

GENII Version 2 NESHAPS Software Design Document

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June 2005

Prepared for
U.S. Environmental Protection Agency
under Contract DE-AC05-76RLO 1830

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PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

GENII NESHAPS SOFTWARE DESIGN DESCRIPTION

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1.0 INTRODUCTION

This report describes the mathematical formulations and implementation structure for version 2 of the GENII software product, NESHAPS edition (GENII V2 NESHAPS). The following sections define the purpose and scope of this report, the framework operating structure for GENII V2 NESHAPS, and definitions and acronyms used in this report.

1.1 PURPOSE

The purpose of this document is to describe the architectural design for the GENII V2 NESHAPS software package. This document defines details of the overall structure of the software, the major software components, their data file interfaces, and specific mathematical models to be used. The design represents a translation of the requirements (Napier et al. 1995) into a description of the software structure, software components, interfaces, and necessary data. The design focuses on the major components and data communication links that are key to the implementation of the software within the operating framework.

The intended audience for this design report is the Pacific Northwest National Laboratory (PNNL) software development team, independent reviewers, testing team, users, and project and line management who need a thorough understanding of the software capabilities.

1.2 SCOPE

The GENII V2 NESHAPS software package has been developed for the Environmental Protection Agency, Office of Radiation and Indoor Air.

The software has two distinct user groups:

- 1) staff of EPA who will use the software frequently to perform analyses,
- 2) a large group of occasional users who may be required to perform analyses with the software.

All users are assumed to be competent in the areas of health physics and environmental analysis, with some basic familiarity with use of computers.

The purpose of the GENII V2 NESHAPS software package is to provide the capability to perform dose and risk assessments of chronic releases of radionuclides to the atmosphere. This report represents a detailed description of the capabilities of the software product with exact specifications of mathematical models that form the basis for the software implementation and testing efforts.

This report also presents a detailed description of the overall structure of the software package, details of main components (implemented in the current phase of work), details of data communication files, and content of basic output reports.

1.3 FRAMEWORK OPERATING STRUCTURE

The components of GENII V2 NESHAPS have been developed to operate within the Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES). An overview of this software concept is provided by Whelan et al. (1997). FRAMES is an open-architecture, object-oriented system that allows the user to choose the most appropriate models to solve a particular simulation problem. The components of GENII V2 NESHAPS are implemented through FRAMES by meeting requirements for data input and output file specifications defined for FRAMES. Details of FRAMES and implementation of the GENII V2 NESHAPS components is described in Section 2.

1.4 DEFINITIONS AND ACRONYMS

Definition of terms, acronyms, and abbreviations used in this report are defined below. Many of the technical term definitions are based on definitions provided in the glossary of Kennedy and Strenge (1992).

Absorbed dose - The energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray (Gy).

Activity - The rate of disintegration (transformation) or decay of radioactive material. The units of activity are the curie (Ci) and the becquerel (Bq).

Acute release - the release of material to the air or surface water over a brief period, assumed in the models to be on the order of a few hours.

ASCII - American Standard Code for Information Interchange, a set of codes used in data communications.

Bq - Abbreviation for becquerel, a unit of activity.

Chronic release - a release of material to the air or surface water that continues essentially uniformly over a long period, taken in the models to be a year.

Ci - Abbreviation for curie, a unit of activity.

Class (or "lung class" or "inhalation class") - A classification scheme for inhaled material according to its rate of clearance from the pulmonary region of the lung. Materials are classified as F, M, or S (previously D, W, or Y), and apply to a range of clearance half-times for F (Fast) of less than 10 days, for M (Medium) from 10 to 100 days, and for S (Slow) of greater than 100 days.

Collective dose - The sum of the individual doses received in a given period of time by a specified population from exposure to a specified source of radiation.

Committed dose equivalent ($H_{T,50}$) - The equivalent dose to organs or tissues of reference (T) that will be received from an intake of radioactive material by an individual during the 50-year period following the intake.

Committed effective dose equivalent ($H_{E,50}$) - The sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated by internally deposited radionuclides and the committed equivalent dose to these organs or tissues ($H_{E,50} = \sum w_T H_{T,50}$)

Database - A collection of logically organized information provided in support of a software program.

Dose or "radiation dose" - A generic term that means absorbed dose, equivalent dose, effective dose, committed dose equivalent, or committed effective dose equivalent.

Dose conversion factor - a precalculated multiplier that translates activity ingested or inhaled into absorbed dose, equivalent dose, or effective dose.

Dose equivalent - see Equivalent dose.

Effective dose (H_E) - The sum of the products of the dose equivalent to the organ or tissue (H_T) and the weighting factors (w_T) applicable to each of the body organ or tissues that are irradiated ($H_E = \sum w_T H_T$)

Effective dose equivalent (H_E) - see Effective dose.

Equivalent dose (H_T) - The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. The units of equivalent dose are the rem and sievert (Sv).

Exposure - Being exposed to ionizing radiation or to radioactive material.

External dose - That portion of the equivalent dose received from radiation sources outside of the body.

FRAMES - Framework for Risk Analysis in Multimedia Environmental Systems, a software platform for construction conceptual site models and linking software to perform environmental transport and health risk assessments.

Gray (Gy) - The SI unit of absorbed dose. One gray is equal to an absorbed dose of 1 joule/kg (100 rads).

GENII - Acronym for the "GENeration II" computer programs developed at Hanford (Napier et al. 1988). Includes by implication the GENII-S stochastic version prepared at Sandia National Laboratories (Leigh et al. 1992).

GENII V2 NESHAPS - Acronym for the version 2 of GENII developed for the EPA for showing compliance with the Clean Air Act and documented in this report.

ICRP - International Commission on Radiological Protection

Internal dose - That portion of the equivalent dose received from radioactive material taken into the body.

JFD - Acronym for Joint Frequency Data; information on the joint probability of occurrence of windspeed, direction, and atmospheric stability class.

Member of the public - An individual in an uncontrolled or unrestricted area. However, an individual is not a member of the public during any period in which the individual receives an occupational dose.

Pathway - The potential routes through which people may be exposed to radiation or radioactive materials. Typical radiation exposure pathways include external exposure to penetrating radiation, inhalation of airborne materials, and ingestion of materials contained in surface contamination, food products, or drinking water.

Public dose - The dose received by a member of the public from exposure to radiation and to radioactive materials in unrestricted areas. It does not include occupational dose, or dose received from natural background, as a patient from medical practices, or from voluntary participation in medical research programs.

Rad - The special unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs/g or 0.01 joule/kg (0.01 gray).

Radiation (ionizing radiation) - Alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, high-speed photons, and other particles capable of producing ions. Radiation, as used here, does not include non-ionizing radiation, such as sound, radio, or microwaves, or visible, infrared, or ultraviolet light.

Reference man - A hypothetical aggregation of human physical and physiological characteristics arrived at by international consensus. These characteristics may be used by researchers and public health workers to standardize results of experiments and to relate biological insult to a common base.

