0	1.0×10^{3}	Pr	2.5×10^{1}	1.0×10^{3}
Cr	2.0×10^{1}	2.0×10^{3}	Nd	2.5×10^{1}	1.0×10^{3}
Mn	4.0×10^{2}	9.0×10^{4}	Pm	2.5×10^{1}	1.0×10^{3}
Fe	1.0×10^{2}	3.2×10^{3}	Sm	2.5×10^{1}	1.0×10^{3}
Co	5.0×10^{1}	2.0×10^{2}	Eu	2.5×10^{1}	1.0×10^{3}
Ni	1.0×10^{2}	1.0×10^{2}	Tb	2.5×10^{1}	1.0×10^{3}
Cu	5.0×10^{1}	4.0×10^{2}	Ho	2.5×10^{1}	1.0×10^{3}
Zn	2.0×10^{3}	1.0×10^{4}	W	1.2×10^{3}	1.0×10^{1}
As	3.0×10^{2}	3.0×10^{2}	Ir	5.0×10^{1}	2.0×10^{2}
Se	1.7×10^{2}	1.7×10^{2}	Hg	2.0×10^{4}	2.0×10^{4}
Br	4.2×10^{2}	3.3×10^{2}	Pb	1.0×10^{2}	1.0×10^{2}
Kr	1.0	1.0	Bi	1.5×10^{1}	1.0×10^{1}
Rb	2.0×10^{3}	1.0×10^{3}	Po	5.0×10^{2}	2.0×10^{4}
Sr	3.0×10^{1}	1.0×10^{2}	Rn	5.7×10^{1}	1.0
Y	2.5×10^{1}	1.0×10^{3}	Ra	5.0×10^{1}	2.5×10^{2}
Zr	3.3	6.7	Ac	2.5×10^{1}	1.0×10^{3}
Nb	3.0×10^{4}	1.0×10^{2}	Th	3.0×10^{1}	5.0×10^{2}
Mo	1.0×10^{1}	1.0×10^{1}	Pa	1.1×10^{1}	1.1×10^{2}
Tc	1.5×10^{1}	5.0	U	2.0	6.0×10^{1}
Ru	1.0×10^{1}	3.0×10^{2}	Np	1.0×10^{1}	4.0×10^{2}
Rh	1.0×10^{1}	3.0×10^{2}	Pu	3.5	1.0×10^{2}
Pd	1.0×10^{1}	3.0×10^{2}	Am	2.5×10^{1}	1.0×10^{3}
Ag	2.3	7.7×10^{2}	Cm	2.5×10^{1}	1.0×10^{3}
Cd	2.0×10^{2}	2.0×10^{3}	Cf	2.5×10^{1}	1.0×10^{3}

where

$ETF_{i7}(t)$ = environmental transport factors for the drinking water pathway (g/yr),

DF_7 = annual intake of drinking water (410 L/yr),

FDW = fraction of drinking water from site (dimensionless),

$WSR_{i1}(t)$ = water/soil concentration ratios for well water (g/L),

$WSR_{i2}(t)$ = water/soil concentration ratios for surface water (g/L), and

FD1 = fraction of well water used for drinking (balanced from surface water; 1.0, dimensionless).

The annual intake of drinking water is a dietary factor from Table D.2. The water/soil concentration ratios are calculated using the models described in Appendix E.

D.3 REFERENCES

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APPENDIX E

WATER PATHWAY FACTORS

APPENDIX E: WATER PATHWAY FACTORS

Water pathway factors are components of the environmental transport factors for water-dependent ingestion pathways. A water-dependent ingestion pathway can be divided into two segments: (1) a water pathway segment, extending from the contaminated zone to a point where transport through the food chain begins (a well or surface water body), and (2) a food chain pathway segment, extending from the point of entry of a radionuclide from water into the food chain to a point of human exposure. Transport through the water pathway segment is characterized by a water/soil concentration ratio, defined as the ratio of the concentration of the radionuclide in water used for drinking, irrigation, or livestock water to the concentration in the contaminated zone. Transport through the food chain pathway segment is characterized by a water exposure factor, defined as the ratio of the quantity of a radionuclide ingested annually to the concentration in water used for drinking, irrigation, or livestock water. The environmental transport factor for the water-dependent ingestion pathway can be expressed as a product of a water exposure factor and a water/soil concentration ratio:

$$ETF_{ipqr}(t) = WEF_{ipqr}(t) \times WSR_{ir}(t) \tag{E.1}$$

where

$ETF_{ipqr}(t) = E_{ipqr}(t)/S_i(t)$ = environmental transport factor at time t for the i^{th} principal radionuclide transported through the pqr^{th} ingestion pathway (g/yr) -- $E_{ipqr}(t)$ is the rate of ingestion (pCi/yr) at time t of the i^{th} principal radionuclide transported through the pqr^{th} pathway from the contaminated zone to a point of human exposure and $S_i(t)$ is the average concentration (pCi/g) at time t of the i^{th} principal radionuclide in the contaminated zone,

p, q, r = pathway indices -- the indices p and q identify the food chain segment of the pathway (see Table 2.1 and Equation D.1) and the index r identifies the water pathway segment, i.e., the segment from the contaminated zone to well water (r = 1) or surface water (r = 2),

$WEF_{ipqr}(t) = E_{ipqr}(t)/W_{ir}(t)$ = water exposure factor at time t for the i^{th} principal radionuclide transported through the pqr^{th} pathway from the point of water use to the point of exposure (L/yr) -- $E_{ipqr}(t)$ is the rate of ingestion (pCi/yr) at time t of the i^{th} principal radionuclide transported through the pqr^{th} pathway, and $W_{ir}(t)$ is the concentration in water (pCi/L) at time t of the i^{th} principal radionuclide transported through the r^{th} water pathway segment at the point of entry into the pq^{th} food chain, and

$WSR_{ir}(t) = W_{ir}(t)/S_i(t)$ = water/soil concentration ratio at time t for the r^{th} water pathway segment (g/L) -- $W_{ir}(t)$ is the concentration in water (pCi/L) at time t of the i^{th} principal radionuclide transported through the r^{th} water pathway segment at the point of entry into a food chain pathway segment, and $S_i(t)$ is the average concentration (pCi/g) at time t of the i^{th} principal radionuclide in the contaminated zone.

The water exposure factor $WEF_{ipqr}(t)$ is discussed in Appendix D. The water/soil concentration ratio $WSR_{ir}(t)$ is discussed as follows.