Rem - The special unit of equivalent dose. The equivalent dose in rem is equal to the absorbed dose in rad multiplied by the quality factor (1 rem = 0.01 Sv).

Risk conversion factor - a precalculated multiplier that translates activity ingested or inhaled into expected likelihood of effect.

Scenario - A combination of radiation exposure pathways used to model conceptually the potential conditions, events, and processes that result in radiation exposure to individuals or groups of people.

Sievert - The SI unit of equivalent dose. The equivalent dose in sieverts is equal to the absorbed dose in grays multiplied by the quality factor (1 Sv = 100 rem).

Software - A sequence of computer-readable instructions suitable for processing by a computer. Same as program and code.

Software Requirement Specification (SRS) - Documentation of the essential requirements (functions, performances, design constraints, and attributes) of the software and its external interfaces (ANSI/IEEE Standard 730-1983).

STAR - Acronym for Stability Array; a standard available format for meteorological summary data.

Sv - Abbreviation for sievert.

Weighting factor, w_T , for an organ or tissue (T) - The proportion of the risk of stochastic effects resulting from irradiation of that organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly.

1.5 REFERENCES FOR SECTION 1

Kennedy, W. E., Jr., and D. L. Streng. 1992. *Residual Radioactive Contamination from Decommissioning: Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent*. NUREG/CR-5512, Vol. 1. U.S. Nuclear Regulatory Commission, Washington, DC.

Leigh, C. D., B. M. Thompson, J. E. Campbell, D. E. Longsine, R. A. Kennedy, and B. A. Napier. 1992. *User's Guide for GENII-S: A Code for Statistical and Deterministic Simulations of Radiation Doses to Humans from Radionuclides in the Environment*. SAND91-0561A. Sandia National Laboratories, Albuquerque, NM.

Napier, B. A., R. A. Peloquin, D. L. Streng, and J. V. Ramsdell. 1988. *HANFORD ENVIRONMENTAL DOSIMETRY UPGRADE PROJECT. GENII - The Hanford Environmental Radiation Dosimetry Software System. Volume 1: Conceptual Representation, Volume 2: Users' Manual, Volume 3: Code Maintenance Manual*. PNL-6584, Vols. 1-3, Pacific Northwest Laboratory, Richland, Washington.

Napier, B.A., J.V. Ramsdell, and D.L. Streng. *Software Requirements Specifications for Hanford Environmental Dosimetry Coordination Project*. May 1995 Draft Report. Prepared for review by the EPA Office of Radiation and Indoor Air.

Whelan, G. K. J. Castleton, J. W. Buck, G. M. Gelston, B. L. Hoopes, M. A. Pelton, D. L. Streng, and R. N. Kickert. 1997. *Concepts of a Framework for Risk Analysis In Multimedia Environmental Systems (FRAMES)*. PNNL-11748. Pacific Northwest National Laboratory, Richland WA.

2.0 SOFTWARE STRUCTURE

This section describes the overall structure of the FRAMES and GENII V2 NESHAPS software packages and provides general information on the purpose and content of the various components.

The controlling component is the FRAMES software package. This package has a framework user interface (FUI) that serves as the primary interface with the user. The FUI allows the user to select specific calculational components to be included in the analysis, select radionuclides, view intermediate and result files, prepare result charts, and perform uncertainty and sensitivity analyses. The framework allows the user to select specific components to be included in an analysis. The general component analyses available under FRAMES are as follows:

- Contaminant Database
- Source Term Definition/Estimation
- Vadose Zone Transport
- Aquifer Transport
- Surface Water Transport
- Overland Transport
- Atmospheric Transport
- Exposure Pathways
- Receptor Intake
- Health Impact Estimation
- Sensitivity/Uncertainty Analysis
- Report Generation

These components represent the building blocks of an analysis from which the user selects in developing a case for analysis. The calculational software for each of these components is not part of the FRAMES software package. In order to be able to perform an analysis, the user must have available calculational software for the components to be included. The original GENII program (Napier et al. 1988) has been revised to be represented by calculational components that can be exercised under the control of FRAMES. The GENII V2 NESHAPS software package provides calculational software for the following components:

- Source Term Definition
- Atmospheric Transport
- Exposure Pathways
- Receptor Intake
- Health Impact Estimation
- Selected report generation

The GENII V2 NESHAPS software package does not include calculational software for vadose zone, overland transport, surface water, or aquifers.

To perform an analysis, the user selects the components to be included in an analysis, provides necessary input data (via the user interfaces), and runs each component. Some of these components may be applied one or more times in an analysis.

For example, the environmental transport via atmosphere may actually be represented by several source units, each of which may have a separate atmospheric transport component, followed by the environmental accumulation and individual exposure calculational components selected for each.

The FUI allows the user to setup an analysis and specify the calculational components to be used. The FRAMES software package also has a radionuclide database, help information, global input data (GID) file, and file specifications for primary data communication files (PDCFs). Summary descriptions of each of these components/files follow. The components and communication links are indicated schematically in Figure 2.1. This figure shows the primary screen for the framework user interface with example modules to illustrate the possible connections. Primary communication data files are indicated showing their use to transfer information between specific modules.

2.1 FRAMEWORK USER INTERFACE

The framework user interface (FUI) controls the overall interface with the user and execution of specific components. A series of well-ordered screens is used to step the user through the process of problem definition and selection of options for setting up the analysis. As may be required for each of the selected options, the FUI activates other user interfaces to control input of parameters for user selected GENII V2 NESHAPS calculational components. The control of input for each component is performed by module user interface (MUI) programs. The MUI's are specific to the software package (e.g., GENII V2 NESHAPS) and have capabilities defined by the developers of the specific package. The GENII V2 NESHAPS components all have help files defining the parameters pertinent to the specific component.