A WSR is determined by the rate at which a radionuclide is leached from the contaminated zone, the time for this radionuclide to be transported along the water pathway from the boundary of the contaminated zone to the point of water use, and the dilution that occurs along this pathway. The model for estimating radionuclide leaching and formulas for calculating the leach rate are given in Section E.1. Formulas that relate the radionuclide concentration in water at the point of use to parameters that characterize the leaching and transport processes are derived in Section E.2.

E.1 RADIONUCLIDE LEACHING FROM THE CONTAMINATED ZONE

Radionuclides adsorbed in soil are subject to leaching by infiltrating water. Radionuclide leaching from the contaminated zone is the source for groundwater contamination. Therefore, the first step in calculating radionuclide concentrations in groundwater is to estimate the leaching of radionuclides from the contaminated zone.

A sorption-desorption, ion-exchange leaching model is used in the RESRAD code. This model is characterized by a nuclide-dependent, first-order leach rate constant, L_i, which is defined as the fraction of available radionuclide i leached out per unit time. The radionuclide release rate (source strength, in Ci/yr), $\dot{R}_i(t)$, can be written as (Yu 1987):

$$\dot{R}_i(t) = L_i \; \rho_b^{(cz)} \; A \; T(t) \; S_i(t) \qquad (E.2)$$

where

L_i = leach rate for radionuclide i (yr^{-1}),

$\rho_b^{(cz)}$ = bulk density of the contaminated zone (kg/m^3),

A = area of the contaminated zone (m^2),

T(t) = thickness of the contaminated zone at time t (m), and

$S_i(t)$ = average concentration of the i^{th} principal radionuclide in the contaminated zone available for leaching at time t (pCi/kg).

The first-order leach rate constant used in the current version of RESRAD is a time-independent radionuclide leach rate constant that is estimated based on the soil residence time for the initial thickness of the contaminated zone. A time-dependent radionuclide leach rate constant for radionuclide i, $L_i(t)$, may be written as

$$L_i(t) = \frac{I}{\theta^{(cz)}\ T(t)\ R_{d_i}^{(cz)}} \tag{E.3}$$

where

I = infiltration rate (m/yr),

$\theta^{(cz)}$ = volumetric water content of the contaminated zone, and

$R_{d_i}^{(cz)}$ = retardation factor in the contaminated zone for radionuclide i (dimensionless).

The infiltration rate is given by

$$I = (1 - C_e)\left[(1 - C_r)P_r + I_{rr}\right] \tag{E.4}$$

where

C_e = evapotranspiration coefficient (0.7, dimensionless),

C_r = runoff coefficient (0.6, dimensionless),

P_r = precipitation rate (annual rainfall, 1.0 m/yr), and

I_{rr} = irrigation rate (0 m/yr).

To calculate the infiltration rate, the average evapotranspiration coefficient is used rather than the average evapotranspiration rate (see Geraghty et al. [1973] for U.S. average). Using the average evapotranspiration rate does not take into account the correlation between precipitation and evapotranspiration and, for arid regions, can give a spurious negative infiltration rate. The evapotranspiration coefficient is related to the evapotranspiration rate by the formula $C_e = E_t/[(1 - C_r)P_r + I_{rr}]$. Runoff coefficients for a specific site may be obtained from Table E.1. It is assumed that irrigation water is controlled by ditching or by the duration of application so that none will be lost by runoff. The default irrigation rate is for humid regions where irrigation is unnecessary; an appropriate generic value for arid regions would be I_{rr} = 1 m/yr. Site-specific values for the precipitation and irrigation rates should be used whenever possible.

The volumetric water content of the contaminated zone, $\theta^{(cz)}$, is the product of the saturated water content of the contaminated zone, $\theta_{sat}^{(cz)}$, and the saturation ratio of the contaminated zone, $R_{sat}^{(cz)}$. The saturated water content is the water content when the soil material is saturated. Hence, θ_{sat}

TABLE E.1 Runoff Coefficient Values

Type of Area	Coefficient	Value
Agricultural Environment[a]		
Flat land, with average slopes of 0.3 to 0.9 m per mile	c_1	0.3
Rolling land, with average slopes of 4.6 to 6.1 m per mile	c_1	0.2
Hilly land, with average slopes of 46 to 76 m per mile	c_1	0.1
Open sandy loam	c_2	0.4
Intermediate combinations of clay and loam	c_2	0.2
Tight, impervious clay	c_2	0.1
Woodlands	c_3	0.2
Cultivated lands	c_3	0.1
Urban Environment		
Flat, residential area -- about 30% imprevious	C_r	0.4
Moderately steep, residential area -- about 50% impervious	C_r	0.65
Moderately steep, built-up area -- about 70% impervious	C_r	0.8

[a] The runoff coefficient for an agricultural environment is given by $C_r = 1 - c_1 - c_2 - c_3$.

Source: Data from Gray (1970).

equals p_t, where p_t is the total porosity of the soil material, that is*

$$\theta_{sat} = p_t \tag{E.5}$$

The saturation ratio, R_s, is defined as the ratio of θ over θ_{sat}, that is

$$R_s = \theta/\theta_{sat} = \theta/p_t \tag{E.6}$$

When the medium is saturated, R_s equals unity. Under unsaturated infiltration conditions, the saturation ratio is a function of the infiltration rate, the saturated hydraulic conductivity, and the texture of the soil. The saturation ratio can be estimated using the following equation (Clapp and Hornberger 1978):

$$R_s = \left(\frac{I}{K_{sat}}\right)^{\frac{1}{2b + 3}} \tag{E.7}$$

where

I = infiltration rate (m/yr),
K_{sat} = saturated hydraulic conductivity (m/yr), and
b = soil-specific exponential parameter (dimensionless).

Representative values of K_{sat}, θ_{sat}, and b for various soil textures are listed in Table E.2.

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*The superscript is omitted for a general definition. The definition applies for all zones.

TABLE E.2 Representative Values of Saturated Hydraulic Conductivity, Saturated Water Content, and the Soil-Specific Exponential Parameter

Texture	Hydraulic Conductivity, K_{sat} (m/yr)	Saturated Water Content, θ_{sat}	Soil-Specific Exponential Parameter, b
Sand	5.55×10^3	0.395	4.05
Loamy sand	4.93×10^3	0.410	4.38
Sandy loam	1.09×10^3	0.435	4.90
Silty loam	2.27×10^2	0.485	5.30
Loam	2.19×10^2	0.451	5.39
Sandy clay loam	1.99×10^2	0.420	7.12
Silty clay loam	5.36×10^1	0.477	7.75
Clay loam	7.73×10^1	0.476	8.52
Sandy clay	6.84×10^1	0.426	10.40
Silty clay	3.26×10^1	0.492	10.40
Clay	4.05×10^1	0.482	11.40

Source: Data from Clapp and Hornberger (1978).