2.2 PRIMARY DATA COMMUNICATION FILES (PDCF)

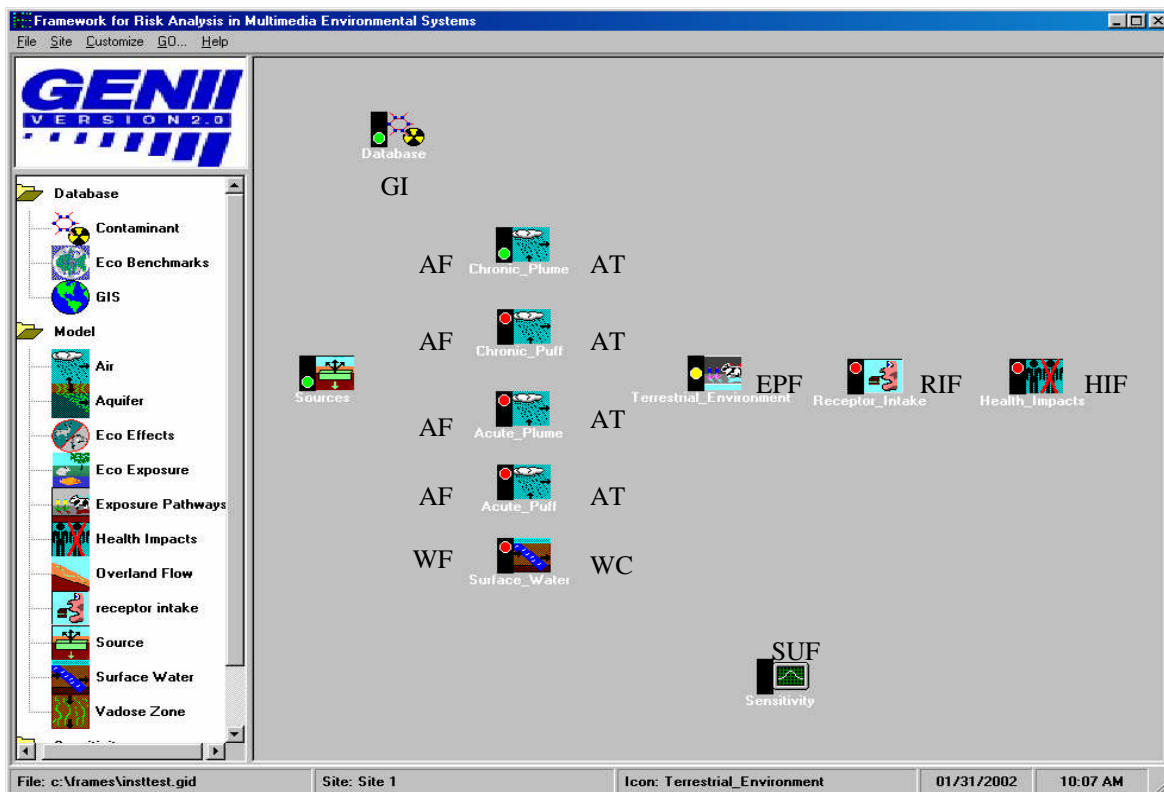
The Primary Data Communication Files are basic files for transferring information between specific calculational components. Files of this type included under FRAMES (and whether they are included in the NESHAPS edition of GENII) are:

<u>File Content</u>	<u>Extension</u>	<u>Extension Acronym</u>	<u>In NESHAPS?</u>
Soil concentration	SCF	Soil Concentration File	No
Flux to air	AFF	Air Flux File	Yes
Flux to surface water	WFF	Water Flux File	No
Air transport output	ATO	Air Transport Output	Yes
Water concentration	WCF	Water Concentration File	No
Exposure pathway concentrations	EPF	Exposure Pathway File	Yes
Receptor Intake	RIF	Receptor Intake File	Yes
Health Impacts	HIF	Health Impacts File	Yes
Sensitivity analysis inputs	SUF	Sensitivity/Uncertainty File	No

Figure 2.1 illustrates use of each of these files as communication links between specific modules. The content and format of these files is defined by the requirements of the FRAMES software package. The calculational components must read and write information consistent with these defined requirements. The user cannot modify PDCF content or format. Definition of the PDCF file content and format has been based on careful consideration of purpose and capabilities of each component. The specifications for the PDCF files are given in Appendix A.

The purpose of the PDCFs can be thought of as following the activity of the radionuclides from the source, through the environment to the exposed individual or population, and then through evaluation of the risk from exposure. The PDCFs, therefore, contain information related to the radionuclides and their amounts in various media along the path of the analysis. The PDCFs will typically not contain parameter values that are specific to a few mathematical models, but not to all models. The PDCFs are generated by the calculational components to provide information to subsequent components. The PDCFs can be generated by calculational components or supplied by users external to components available under the framework user interface.

Figure 2.1. The primary FRAMES interface screen showing GENII icons and file types



2.3 GENII V2 NESHAPS CALCULATIONAL MODULES

The calculational modules provide the user with ability to evaluate specific components of the analysis. The GENII V2 NESHAPS software package contains calculational modules for the following components.

- Source Term Definition
- Atmospheric Transport
- Exposure Pathways
- Receptor Intake
- Health Impact Estimation

Summaries of each of these calculational components follow.

2.3.1 GENII V2 NESHAPS Source Term Definition Module

The radionuclide source term is defined using the “User Defined” source term module provided with the GENII V2 NESHAPS software package. This module allows the user to define the release rates to the atmosphere (for the atmospheric transport modules). The output from the source term module is written to primary data communication file (PDCF) as the air flux file (AFF) for coupling to the atmospheric transport modules. Parameters defined by the user through the source term module user interface are also saved in the global input data file in a section for the source term module. No auxiliary input or output files are used or generated by the source term module.

2.3.2 GENII V2 NESHAPS Atmospheric Transport Module

The GENII V2 NESHAPS software package contains a calculational program for the atmospheric transport component. This is a plume-based program for chronic releases. The code accounts for the transport, diffusion, deposition, depletion, and decay of radionuclides while in the atmosphere. Input to the model is the air release rate supplied in the air flux file (AFF), and output is to the air transport output (ATO) file. Additional input of meteorological data is through an auxiliary data file.

The chronic plume module uses the sector-averaged straight-line Gaussian plume model. The mathematical formulations for this modules are provided in Section 4.0.

2.3.3 GENII V2 NESHAPS Exposure Pathways Modules

The exposure pathway module is provided in the GENII V2 NESHAPS software package. The chronic exposure component allows evaluation of exposure from routine releases to air.

The chronic exposure model is used to evaluate exposures over extended periods of media contamination. Transport may be via the atmosphere. Exposure pathways

linked to the chronic exposure model are those associated with air exposure (inhalation and external exposure), contact with soil following atmospheric deposition, resuspension of surface soil, and agricultural pathways contaminated by airborne deposition. Exposure to agricultural products is evaluated assuming the deposition occurs uniformly over annual periods, with deposition rates defined as a function of time from atmospheric concentration files (ATO).

The input to the chronic transport module is read from air concentration files (ATO). Output from the module is the annual average exposure media concentration for each exposure pathway for the user-defined exposure duration, and written to the exposure pathway file (EPF). The mathematical formulations for the chronic exposure module are provided in Section 5.0.

2.3.4 GENII V2 NESHAPS Receptor Intake Module

The receptor intake module uses the exposure media concentration values from the exposure pathway module to estimate the intake by the exposed individual(s). The intake is represented as the total activity taken in (via inhalation or ingestion). For external exposure pathways, the result is expressed as the average concentration in the exposure media over the exposure duration, corrected for any appropriate modification factors (e.g., occupancy fraction by the exposed individual). Several user-defined age groups may be used. Results of the analysis are written to the receptor intake file (RIF). The mathematical formulations for the receptor intake module are provided in Section 6.0.

2.3.5 GENIIV2 Health Impact Module

The health impacts from the receptor intake module are converted to estimates of radiation or health impacts by the health impacts module. The user may choose the method for evaluation of health impacts and the endpoint of interest (e.g. radiation dose, cancer incidence, cancer fatality, etc). Results may be calculated and reported by organ or cancer site. Output from this module is written to the health impacts file (HIF). The mathematical formulations for the health impacts module are provided in Section 7.0.