The retardation factor for radionuclide i, R_{d_i}, is the ratio of average pore water velocity to radionuclide transport velocity. Assuming that the adsorption-desorption process can be represented with a linear Freundlich isotherm, the retardation factor can be calculated with the formula (Yu 1987)

$$R_{d_i} = 1 + \frac{\rho_b K_{d_i}}{\theta} = 1 + \frac{\rho_b K_{d_i}}{p_t R_s} \tag{E.8}$$

where

ρ_b = bulk soil density (g/cm^3),

K_{d_i} = distribution coefficient for the i^{th} principal radionuclide (cm^3/g), and

θ = volumetric water content (dimensionless).

The distribution coefficient is the radionuclide equilibrium concentration ratio of the adsorbed radionuclide (in soil) to the desorbed radionuclide (in water). Representative distribution coefficients are given in Tables E.3 through E.6.

E.2 WATER/SOIL CONCENTRATION RATIOS IN TERMS OF NUCLIDE WATER-TRANSPORT PARAMETERS

A water/soil concentration ratio can be expressed in terms of functions that characterize the source terms and transport processes and are applicable for both simple and complex hydrogeological strata. By introducing simplifying approximations for the functional form of the breakthrough curve* that are generally applicable even for complex hydrogeological structures, the transport and source functions can be specified by a small number of nuclide water-transport parameters, and various models can be used to derive relations between these parameters and measurable quantities. The analysis is applicable to either the groundwater or surface water pathway; hence, in the following derivation, the subscript r used to identify different water pathways has been omitted in order to simplify the expressions.

Let $W_i^s(t')$ be the average concentration at time t' of the i^{th} radionuclide in water that has percolated through the contaminated zone, measured at the lower boundary of the contaminated zone. This source of groundwater contamination will result in a concentration $W_i(t)$ at time t $(t \geq t')$ of the i^{th} radionuclide in water at the point of use (e.g., a well or surface water body). One may express the relation between the source concentration $W_i^s(t')$

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*The breakthrough curve is the concentration of a radionuclide in water at the point of use as a function of time.

TABLE E.3 Typical Average Distribution Coefficients for Various Elements in Sand, Soils, and Clays

	Average Distribution Coefficient,[a] K_d (cm^3/g)				Average Distribution Coefficient,[a] K_d (cm^3/g)		
Element	Soils and Clays	Sand[b]	Geometric Standard Deviation	Element	Soils and Clays	Sand[b]	Geometric Standard Deviation
As	3	0.3	1.8	Hg	100	10	-
Ba	50	5	-	Ni	1,000	100	-
Cd	7	0.7	2.4	Pu	2,000	200	10
Ce	1,000	100	3.7	Ra[d]	70	7	7
Cs[c]	500	80	2.4	Se	3	0.3	1.9
Cr (+6)	4	0.4	9.0	Ag	100	10	3.7
Co	1,000	100	-	Sr[d,e]	30	3	7.4
Cu	20	2	3.0	Th	60,000	6,000	4.5
F	0	0	-	Tritium	0	0	-
Fe	1,000	100	-	U	50	5	3.6
La	1,000	100	-	Va	1,000	100	-
Pb	100	10	5.5	Zn	20	2	6.7
Li	500	50	-	Zr	1,000	100	-
Mn	200	20	15				

[a] Data for As, Cd, Ce, Cr, Co, Cu, Pb, Mn, Pu, Se, Ag, Sr, Th, U, and Zn from Baes and Sharp (1983); the values of K_d are the geometric means of the literature data (see also Gilbert et al. [1983, pp. 3-57 to 3-60]). Data for other elements from Nuclear Safety Associates (1980), except as noted. All values have been rounded to one significant figure.

[b] The values are taken to be 10% of the values of soils and clays (Nucl. Saf. Assoc. 1980), except for cesium.

[c] From Isherwood (1981), using soil and quartz sand data, rounded to one significant digit.

[d] Sources: U.S. Nuclear Regulatory Commission (1980); Gee et al. (1980).

[e] The corresponding values from Isherwood (1981) for Sr are 73 for soils, 2.5 for quartz sand, and 24 for other sands.

TABLE E.4 Distribution Coefficients for Strontium and Cesium[a]

Conditions	K_d (cm^3/g) Strontium	Cesium
Basalt, 32-80 mesh	16-140	790-9,500
Basalt, 0.5-4 mm, 300 ppm TDS	39-280	220-1,200
Basalt, 0.5-4 mm, sea water	1.1	6.5
Basalt-fractured in-situ measurement	3	
Sand, quartz - pH 7.7	1.7-3.8	22-310
Sands	13-43	100
Carbonate, greater than 4 mm	0.19	14
Dolomite, 4,000 ppm TDS	5-14	
Granite, greater than 4 mm	1.7	34
Granodiorite, 100-200 mesh	4-9	8-9
Granodiorite, 0.5-1 mm	11-23	1,000-1,800
Hanford sediments	50	300
Tuff	45-4,000	800-18,000
Soils	19-280	190-1,000
Shaley siltstone, greater than 4 mm	8	310
Shaley siltstone, greater than 4 mm	1.4	100
Alluvium, 0.5-4 mm	48-2,400	120-3,200
Salt, greater than 4 mm saturated brine	0.19	0.027

[a] All values have been rounded to two significant figures.

Source: Data from Isherwood (1981).

TABLE E.5 Distribution Coefficients for Thorium and Uranium

Conditions	K_d (cm^3/g)
Thorium	
Silt loam, Ca-saturated clay, pH 6.5	160,000
Montmorillonite, Ca-saturated clay, pH 6.5	400,000
Clay soil, 5 mM $Ca(NO_3)_2$, pH 6.5	160,000
Medium sand, pH 8.15	40-130
Very fine sand, pH 8.15	310-470
Silt/clay, pH 8.15	270-10,000
Schist soil, 1 g/L Th, pH 3.2	8
Schist soil, 0.1 g/L Th	603.2
Illite, 1 g/L Th, pH 3.2	120
Illite, 0.1 g/L Th, pH 3.2	1,000
Illite, 0.1 g/L Th, pH > 6	<100,000
Uranium	
Silt loam, U(VI), Ca-saturated, pH 6.5	62,000
Clay soil, U(VI), 5 mM $Ca(NO_3)_2$, pH 6.5	4,400
Clay soil, 1 ppm UO^{+2}, pH 5.5	300
Clay soil, 1 ppm UO^{+2}, pH 10	2,000
Clay soil, 1 ppm UO^{+2}, pH 12	270
Dolomite, 100-325 mesh, brine, pH 6.9	4.5
Limestone, 100-170 mesh, brine, pH 6.9	2.9

Source: Data from Isherwood (1981).