2.4 GLOBAL INPUT DATA FILE

The global input data file (GID) contains values for all parameters required by FRAMES, and for each component selected by the user to be included in the analysis. The parameters for FRAMES are automatically added to the GID as the user defines the scope of the analysis and selects contaminants to be considered. The parameters for each selected component are added by the user interface for the component. Under normal operating conditions, the user will not need to access or view the GID. The specifications for the GID file are given in Appendix A.

2.5 AUXILIARY DATA INPUT/OUTPUT FILES (ACDFs)

Each calculational component may require special input files and may generate output files that are in addition to the primary data communication files. The definition and use of the auxiliary files is up to the software developer.

The ACDFs are typically component specific and will vary between calculational components for a specific analysis. For example, if three calculational components are available for estimation of chronic atmospheric transport, it is likely that each of the components will require ADFs with different content and structure. However, all three of the components must be capable of generating output in the same form defined for the PDCFs for the next component (chronic terrestrial and aquatic transfer and accumulation module).

Examples of ACDFs used in the GENII V2 NESHAPS components are atmospheric data files used by the various atmospheric transport models, and dose rate and risk conversion factors used in the calculation of impact. More information on GENII V2 NESHAPS specific ACDFs is provided in Section 3.

2.6 REFERENCE FOR SECTION 2

Napier, B. A, R. A. Peloquin, D. L. Streng, and J. V. Ramsdell. 1988. *HANFORD ENVIRONMENTAL DOSIMETRY UPGRADE PROJECT. GENII - The Hanford Environmental Radiation Dosimetry Software System. Volume 1: Conceptual Representation, Volume 2: Users' Manual, Volume 3: Code Maintenance Manual.* PNL-6584, Vols. 1-3, Pacific Northwest Laboratory, Richland, Washington.

3.0 AUXILIARY DATA COMMUNICATION FILES (ADCF)

The auxiliary data communication files (ADCFs) contain input parameter values for specific components. The format and content of the ADCFs are defined by the developer of the specific component and include information necessary to exercise the models of the component. ADCFs defined for GENII V2 NESHAPS are described in this section. The use of ADCFs has been minimized by placing as much data as possible into the global input data file (GID). This is desirable because the GID is intended to contain all data necessary to perform an analysis.

3.1 AUXILIARY DATA COMMUNICATION FILE SUMMARIES

The ADCFs necessary for the components implemented in GENII V2 NESHAPS are summarized in Table 3.1. Summaries of each ADCF are given in the following sections, with detailed file descriptions given in Appendix B.

3.2 RADIONUCLIDE MASTER DATA FILE

The radionuclide master data library (RMDLIB.DAT) contains all radiological decay data in addition to the specification of all radionuclides for which data is included in the GENII V2 NESHAPS software system. The radionuclides are organized into decay chains ordered by atomic number under the radionuclides highest in the chain. The data in this file are used by the chain decay processor to account for radioactive decay and progeny ingrowth with time. RMDLIB.DAT currently contains information on 839 explicit radionuclides. Decay of a number of very short-lived radionuclides within the decay chains of longer-lived radionuclides is also considered. The criteria for inclusion in RMDLIB.DAT as an explicitly considered chain member include a half-life greater than 10 minutes.

The file is provided with the software package and is not intended to be modified. However, a knowledgeable user should be able to modify the file (to add, delete, or change decay chain representation) using an ASCII file editor, as long as comparable changes are made to the GENII v2 NESHAPS database with the database editor. The content and structure of the file is described in Appendix B.

3.3 METEOROLOGICAL DATA

Because of the specialized nature of this input data, the file formats are discussed separately in Appendix B of the GENII V2 NESHAPS Users' Guide. Automated utility codes are provided to take meteorological data from several common sources and put it into the necessary format for GENII V2 NESHAPS input.

Appendix B to the GENII Users' Guide describes the use of hourly and joint frequency data in multiple formats, and the structure of the library of air submersion dose coefficients (cloud shine doses) CSHNLIB.DAT.

Table 3.1 Summary of ADCFs for GENII V2 NESHAPS

<u>File Description</u>	<u>Components using file</u>
Radionuclide master data - RMDLIB.DAT	Atmospheric Transport Exposure Pathways Receptor Intake Health Impacts
Meteorological data – Site specific hourly data Site specific joint frequency data Air submersion dose rate data	Atmospheric transport
Radon working level output	Receptor Intake
Radiation factor index file – FGR13PAK.NDX	Health Impacts
Radiation External dose rate factors Air submersion - F12TIII1.EXT Water immersion - FGR12F32.DAT Soil surface - F12TIII3.EXT Soil volume - F12TIII7.EXT	Health Impacts
Radiation internal dose conversion factors Inhalation – FGR13INH.HDB Ingestion – FGR13ING.GDB	Health Impacts
Radiation exposure risk factors Inhalation - FGR13INH.RBS Ingestion - FGR13ING.RBS External – FGR13EXT.RBS	Health Impacts

3.4 DOSIMETRY/RISK FILES

The GENII V2 NESHAPS options for calculating radiation dose are quite complex, and a large amount of radionuclide/pathway/age specific data is required. Because the calculation of dose and risk using ICRP Publication 26 and 30 (ICRP 1979 - 1982), calculation of risk using EPA slope factors (EPA 1997), and calculation of dose and risk using ICRP Publication 60 and 72 (ICRP 1990; ICRP 1997) and Federal Guidance Report 13 (Eckerman et al.1998) factors are essentially redundant, much of the data are required in separate formats. The calculation capabilities for the ICRP26/30 and EPA slope factor methods are derived from parallel capabilities in the MEPAS code system (Whelan et al. 1992), and so the data are available within the FRAMES system. The ICRP-60 and Federal Guidance Report 13 methods are derived from methods developed for EPA at Oak Ridge National Laboratory, and use that file structure.

3.4.1 Radiation Dose Factor Index File

The dose and risk factors provided with the GENII V2 NESHAPS system were developed at Oak Ridge National Laboratory for Federal Guidance Report 13 (Eckerman et al. 1998). The internal (inhalation and ingestion) age-dependent dose conversion factors are the basis of those found in ICRP Publications 60 through 72. Because the development of the files containing these factors was independent of the RMDLIB.DAT file, the file structure differs from that of the rest of the GENII V2 NESHAPS files. The file FGR13PAK.NDX allows the GENII V2 NESHAPS system to have direct access to the dose and risk files. This file has radionuclide identifiers, half-life information, and cross-reference line numbers for the remaining data files.

3.4.2 External Dose Rate Conversion Factor Files

The data files F12TIII1.EXT, F12TIII3.EXT, and F12TIII7.EXT contain factors that relate radionuclide concentrations in air, soil surface, and soil volume, respectively, to dose rate. Each of these files is parallel in structure and size; each radionuclide line number is identified in the index file FGR13PAK.NDX described above. Each of these files provides dose conversion factors for 24 human body organs and tissues.