TABLE E.6 Distribution Coefficients for Several Radionuclides

Element	pH	K_d (cm^3/g)	Source	Element	pH	K_d (cm^3/g)	Source
Uranium	2	0	A	Lead	2.2	1,850	B
	8	100			7.7	10,000	
	10	600					
	13	50			4-9	99[c]	C
	2.2	1.3	B	Strontium	2	0.1	E
	7.7	23,000			3	6	
					7	500	
	4-9	45[a]	C		10	170	
Thorium	2	500	A		4-9	27[d]	C
	5	3,000					
	7	50,000		Cesium	3	45	E
	13	50			5	150	
					8	905	
	2.2	1.2	B		10	650	
	7.7	80,000					
					4-9	1,100[e]	C
	4-9	60,000[b]	C				
				Plutonium	2	150	E
Radium	2	0	D		5	250	
	4	12			7	8,500	
	6	60			11	1,000	
	7	100					
					4-9	1,800[f]	C
	2.2	13	B				
	7.7	2,400		Deuterium	All	0	

[a] Geometric mean (GM) of values ranging from 11 to 4,400, with a geometric standard deviation (GSD) of 3.7.

[b] GM of values ranging from 2,000 to 510,000, with a GSD of 4.5.

[c] GM of values ranging from 4.5 to 7,600, with a GSD of 5.5.

[d] GM of values ranging from 0.15 to 3,300, with a GSD of 7.4.

[e] GM of values ranging from 10 to 52,000, with a GSD of 6.7.

[f] GM of values ranging from 11 to 300,000, with a GSD of 10.

Sources: A = Rancon (1973); B = Gee et al. (1980); C = Baes and Sharp (1983); D = U.S. Nuclear Regulatory Commission (1980); E = Staley et al. (1979).

and the point-of-use concentration $W_i(t)$ in terms of a nuclide water-transport function $G_i(t,t')$ that is valid for any hydrogeological system.

Let $\delta W_{i,k}(t)$ be the concentration at time t at the point of use due to release of a pulse of unit concentration for a time interval $\delta t'$ at time $t'_k = k\delta t'$ [i.e., for a source pulse where k is an integer, $\delta W^s_{i,k}(t') = 1$ when $k\delta t' \le t' < (k+1)\delta t'$ and $\delta W^s_{i,k}(t') = 0$ otherwise]. The point-of-use concentration may then be expressed as the sum of the contributions from the unit pulses multiplied by the source concentration for each pulse:

$$W_i(t) \approx \sum_k W^s_i(t'_k) \times \delta W_{i,k}(t) \tag{E.9}$$

If the duration $\delta t'$ of each unit source pulse is sufficiently small ($\delta t' \to 0$), the magnitude of each point-of-use pulse will be proportional to the source-pulse duration and one can write

$$\delta W_{i,k}(t) \approx G_i(t,t'_k)\ \delta t' \tag{E.10}$$

where $G_i(t,t'_k)$ is, by definition, the nuclide water-transport function. In the limit as $\delta t' \to 0$, Equation E.9 becomes

$$W_i(t) = \int_0^t G_i(t,t')\ W^s_i(t')\ dt' \tag{E.11}$$

Using Equation E.11, one obtains the following general formula for the water/soil concentration ratio:

$$WSR_i(t) = \frac{\rho_b^{(cz)}}{\theta^{(cz)} S_i(t)} \int_0^t G_i(t,t')\ Q_i(t')\ S_i(t')\ dt' \tag{E.12}$$

where*

$WSR_i(t)$ = $W_i(t)/S_i(t)$ = water/soil concentration ratio for the i^{th} principal radionuclide at time t, the time of use (kg/m^3),

$W_i(t)$ = average concentration of the i^{th} principal radionuclide in water at the end of the water pathway segment at the point and time of use (Ci/m^3),

$S_i(t)$ = average concentration of the i^{th} radionuclide in the contaminated zone at the time of use, including contributions from ingrowth from other principal radionuclides and the decrease due to removal by radioactive decay and leaching (Ci/kg),

$\rho_b^{(cz)}$ = bulk density of the contaminated zone (kg/m^3),

$\theta^{(cz)}$ = volumetric water content of the contaminated zone (dimensionless),

$G_i(t,t')$ = nuclide water-transport function for the i^{th} principal radionuclide (1/yr),

t = time at which water is used for irrigation or drinking (yr), and

t' = time at which water leaves the contaminated zone (yr).

The volumetric water content $\theta^{(cz)}$ is discussed in Section E.1. The source term $Q_i(t')$ in Equation E.12 is the leaching ratio, defined as the

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*Note that some quantities are expressed in different units in different formulas, e.g., $WSR_i(t)$ is expressed in g/L in Equation E.1 and kg/m^3 in Equation E.5. Units of meters, kilograms, and curies are used for intermediate calculations. Units of centimeters, grams, and picocuries are generally used for input and output data or quantities that are more easily interpreted and compared when expressed in terms of these units. Conversion factors for activity concentrations and densities are 1 Ci/kg = 10^9 pCi/g, 1 Ci/m^3 = 1×10^6 pCi/cm^3, and 1 kg/m^3 = 1 g/L = 1×10^{-3} g/cm^3.

water/soil concentration ratio for the i^{th} principal radionuclide in the contaminated effluent water from the contaminated zone:

$$Q_i(t') = \theta^{(cz)} W_i^s(t')/[\rho_b^{(cz)} S_i(t')] \tag{E.13}$$

where

$W_i^s(t')$ = average volume concentration of the i^{th} principal radionuclide in effluent contaminated water at the beginning of the water pathway as it crosses the lower boundary of the contaminated zone at time t' (Ci/m^3), and

$S_i(t')$ = average concentration of the i^{th} principal radionuclide in the soil in the contaminated zone at time t', including contributions from ingrowth from other principal radionuclides and the decrease due to removal by radioactive decay and leaching (Ci/kg).

$W_i^s(t')$ can be estimated as the ratio of the source release rate $\dot{R}_i(t')$ and the water flow rate IA. That is,

$$W_i^s(t') = \dot{R}_i(t')/IA. \tag{E.14}$$

Substituting Equations E.2 and E.14 into Equation E.13 yields

$$Q_i(t') = \frac{1}{R_{d_i}^{(cz)}} . \tag{E.15}$$

Thus, the leaching ratio for a sorption-desorption, ion-exchange leaching model is a constant.