The data file FGR12F32.DAT is a file parallel in structure to the three taken from Federal Guidance Report 12 but containing external dose rate factors for submersion in contaminated water (a pathway not included in FGR 12). This data set was added to give GENII V2 NESHAPS the capability of handling these types of exposure, requiring the modification of the file reading software appropriately. This file is not explicitly used for GENII V2 NESHAPS, but is required for successful operation of the code.

These files are provided with the GENII V2 NESHAPS software package, and each is used by the health impacts calculational component. Data are provided for more radionuclides than are explicitly listed in RMDLIB.DAT – however, many are considered to be implicit progeny radionuclides within the RMDLIB.DAT structure. The GENII V2 NESHAPS health risk component accounts for the decay energies of the implicit progeny in the dose rate factor assigned for the explicit parent radionuclides. The content and structure of the files are described in Appendix B.

3.4.3 Internal Dose Conversion Factor Files

The files FGR13ING.GDB and FGR13INH.HDB contain age dependent radiation dose factors for the pathways of ingestion and inhalation. Each of these files is parallel in structure and size; each radionuclide line number is identified in the index file FGR13PAK.NDX described above. Each of these files provides dose conversion factors for 24 human body organs and tissues. The ingestion file further provides information subdivided by the potential GI-tract uptake fraction (f1) for each radionuclide. The inhalation file provides information subdivided by the ICRP lung model retention classes F, M, and S (fast, medium, and slow clearance rates).

These files are provided with the GENII V2 NESHAPS software package, and each is used by the health impacts calculational component. Data are provided for more radionuclides than are explicitly listed in RMDLIB.DAT – however, many are considered to be implicit progeny radionuclides within the RMDLIB.DAT structure. The GENII V2 NESHAPS health risk component accounts for the decay energies of the implicit progeny in the dose rate factor assigned for the explicit parent radionuclides. The content and structure of the files are described in Appendix B.

3.4.4 Risk Conversion Factor Files

The files FGR13ING.RBS and FGR13INH.RBS contain radiation risk conversion factors for the pathways of ingestion and inhalation. Each of these files is parallel in structure and size. The file FGR13EXT.RBS provides similar factors for the external pathways of air submersion, surface soil, and soil volume. Each of these files provides risk conversion factors for 15 potential human cancer sites; each radionuclide line number is identified in the index file FGR13PAK.NDX described above. The ingestion file further provides information subdivided by the intake pathways of drinking water and food, as described in Federal Guidance Report 13, for each radionuclide. The inhalation file provides information subdivided by the ICRP lung model retention classes F, M, and S (fast, medium, and slow clearance rates).

These files are provided with the GENII V2 NESHAPS software package, and each is used by the health impacts calculational component. Data are provided for more radionuclides than are explicitly listed in RMDLIB.DAT – however, many are considered to be implicit progeny radionuclides within the RMDLIB.DAT structure. The GENII V2 NESHAPS health risk component accounts for the decay energies of the implicit progeny in the dose rate factor assigned for the explicit parent radionuclides. The content and structure of the files are described in Appendix B.

3.5 RADON OUTPUT FILES

If requested, the GENII V2 NESHAPS receptor intake module prepares a file of radon Working Levels and Working Level Months for each exposure location. This file has the extension *.WLM, and it may be accessed with any standard ASCII text editor.

3.6 REFERENCES FOR SECTION 3

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4.0 ATMOSPHERIC TRANSPORT AND DEPOSITION MODULE

The atmospheric model CHRONSRC for the GENII V2 NESHAPS system, is a code to account for the transport, diffusion, deposition, depletion, and decay of radionuclides while in the atmosphere. The basic diffusion model used in this code is the Gaussian solution to the diffusion equation. The model includes estimations for chronic releases. Elements of the model representing the physical processes of diffusion, deposition, depletion, cloud shine, and decay of radionuclides have been selected to be as realistic as possible yet be consistent with readily available meteorological and climatological data. In the case of dispersion coefficients and the effects of building wakes, alternative models for these physical processes have been included in the suite to provide users with flexibility.

In the rest of this section includes the descriptions the straight-line plume model and its components. Section 4.1 describes the straight-line plume. The components of the models are described in Section 4.2. The optional air submersion dose calculations performed by these models are described in Section 4.3.

4.1 STRAIGHT-LINE GAUSSIAN PLUME MODEL

This section describes the straight-line Gaussian model. It covers the basic plume and its variations. It also describes modification of the model to account for area sources, multiple sources, and the finite flow from short stacks and vents.

4.1.1 Basic Model

The complete straight-line Gaussian plume model is

$$\frac{\chi(x, y, z, H, h_{\text{eff}})}{Q'(x)} = \frac{1}{2\pi U(h_s) \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) G(z) \quad (4.1)$$

where χ = the concentration at distance x , crosswind position y , and height z , in a plume with axis at height h_{eff} (Ci/m^3)

$Q'(x)$ = the release rate, corrected for deposition and decay as appropriate (Ci/s)

$U(h_s)$ = the wind speed at release height, h_s (m/s)

σ_y = the horizontal dispersion coefficient (m)

σ_z = the vertical dispersion coefficient (m)

$G(z)$ = the vertical dispersion factor.

The vertical factor includes plume reflection off the ground and the mixing layer and is given by

$$G(z) = \sum_{n=-\infty}^{\infty} \exp\left[-\frac{(2nH + (h_{\text{eff}} - z))^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(2nH - (h_{\text{eff}} + z))^2}{2\sigma_z^2}\right] \quad (4.2)$$

where h_{eff} = the effective release height (h_s + plume rise) (m)
 H = the mixing layer thickness (m).

The limits of the summations in Equation 4.2 can be truncated to n from -2 to +2 without significantly reducing the accuracy of the equations. In the plume models, the receptor height (z) is assumed to be 1 meter.

For the case of release height above the atmospheric mixing layer, the top of the mixing layer serves as a permeable surface for material approaching the surface from above, and a reflecting surface for material reflected from the ground. $G(z)$ for this case is still given by (4.2) with the following modifications: if $n < 0$, then only the exponential with $2nH - (h + z)$ is summed; if $n > 0$, then only the exponential with $2nH + (h_e - z)$ is summed; and if $n = 0$, both exponentials are summed.

This model is appropriate for short duration releases. Typically, it is used to estimate hourly-average concentrations. Release rates for depositing or decaying effluents must be adjusted to account for deposition and decay to maintain mass continuity for the effluent. If the release rate is not adjusted, the equation will systematically overestimate the concentration, and the magnitude of the overestimate will increase with increasing distance from the source. The wind speed at release height is used for elevated releases. If the release is at or near ground level, the 10-meter wind speed generally replaces the release-height wind speed. For these codes, releases below 12 meters use the 10-meter wind speed. Empirical parameterizations, based on experimental data, are commonly used to estimate the effective release height and the dispersion coefficients, which are discussed later in Section 4.2.3.

If the distance from the source is sufficiently large, the vertical dispersion coefficient approaches the mixing thickness in magnitude signifying that the effluent is uniformly mixed in the vertical. Under this condition, the straight-line Gaussian model can be simplified to

$$\frac{\chi(x, y, z)}{Q'(x)} = \frac{1}{\sqrt{2\pi} U(h_s) H_u \sigma_y} \exp\left[-\frac{1}{2} \left(\frac{y}{\sigma_y}\right)^2\right] \quad (4.3)$$

where H_u = The height of uniform depth which is the mixing layer or the effective release height, whichever is higher.

In the codes, the effluent is considered to be uniformly mixed in the vertical when the vertical dispersion coefficient is 1.2 times the uniform depth.

4.1.2 Sector-Average Model

It is unlikely that a plume will remain in the same location for prolonged periods. Therefore, a sector-average plume model is used for chronic or long duration releases. The sector-average model is derived by integrating the straight-line plume model crosswind and dividing the result by the sector width. Historically, a 22.5° (2π radians/16 sectors) sector width has been used because wind directions were recorded by sector (N, NNE,...S,...NNW). However, since 1965 directions have been recorded in tens of degrees.

The sector average model is

$$\frac{\chi(\theta, r, z)}{Q'(r)} = \frac{1}{\sqrt{2\pi} U \sigma_z \theta_w} G(z) \quad (4.4)$$

where $\chi(\theta, r, z)$ = the concentration at distance r , in sector θ , at height z (Ci/m^3)
 $Q'(r)$ = the total mass of material released corrected for deposition and decay
 θ_w = the sector width, which is the larger of the arc length in a 22.5° wide sector or 4 times σ_y
 U = wind speed, m/s
 σ_z = vertical dispersion coefficient for distance r (or time $t = x/U$)
 $G(z)$ = vertical factor given by Equation (4.2)

Note that the sector-average model is given in cylindrical coordinates and the straight-line plume model is given in Cartesian coordinates. This follows the normal convention in the literature.

At long distances, the model further simplifies, due to uniform mixing in the vertical, to

$$\frac{\chi(\theta, r, z)}{Q'(r)} = \frac{1}{U H_u \theta_w} \quad (4.5)$$

As in the basic model, the code assumes that the plume is uniformly mixed in the vertical when σ_z is 1.2 times the uniform depth.

4.1.3 Area Source Model

The area source model starts with the following assumptions:

- 1) The area is a square with dimension $2a$.
- 2) The square is centered on the origin and oriented with sides parallel and perpendicular to the wind direction. (The orientation of the square rotates with the

- wind.) If the x-axis is aligned with the transport direction, the square covers the area defined by $-a < x < a$, $-a < y < a$.
- 3) Material is released at a uniform rate, Q_A , which has units of mass/ (area x time). The equivalent point source release rate is $4a^2Q_A$.

Two area source models are provided: a centerline model and a sector-averaged model.

4.1.3.1 Centerline Area Model

The concentration in the plume from an area source is determined as a function of the distance from the upwind edge of the area and the crosswind position. For receptors with x-coordinates $> -a$ and $< a$, the concentration is given by

$$\chi(x, y, z) = \int_{-a}^x \frac{Q_A}{\sqrt{2\pi} \sigma_z(x-\zeta) U} G(z, \zeta) \left\{ \frac{1}{2} \left(\operatorname{erf} \left[\frac{a+y}{\sqrt{2} \sigma_y(x-\zeta)} \right] + \operatorname{erf} \left[\frac{a-y}{\sqrt{2} \sigma_y(x-\zeta)} \right] \right) \right\} d\zeta \quad (4.6)$$

where ζ is the variable of integration, erf is the error function, and $G(z, \zeta)$ is Equation (5.2) except σ_z is $\sigma_z(x-\zeta)$.

For receptors with x-coordinates $> a$, the concentration is given by

$$\chi(x, y, z) = \int_{-a}^a \frac{Q_A}{\sqrt{2\pi} \sigma_z(x-\zeta) U} G(z, \zeta) \left\{ \frac{1}{2} \left(\operatorname{erf} \left[\frac{a+y}{\sqrt{2} \sigma_y(x-\zeta)} \right] + \operatorname{erf} \left[\frac{a-y}{\sqrt{2} \sigma_y(x-\zeta)} \right] \right) \right\} d\zeta \quad (4.7)$$

Analytical solutions of the integrals in Equations (4.6) and (4.7) do not exist. The integrals are solved numerically. The codes use a Simpson's Integration scheme to estimate the integrals.

At large downwind distances the concentrations can be estimated by assuming that the dispersion coefficients are independent of ζ . That is, the concentration can be estimated by

$$\chi(x, y, z) = \frac{2a Q_A}{\sqrt{2\pi} \sigma_z U} G(z) \left\{ \frac{1}{2} \left(\operatorname{erf} \left[\frac{a+y}{\sqrt{2} \sigma_y(x)} \right] + \operatorname{erf} \left[\frac{a-y}{\sqrt{2} \sigma_y(x)} \right] \right) \right\} \quad (4.8)$$

where the $2a$ comes from the integration. The distance at which the concentrations predicted by Equation (4.7) approaches the concentration predicted by Equation (4.8) is a function of the atmospheric stability and a function of the way in which σ_y and σ_z are parameterized. For all stability classes and diffusion parameterization schemes, concentrations using Equation (4.7) and Equations (4.8) are within about 1% when the distance is 10 times a .

When σ_z becomes 1.2 time the mixing height, Equation (4.8) can be simplified to

$$\chi(x, y, z) = \frac{2 a Q_A}{U H} \left\{ \frac{1}{2} \left(\operatorname{erf} \left[\frac{a+y}{\sqrt{2} \sigma_y(x)} \right] + \operatorname{erf} \left[\frac{a-y}{\sqrt{2} \sigma_y} \right] \right) \right\} \quad (4.9)$$

4.1.3.2 Sector-Averaged Area Model

In sector-average models, dispersion of material released from area sources are treated by considering three regions: The source region, an intermediate region, and a sector-average region. Concentrations in the source region are calculated using following equation:

$$\chi(\theta, r, z) = \int_{-a}^r \frac{Q_A}{\sqrt{2\pi} \sigma_z(r-\zeta) U} G(z, \zeta) d\zeta \quad (4.10)$$

Equation (4.10) is the same as Equation (4.6) except that the term involving the error function has been deleted. In effect, deleting the error function term neglects lateral diffusion.

The intermediate region extends from the downwind edge of the source to the distance at which the arclength of the sector equals the width of the source. When there are 16 sectors this distance, r_{16} , is

$$r_{16} = \frac{a}{(\pi/16)} = 5.093 a \quad (4.11)$$

In the intermediate region the concentration is given by

$$\chi(\theta, r, z) = \int_{-a}^a \frac{Q_A}{\sqrt{2\pi} \sigma_z(r-\zeta) U} G(z, \zeta) d\zeta \quad (4.12)$$

Equation (4.12) is Equation (4.7) without lateral diffusion.