If the change in the hydrogeological environment within the time horizon is small, the nuclide water-transport function will depend only on the time difference $t - t'$, and the nuclide water-transport function will have the functional form $G_i(t,t') = G_i(t - t')$. If it is assumed that all decay products migrate at the same rate as the parent radionuclide, the nuclide water-transport function can be written as

$$G_i(t,t') = ID_i(t,t')\ g_i(t - t') \tag{E.16}$$

where

$ID_i(t,t')$ = ingrowth and decay correction factor for radionuclide i from time t' to time t (dimensionless)

$= [\sum_j S_j(0)\ ID_{ji}(t)]/[\sum_j S_j(0)\ ID_{ji}(t')]$, and

$g_i(t - t')$ = ingrowth- and decay-independent nuclide water-transport function for the i^{th} principal radionuclide (1/yr).

The term $ID_{ji}(t)$ is defined in Appendix F.

By using the source factor $SF_{ji}(t)$ (defined in Appendix F), the average concentration of the i^{th} principal radionuclide in the contaminated zone at time t can be written as

$$S_i(t) = \sum_j S_j(0)\ SF_{ji}(t) \tag{E.17}$$

In order to simplify Equation E.12, it is further assumed for the groundwater pathway that the source factor $SF_{ji}(t)$ can be replaced by an ingrowth and decay factor $ID_{ji}(t)$ and a leaching factor $L_{f_i}(t)$, that is

$$SF_{ji}(t) = ID_{ji}(t)\, L_{f_i}(t) \tag{E.18}$$

The leaching factor may be written as

$$L_{f_i}(t) = \exp(- L_i t) \tag{E.19}$$

where L_i is the leach rate for a first-order, ion-exchange leaching mechanism as defined in Section E.1.

The expression for the water/soil concentration ratios (Equation E.12) then reduces to

$$WSR_i(t) = \frac{\rho_b^{(cz)}}{\theta^{(cz)}\, L_{f_i}(t)} \int_0^t g_i(t - t')\, Q_i(t')\, L_{f_i}(t')\, dt' \tag{E.20}$$

Equation E.20 is used in this manual for deriving formulas for estimating the concentrations of radionuclides in water used for drinking or irrigation.

The general form of the nuclide water-transport function is such that, if a short pulse of contaminated water is released from the contaminated zone during the time period $0 \le t' \le \delta t'$, there will be a time interval Δt_i (the breakthrough time) before the contamination reaches the point of use. Following breakthrough, the concentration of the i^{th} radionuclide at the point of use will increase to a maximum and then decrease back to a near-zero value in a time interval δt_i. This time is referred to as the rise time because it is also the time for the contamination at the point of use to increase from zero to a maximum value when the pulse release is replaced by a steady release starting at the same time.* The pulse of contamination at the point of use may be idealized as a rectangular pulse of duration δt_i. Thus, the nuclide water-transport function may be approximated by a function of the form

$$\begin{aligned} g_i(t) &= 0, && t \le \Delta t_i \\ &= g_i, && \Delta t_i < t < \Delta t_i + \delta t_i \\ &= 0, && \Delta t_i + \delta t_i \le t \end{aligned} \tag{E.21}$$

where

Δt_i = breakthrough time for i^{th} principal radionuclide (yr),

g_i = $f_i/\delta t_i$ = rate of change of the concentration of i^{th} principal radionuclide at the point of water use for a unit input pulse (1/yr),

δt_i = rise time for i^{th} principal radionuclide (yr), and

f_i = steady-state dilution factor = ratio of average concentration of i^{th} principal radionuclide in water at the point of use to the average concentration in effluent water at the contaminated zone boundary for a steady-state release when there is no ingrowth or decay (dimensionless).

Using Equations E.15, E.20, and E.21, the time dependence of the water/soil concentration ratio for the groundwater pathway, after being

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*The rise time δt_i and the release pulse duration $\delta t'$ are independent quantities when the pulse duration is small; δt_i is determined by the transport properties of the groundwater pathway and will remain finite as $\delta t' \rightarrow 0$.

corrected for radionuclide leaching, is

$$
\begin{aligned}
WSR_i(t) &= 0, && t \le \Delta t_i \\
&= \frac{\rho_b f_i}{\theta^{(cz)} R^{(cz)}_{d_i} \delta t_i L_i} \left[1 - \exp[-\left(L_i(t - \Delta t_i)\right)]\right], && \\
& && \Delta t_i < t \le \Delta t_i + \delta t_i \\
&= \frac{\rho_b f_i}{\theta^{(cz)} R^{(cz)}_{d_i} \delta t_i L_i} \left[\exp[- L_i(t - \Delta t_i - \delta t_i)] - \exp[-\left(L_i(t - \Delta t_i)\right)]\right], && \\
& && \Delta t_i + \delta t_i < t \qquad \text{(E.22)}
\end{aligned}
$$

where the various parameters are as defined before.

If the rise time is negligibly small ($\delta t_i \approx 0$), Equation E.22 reduces to

$$
\begin{aligned}
WSR_i(t) &= 0, && t \le \Delta t_i \\
&= \frac{\rho_b^{(cz)} f_i}{\theta^{(cz)} R^{(cz)}_{d_i}} \exp\left[-\left(L_i(t - \Delta t_i)\right)\right], && \Delta t_i < t \qquad \text{(E.23)}
\end{aligned}
$$

Formulas for calculating the transport parameters (dilution factors, f_i; breakthrough times, Δt_i; and rise times, δt_i) for simple hydrogeological systems are derived in Section E.3.

E.3 WATER TRANSPORT PARAMETERS

E.3.1 On-site Groundwater Pathway

The water transport parameters for radionuclide i are the breakthrough time Δt_i (the time following the radiological survey at which radionuclides first appear in the water at the point of use), the rise time δt_i (the time following the breakthrough time for the radionuclide concentration in the water to attain a maximum value), and the dilution factor f_i (the ratio between the concentration in the water at the point of use to the concentration in the infiltrating water as it leaves the contaminated zone). Two models are used for calculating these parameters: a mass-balance (MB) model and a nondispersion (ND) model. In the MB model, it is assumed that all of the radionuclides released from the contaminated zone are withdrawn through the well. In the ND model, it is assumed that the dispersivity is nil, the unsaturated zone consists of one or more horizontal homogeneous strata, the saturated zone is single homogeneous stratum, and water withdrawal introduces only a minor perturbation in the water flow. These assumptions lead to a pattern of flow lines from which the dilution factor can be estimated by geometric considerations.

The user has the option to select which model to use. Usually, the MB model is used for smaller contaminated areas (e.g., 1,000 m^2 or less), and the ND model is used for larger areas. The breakthrough times are the same for both models; the rise times and dilution factors are different.

E.3.1.1 Breakthrough Time

The well from which water is withdrawn for domestic use or irrigation is conservatively assumed to be located either in the center of the contaminated zone (in the MB model) or at the downgradient edge of the contaminated zone (in the ND model). For either location, radionuclides are assumed to enter the well as soon as they reach the water table; hence, the transport time through the aquifer is nil and the breakthrough time is equal to the transport time through the unsaturated zone, which is the sum of the times for a radionuclide to be transported through those strata of the unsaturated zone that lie below the contaminated zone.

$$\Delta t_i = \sum_{m=1}^{n+1} \Delta t_{im}^{(uz)} \qquad \text{(E.24)}$$

where

n = number of distinct horizontal strata in the unsaturated zone below the contaminated zone at time 0, and

$\Delta t_{im}^{(uz)}$ = transport time for the i^{th} principal radionuclide through the m^{th} stratum (yr).

The upper bound, n+1, of the summation in Equation E.24 is for the $(n+1)^{th}$ unsaturated stratum created by the decrease in the water table. The thickness of this $(n+1)^{th}$ stratum, Δz_{n+1}, is equal to the product of the water table drop rate, v_{wt}, and time. That is,

$$\Delta z_{n+1} = v_{wt} \times t \qquad \text{(E.25)}$$

where v_{wt} = water table drop rate (0 m/yr).

The hydrogeological and hydrogeochemical properties of the $(n+1)^{th}$ unsaturated stratum are assumed to be the same as those of the saturated stratum. The RESRAD code allows up to five horizontal strata below the contaminated zone, i.e., $n \le 5$. If $n = 0$, the contaminated zone extends down to the aquifer.

The formula for the transport time is:

$$\Delta t_{im}^{(uz)} = \Delta z_m \, R_{d_{im}}^{(uz)} \, p_{e_m}^{(uz)} \, R_{s_m}^{(uz)}/I \qquad (E.26)$$

where

Δz_m = thickness of the mth stratum ($\Delta z_1 = 4$ m, $\Delta z_2, \ldots, \Delta z_5 = 0$)

$R_{d_{im}}^{(uz)}$ = retardation factor of the ith principal radionuclide in the mth stratum of the unsaturated zone,

$p_{e_m}^{(uz)}$ = effective porosity of the mth stratum of the unsaturated zone (0.2, dimensionless), and

$R_{s_m}^{(uz)}$ = saturation ratio of the mth stratum (0.5, dimensionless).

The unsaturated zone retardation factors, $R_{d_{im}}^{(uz)}$, are calculated by the formula

$$R_{d_{im}}^{(uz)} = 1 + \rho_{b_m}^{(uz)} \, K_{d_{im}}^{(uz)}/\left(p_{t_m}^{(uz)} \, R_{s_m}^{(uz)}\right) \qquad (E.27)$$

where

$\rho_{b_m}^{(uz)}$ = bulk soil density in the mth stratum (1.6 g/cm^3),

$K_{d_{im}}^{(uz)}$ = distribution coefficient for the ith principal radionuclide in the mth stratum (cm^3/g), and

$p_{t_m}^{(uz)}$ = total porosity of the mth stratum (0.4, dimensionless).

The saturation ratio, $R_{s_m}^{(uz)}$, can be determined using Equation E.7.

Data that may be used to estimate breakthrough times when site-specific measurements are not available are given in Tables E.2 through E.7, as follows: saturated water contents (porosities), soil-specific exponential parameters, and saturated hydraulic conductivities in Table E.2; distribution coefficients in Tables E.3 through E.6; and total porosities and effective porosities in Table E.7.

Hydraulic conductivity is a critical hydrological parameter that can differ by several orders of magnitude from one site to another. Site-specific values should be used for deriving soil guidelines. Default values of the distribution-coefficient values used in the RESRAD code are the values for soils and clays from Table E.3. The default distribution coefficient for technetium is zero. The default distribution coefficient for plutonium in Table E.3 is used for all transuranic elements. For other elements not listed in Table E.3, the default value is the value of the nearest listed element in the same column of the periodic table. If there are no other elements in the same column, a zero value is assumed.

Distribution coefficients depend strongly on soil type, the pH and Eh of the soil, and the presence of other ions (see Tables E.4 through E.6). Thus, the uncertainty introduced by using default values for the distribution coefficients can be very large. This is a critical matter, especially in those cases where the water-dependent pathways are the dominant contributors to the total dose/source concentration ratios; the single-radionuclide soil guidelines will be directly proportional to the distribution coefficients for the contaminated zone. Default values for the distribution coefficients are provided only for the purpose of obtaining preliminary estimates; site-specific values should be used for deriving soil guidelines whenever possible.

TABLE E.7 Representative Porosity Values

Material	Total Porosity, p_t Range	Total Porosity, p_t Arithmetic Mean	Effective Porosity, p_e Range	Effective Porosity, p_e Arithmetic Mean
Sedimentary Material				
Sandstone (fine)			0.02 - 0.40	0.21
Sandstone (medium)	0.14 - 0.49	0.34	0.12 - 0.41	0.27
Siltstone	0.21 - 0.41	0.35	0.01 - 0.33	0.12
Sand (fine)	0.25 - 0.53	0.43	0.01 - 0.46	0.33
Sand (medium)	-	-	0.16 - 0.46	0.32
Sand (coarse)	0.31 - 0.46	0.39	0.18 - 0.43	0.30
Gravel (fine)	0.25 - 0.38	0.34	0.13 - 0.40	0.28
Gravel (medium)	-	-	0.17 - 0.44	0.24
Gravel (coarse)	0.24 - 0.36	0.28	0.13 - 0.25	0.21
Silt	0.34 - 0.51	0.45	0.01 - 0.39	0.20
Clay	0.34 - 0.57	0.42	0.01 - 0.18	0.06
Limestone	0.07 - 0.56	0.30	~0 - 0.36	0.14
Wind-Laid Material				
Loess	-	-	0.14 - 0.22	0.18
Eolian sand	-	-	0.32 - 0.47	0.38
Tuff	-	-	0.02 - 0.47	0.21
Igneous Rock				
Weathered granite	0.34 - 0.57	0.45	-	-
Weathered gabbro	0.42 - 0.45	0.43	-	-
Basalt	0.03 - 0.35	0.17	-	-
Metamorphic Rock				
Schist	0.04 - 0.49	0.38	0.22 - 0.33	0.26

Source: Data from McWorter and Sunada (1977).