Farther downwind, the lateral diffusion is proportional to $1/r$, as it is in the point-source, sector-average model. In this region the concentration is calculated from

$$\chi(r, 0) = \frac{r_{16}}{r} \int_{-a}^a \frac{2 Q_A}{\sqrt{2\pi} \sigma_z(r-\zeta) U} \exp \left[-\frac{1}{2} \left(\frac{h_e}{\sigma_z(r-\zeta)} \right)^2 \right] d\zeta \quad (4.13)$$

Eventually, as the distance from the origin increases, the sector-average concentration from an area source converges to the sector-average concentration for a point source. The sector-average model for a point-source is

$$\chi(\theta, r, z) = \frac{Q_p G(z)}{\sqrt{2\pi} \sigma_z(r) U \frac{2\pi r}{16}} \quad (4.14)$$

where $Q_p (= 4aQ_a)$ is the point equivalent to the area source.

For the diffusion parameterizations in the code, the area sector-averaged model is within 1% of the point sector-averaged model for distance of $5a$. Because the intermediate region occurs at a distance greater than $5a$, in the codes there are only two regions: the source region (Equation (4.10)) and the sector-average point-source (Equation 4.14).

4.1.4 Finite Source Correction

The equations presented to this point all assume that the release flow is negligible. This assumption is not valid for releases from short stacks and vents if the receptor is near the release point. If the flow from the stack is neglected the result may be concentration estimate in atmosphere that exceed the concentration in the stack. In simple cases, this unwanted result can be avoided by modification of the equations to include the stack flow in the denominator of the leading term on right hand side of the equations. For example, Equation (4.1) becomes

$$\frac{\chi(x, y, z, H, h_{\text{eff}})}{Q'(x)} = \frac{1}{2\pi U(h_s) \sigma_y \sigma_z + f_0} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) G(z) \quad (4.15)$$

where f_0 is the stack flow in cubic meters per second.

Unfortunately, this simple modification does not work in all instances. A more general correction can be made by assuming the dilution in the stack and atmosphere are additive in manner of resistances in a parallel electrical circuit. If the concentration calculated assuming a point source is denoted by $(X/Q)^*$, and f_0 is the flow, then the correct concentration in the atmosphere near the source would be

$$\frac{\chi}{Q} = \frac{1}{\left[\left(\frac{\chi}{Q} \right)^* \right]^{-1} + f_0} \quad (4.16)$$

4.1.5 Multiple Sources

On occasion it may be necessary to consider the combined effects of releases from more than one source within the context of a straight line plume model. This is accomplished by establishing a polar grid, determining the position of each source within the grid, and calculating the position of the receptors relative to the source. For the chronic model, sources are allowed to be located anywhere on the grid. The positions of the sources are specified by distance and direction from the origin of this grid.

The following convention is used for treatment of multiple sources with the straight-line plume model. A polar grid is defined, and the sources are specified by the distance and direction from the origin of this grid. Source definition is completed when the number of sources, m , is defined and a position is specified for each source. Table 4.1 shows a symbolic representation of a complete definition of source positions (assuming the first source is located at the center of the grid). In general, the position of source m is given by coordinates (r_{sm}, θ_{sm}) , where the subscript s indicates source and the subscript m identifies the specific source.

The position of each receptor must be specified in polar grid coordinates. Specification of the position of receptors by polar grid coordinates is sufficient if there is only one source or the if sources are collocated. In the general case, however, the position of each receptor must be determined with respect to each source. Given source and receptor locations in polar grid coordinates, the distance from a source m to a receptor n can be calculated by:

$$r_{m,n} = [r_{sm}^2 + r_{rn}^2 - 2 r_{sm} r_{rn} \cos(\theta_{sm} - \theta_{rn})]^{1/2} \quad (4.17)$$

The bearing from source m to receptor n can be calculated by

$$\theta_{m,n} = \tan^{-1} \left[\frac{r_{sm} \sin(\theta_{sm}) - r_{rn} \sin(\theta_{rn})}{r_{sm} \cos(\theta_{sm}) - r_{rn} \cos(\theta_{rn})} \right] \quad (4.18)$$

Table 4.1. Source position definition

Source	Distance	Direction
1	0	0
2	r_{s2}	θ_{s2}
...
m	r_{sm}	θ_{sm}

Upon completion of calculation of the positions of all receptors with respect to all sources, a matrix similar to that shown in Table 4.2 will have been filled. This matrix provides the information necessary to compute the total concentrations at each receptor. However, the information is not organized in a manner that promotes computational efficiency. To promote computational efficiency, the information in Table 4.2 will be sorted and reorganized. When the reorganization is complete the revised source/receptor position matrix will have the appearance of Table 4.3.

Given the wind direction, the relationships shown in Table 4.3 can be used to quickly identify all receptors downwind of each source. Each receptor will appear just once for each source. However, the revised source/receptor matrix may be larger than the initial matrix because for a given wind direction there may not be an equal number of receptors downwind of all sources. For example, for the first downwind direction Table 4.3 shows two receptors downwind of source 1 and three receptors downwind of source m.

Table 4.2. Initial Source/Receptor Position Matrix

Receptor	Source 1		...	Source m	
	Distance	Direction		Distance	Direction
1	$r_{1,1}$	$\theta_{1,1}$	...	$r_{m,1}$	$\theta_{m,1}$
2	$r_{1,2}$	$\theta_{1,2}$	...	$r_{m,2}$	$\theta_{m,2}$
3	$r_{1,3}$	$\theta_{1,3}$	...	$r_{m,3}$	$\theta_{m,3}$
...
n	$r_{1,n}$	$\theta_{1,n}$	...	$r_{m,n}$	$\theta_{m,n}$

Table 4.3. Revised Source/Receptor Position Matrix

Downwind Direction	Source 1		...	Source m	
	Distance	Receptor		Distance	Receptor
θ_1	$r_{1,1}$	1	...	$r_{m,n}$	n
θ_1	$r_{1,2}$	2	...	$r_{m,3}$	3
θ_1				$r_{m,4}$	4
...
θ_i	$r_{1,n}$	n	...	$r_{m,9}$	9
...

4.1.6 Calm Winds

The derivation of the straight-line Gaussian plume model given in (4.1) is defined under the assumption of a non-zero wind speeds. In the case of calm winds, there are two problems. First, there is a zero wind speed, and second, there is no direction defined. For these codes, the first problem is solved by assuming a minimum wind speed (1 m/s) for calm winds and applying the straight-line Gaussian plume model. To solve the second problem, no defined direction, the code randomly picks a direction. The code assumes an equal weighting for each direction unless the user supplies a distribution of low wind speed directions.

4.1.7 Calculation of Average Concentrations

The chronic model outputs the average. In the plume model, the average concentration is given by

$$\chi_{av}(x, y, z) = \frac{1}{T} \sum_{i=0}^{n(T)} \chi_i(x, y, z) W_i \quad (4.19)$$

where $\chi_{av}(x, y, z)$ = the average concentration at distance x, crosswind position y, and height z (Ci/m³)
 $\chi_i(x, y, z)$ = the ith concentration
 $n(T)$ = the number of concentrations during the time period, T
 W_i = a weighting factor, which is the number of hours of the ith concentration in time period, T

4.2 MODEL COMPONENT PARAMETERIZATIONS

The preceding sections describe the basic dispersion models included in the model suite. This section describes the parameterizations for the components included in the models.