The distance from the ground surface to the water table, $D_{wt}(t)$, at time t is

$$D_{wt}(t) = C_d(t) + T(t) + \sum_{m=1}^{n+1} \Delta z_m \qquad (E.28)$$

where

$C_d(t)$ = cover depth at time t (m),

$T(t)$ = thickness of contaminated zone at time t (m), and

Δz_m is as defined in Equations E.25 and E.26.

When the RESRAD code is being run, the code will check Equation E.28 for the accuracy of the input data. If Equation E.28 is not satisfied for t = 0 -- i.e., incorrect input data for $D_{wt}(0)$, $C_d(0)$, $T(0)$, or Δz_m -- the user will have to modify the input data before the code can be executed. In the current version of RESRAD, the water table is assumed to be below the contaminated zone, i.e., $D_{wt}(0) \geq C_d(0) + T(0)$.

E.3.1.2 Rise Time

When the well is located at the downgradient edge of the contaminated zone, as shown in Figure E.1 (i.e., if the ND model is used), the rise time is given by the formula

$$\begin{aligned} \delta t_i &= \tau_{\ell_i}, && \zeta \leq d_w,\ D_{wt}(t) \geq C_d(t) + T(t) \\ &= \tau_{\ell_i}/(\zeta/d_w), && \zeta > d_w,\ D_{wt}(t) \geq C_d(t) + T(t) \\ &= 0, && D_{wt}(t) < C_d(t) + T(t) \end{aligned} \qquad (E.29)$$

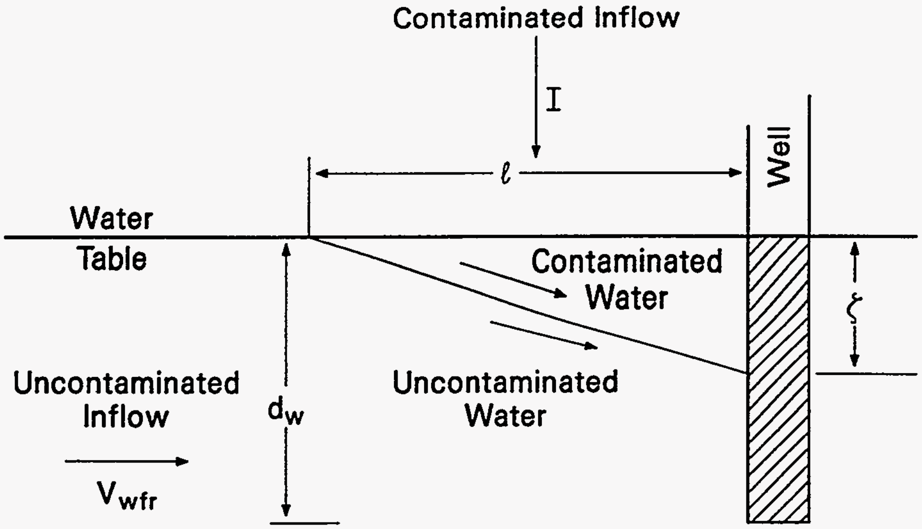

FIGURE E.1 Dilution of Contaminated Inflow by Uncontaminated Inflow in the Nondispersion Model for a Well Adjacent to the Contaminated Area

where

$\zeta = (I/V_{wfr})\ell$ = distance from water table to lower boundary of contamination in aquifer at the downgradient edge of the contaminated zone (m),

I = infiltration rate (m/yr),

J_x = hydraulic gradient (0.02, dimensionless),

$K_s^{(sz)}$ = saturated hydraulic conductivity of saturated zone (100 m/yr),

ℓ = length of contaminated zone parallel to the hydraulic gradient (maximum distance from upgradient edge to downgradient edge parallel to the hydraulic gradient, 100 m),

d_w = distance of well intake below the water table (10 m),

$\tau_{\ell_i} = p_e^{(sz)} R_{d_i}^{(sz)} \ell / V_{wfr}$ = time for the ith principal radionuclide to be transported from the upgradient edge to the downgradient edge of the contaminated zone (yr),

$R_{d_i}^{(sz)}$ = retardation factor for the i^{th} principal radionuclide in the saturated zone (dimensionless), and

$p_e^{(sz)}$ = effective porosity of aquifer (0.2, dimensionless).

Equation E.29 is used only in the ND model. Representative porosities are given in Tables E.2 and E.7. The infiltration rate is given by Equation E.4. Representative saturated hydraulic conductivities are given in Table E.2. Representative distribution coefficients are given in Tables E.3 through E.6.

If the well is in the center of the contaminated zone (i.e., if the MB model is used), the rise time is assumed to be zero. That is, for the MB model,

$$\delta t_i = 0 \ . \tag{E.30}$$

E.3.1.3 Dilution Factor

It is assumed that the water flow is vertically downward from the bottom of the contaminated zone to the water table; hence, no dilution will occur in the unsaturated zone. The dilution in the saturated zone is estimated using the conservative assumption that the dispersivity is zero.

The dilution factor for the MB model is a radionuclide-independent factor given by the formula

$$\begin{aligned} f_i &= A\ I/U_w, & A\ I &< U_w \\ &= 1, & A\ I &\geq U_w \end{aligned} \tag{E.31}$$

where

A = area of contaminated zone (m^2),

I = infiltration rate (m/yr), and

U_w = annual volume of water withdrawn from well for use by a single individual (150 m^3/yr).

The infiltration rate is calculated by Equation E.4.

For a well located at the downgradient edge of the contaminated zone, the dilution factor for the ND model is given by the formula

$$\begin{aligned} f_i &= \zeta/d_w, \qquad && \zeta < d_w \\ &= 1, && \zeta \geq d_w, \end{aligned} \tag{E.32}$$

where the parameters are as defined for Equation E.29.

The dilution factors for a well that is located away from the edge of the contaminated zone can be significantly smaller than dilution factors estimated by Equations E.31 and E.32 for a well located in or immediately adjacent to the contaminated zone. The one-dimensional models used to obtain Equations E.31 and E.32 cannot be used to estimate this reduction; a two- or three-dimensional model, such as the FEWA and FEMA codes developed by Yeh and Huff (1983, 1985), must be used to estimate a more realistic dilution factor. In addition, the assumption of no dispersivity may be unnecessarily conservative if the well is not located very close to the contaminated zone.

E.3.2 Surface Water Pathway

The surface water pathway will consist of an on-site groundwater pathway segment that extends to the edge of the contaminated zone, an off-site groundwater pathway segment that extends from the edge of the contaminated zone to a location where surface seepage occurs, and a surface water segment in which the contaminated groundwater is mixed with uncontaminated surface water. Contamination of the surface water can also occur as a consequence of erosion as contaminated soil is deposited in a nearby streambed or pond. This pathway is not included in the current version of RESRAD.

The derived water transport parameters for the surface water pathway are identified by primes -- $\Delta t_i'$, $\delta t_i'$, and f_i' -- in order to distinguish them from the corresponding groundwater pathway parameters -- Δt_i, δt_i, and f_i.

E.3.2.1 Breakthrough Time

The breakthrough time for the surface water pathway is assumed to be the same as that for the groundwater pathway, i.e.,

$$\Delta t_i' = \Delta t_i \tag{E.33}$$

where Δt_i is calculated using Equations E.24 through E.27.

E.3.2.2 Rise Time

The rise time for the surface water pathway is assumed to be the same as that used in the ND model for the groundwater pathway, i.e.,

$$\delta t_i' = \delta t_i \tag{E.34}$$

where δt_i is given by Equation E.29.

E.3.2.3 Dilution Factor

The dilution factor for the surface water pathway is based on the assumption that the surface water is a pond and (1) the inflow and outflow for the pond are in steady-state equilibrium and (2) the annual inflow of radioactivity into the pond is equal to the annual quantity of radioactivity leached from the contaminated zone. With these assumptions, the dilution factor is the ratio of the annual volume of water that percolates through the contaminated zone to the annual total inflow of water into the pond. If, in addition, it is assumed that the infiltrating water flow is vertically downward, the dilution factor is given by the formula

$$f_i' = A/A_w \tag{E.35}$$

where

A = area of contaminated zone (10^4 m^2) and

A_w = area of watershed (10^6 m^2).

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APPENDIX F

SOURCE FACTORS

APPENDIX F: SOURCE FACTORS

The time dependence of dose/source ratios due to radioactive ingrowth and decay and infiltration leaching is taken into account by introducing source factors, $SF_{ij}(t)$. Radionuclides are divided into two groups: those with half-lives longer than 1 year (principal radionuclides) and those with half-lives of 1 year or less (associated radionuclides) (see Table 3.1). It is assumed that the associated radionuclides are in secular equilibrium with their principal radionuclide and that the leach rate of the associated radionuclides is the same as the leach rate of their principal radionuclide. Hence, only the source factors for the principal radionuclides need to be calculated.

Let $S_{ii}(0)$ be the initial concentration of the i^{th} principal radionuclide and let $S_{ij}(t)$ be the concentration at time t of the j^{th} principal radionuclide that results from ingrowth from the initial inventory of the i^{th} principal radionuclide. $S_{ii}(t)$ is the concentration of the undecayed portion that is available for leaching of the i^{th} principal radionuclide. [$S_{ii}(t)$, which does not include any contribution from ingrowth, should be distinguished from $S_i(t) = \sum_j S_{ji}(t)$, which does include the contribution from ingrowth.] $S_{ij}(0) = 0$ unless $i = j$, and $S_{ij}(t) = 0$ unless $i = j$ or the j^{th} principal radionuclide is a decay product of the i^{th} principal radionuclide. The source factor is defined as

$$SF_{ij}(t) = S_{ij}(t)/S_i(0) \tag{F.1}$$

The initial values of the source factors are $SF_{ij}(0) = 0$ unless $i = j$, and $SF_{ii}(0) = 1$. For $t > 0$, $SF_{ij}(t) = 0$ unless $i = j$ or the j^{th} principal radionuclide is a decay product of the i^{th} principal radionuclide. When $i = j$, the inequality $1 > SF_{ii}(t) > 0$ will be satisfied for $t > 0$.

The source factor is a correction factor for the source term (radionuclide concentration in the contaminated zone), which includes the contribution from ingrowth and the removal due to radioactive decay and leaching. If leaching is negligible, the source factor reduces to a factor that accounts for ingrowth and decay only. This factor is called the ingrowth-and-decay factor, $ID_{ij}(t)$.

Formulas for calculating source factors and ingrowth-and-decay factors are given below. Because all of the branching radionuclides are associated radionuclides and the longest half-life is 18.7 days (see Table 3.1), the branching radionuclides are assumed to be in equilibrium with their principal radionuclide. Thus, branching need not be considered in deriving source factors and ingrowth-and-decay factors.

The equation for ingrowth and decay and leaching of a nonbranching chain, assuming a first-order ion-exchange leaching (see Appendix E), is

$$dA_k/dt = \lambda_k A_{k-1} - (\lambda_k + L_k) A_k \tag{F.2}$$

where

A_k = activity concentration of the k^{th} radionuclide in the chain (pCi/g),

$\lambda_k = \ell n(2)/T_{\frac{1}{2},k}$ = radioactive decay constant of the k^{th} radionuclide (yr^{-1}),

$T_{\frac{1}{2},k}$ = radioactive decay half-life of the k^{th} radionuclide (yr), and

L_k = leach rate of the k^{th} radionuclide (yr^{-1}); the radionuclide leach rate is defined in Appendix E (Equation E.3).

The solution to Equation F.2 is

$$A_k(t) = \sum_{\ell=0}^{k} a_{k\ell} \times \exp[-(\lambda_\ell + L_\ell)t] \tag{F.3}$$

where

$$a_{00} = A_0(0);$$

$$a_{k\ell} = [\lambda_k/(\lambda_k + L_k - \lambda_\ell - L_\ell)]\, a_{k-1,\ell}\,, \qquad \ell = 0,1,\ \ldots,\ k-1;\ \text{and}$$

$$a_{kk} = A_k(0) - \sum_{\ell=0}^{k-1} a_{k\ell}.$$

The source factor $SF_{ij}(t)$ can be calculated as

$$SF_{ij}(t) = A_{\ell(ij)}(t)/A_0(0) \tag{F.4}$$

where $\ell(ij)$ is the sequence number for the j^{th} principal decay product of the i^{th} principal radionuclide, numbered from the i^{th} principal radionuclide [$\ell(ii) \equiv 0$]. The ingrowth-and-decay factor $ID_{ij}(t)$ is the source factor $SF_{ij}(t)$ when the leach rates L_ℓ and L_k are set to zero.

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