4.2.1 Effective Release Height

Both the plume and puff models in the suite have the ability to calculate concentrations resulting from elevated releases. In each case the height of release is the effective release height. Effective release height is defined as the actual release height with corrections for plume downwash and plume rise. Formally,

$$h_e = h_s + \Delta h_{pr} + \Delta h_{dw} \quad (4.20)$$

where h_s is the stack height, Δh_{pr} is the correction to the effective height due to plume rise, and Δh_{dw} is the correction to the effective height due to downwash. The downwash correction is a

function of time (effluent vertical velocity and wind speed); the plume rise correction is a function of both time and distance from the source.

4.2.1.1 Downwash Correction

A plume downwash correction is applied in all plume rise calculations when the effluent vertical velocity at the stack exit is less than 1.5 times the wind speed at release height. This correction, which accounts for aerodynamic effects, is

$$\Delta h_{dw} = 4 r_o \left[\frac{w_o}{U(h_s)} - 1.5 \right] \quad (4.21)$$

where w_o = stack effluent vertical velocity (m/s)
 r_o = stack inside radius (m).

If the stack-exit vertical velocity is equal to or greater than 1.5 times the release height wind speed, the downwash correction is zero.

The correction described above is applied in all wind speeds in the EPA's Industrial Source Complex (ISC3) codes (EPA 1995). However, there is some question about the appropriateness of the correction as the stack height wind speed approaches zero. For example, Petersen and Lavadas (1986) assume a minimum release-height wind speed of 1.37 m/s when the winds are near calm. In the codes, the default minimum wind speed for calculating plume rise is 1.5 m/s, but this variable can be defined by the user.

4.2.1.2 Plume Rise

Plume rise is calculated using the methods of Briggs (1969, 1972, 1973, 1975 and 1984). The RATCHET (Ramsdell et al. 1994), ISC3 (EPA 1995), and INPUFF (Petersen and Lavdas 1986) codes use essentially the same set of equations for estimating final plume rise. These equations are implemented in the suite of codes with minor modifications. In addition for the plume model, transition plume rise equations are implemented for receptors near the source. Plume rise calculated with the transition equations is compared with plume rise calculated with final rise equations and the lesser value is used to determine the effective release height.

The primary factors entering into plume rise calculations are the inside radius of the stack, momentum and buoyancy fluxes from the stack, wind speed at release height, and atmospheric stability. The specific plume rise equation used depends on relative importance of the momentum and buoyancy fluxes, atmospheric stability (unstable/neutral and stable), wind speed, and for buoyant plumes the magnitude of the buoyant flux.

The momentum flux, F_m , is defined as

$$F_m = \frac{\rho_o}{\rho_a} w_o^2 r_o^2$$

$$\approx \frac{T_a}{T_o} w_o^2 r_o^2 \quad (4.22)$$

where ρ_o = stack effluent density (kg/m³)
 ρ_a = ambient air density (kg/m³)
 w_o = stack effluent vertical velocity (m/s)
 r_o = stack inside radius (m)
 T_a = ambient air temperature at stack height (K)
 T_o = stack effluent temperature (K).

If the release is through an uncapped vent that is not circular, the stack radius may be approximated by the cross-sectional area divided by pi. The buoyancy flux is

$$F_b = g \frac{\rho_o - \rho_a}{\rho_a} w_o r_o^2$$

$$\approx g \frac{T_o - T_a}{T_a} w_o r_o^2 \quad (4.23)$$

Plumes are referred to as either momentum dominated (jets) or buoyancy dominated. Very near the stack, plumes are generally momentum dominated. As rise continues, plumes tend to become buoyancy dominated unless the density of the stack effluent and the air are the same.

Momentum Rise - Unstable and Neutral Conditions. During unstable and neutral atmospheric conditions, the final plume rise, Δh_{prf} , for momentum-dominated plumes is

$$\Delta h_{prf} = 6 r_o \left[\frac{w_o}{U(h_s)} \right] \quad (4.24)$$

This rise is generally small and will reach its maximum value near the stack.

Buoyancy Rise - Unstable and Neutral Conditions. For buoyancy-dominated plumes in unstable and neutral conditions, the final plume rise is

$$\Delta h_{prf} = 1.6 F_b^{1/3} \frac{x_f^{2/3}}{U(h_s)} \quad (4.25)$$

where x_f is the distance to final plume rise. This distance is directly related to the buoyancy-flux parameter. For small sources ($F_b < 55$) the distance to final rise, in meters, is

$$x_f = 49 F_b^{5/8} \quad (4.26)$$

and for large sources ($F_b \geq 55$) it is

$$x_f = 119 F_b^{2/5} \quad (4.27)$$

Critical Temperature Difference. A critical temperature difference can be calculated for use in determining whether a plume is dominated by momentum or buoyancy. This critical temperature difference is found by combining Equations (4.24) and (4.25), setting $\Delta T_c = (T_o - T_a)$, and solving ΔT_c . The results of these manipulations are

$$\Delta T_c = 0.0187 \left(\frac{W_o^2}{r_o} \right)^{1/3} T_a \quad (4.28)$$

for small sources, and

$$\Delta T_c = 0.00456 \left(\frac{W_o^2}{r_o} \right)^{1/3} T_a \quad (4.29)$$

for large sources. Note that the leading constants in these equations have dimensions. If the actual difference between the initial effluent temperature and the ambient air at stack height is less than the critical temperature difference, plume rise is dominated by momentum. Otherwise, the plume rise is buoyancy dominated.

Calm Winds. Equations (4.24) and (4.25) cannot be used to calculate plume rise in calm winds because wind speed is in the denominator in the equations. To prevent this problem, a minimum stack height wind speed is specified. This minimum wind speed is the same as that used in the downwash calculations.

Stable Conditions. During stable atmospheric conditions, plume rise calculations include an atmospheric stability parameter. The atmospheric stability parameter is defined as

$$S = \frac{g}{T_a} \frac{\partial \theta}{\partial z} \quad (4.30)$$

where g is the gravitational acceleration ($\sim 9.8 \text{ m/s}^2$) and $\partial \theta / \partial z$ is the potential temperature lapse rate. Potential temperature lapse rates of 0.02 K/m, 0.035 K/m, and 0.05 K/m are assumed for stability classes 5, 6, and 7, respectively.

Momentum Rise - Stable Conditions. The final rise momentum-dominated plumes in stable conditions is given either by

$$\Delta h_{\text{prf}} = 1.5 \left(\frac{F_m}{U(h_s) \sqrt{S}} \right)^{1/3} \quad (4.31)$$

or equation (4.24), whichever is smaller. Again, momentum-dominated plume rise is generally small and reaches its maximum value near the stack.

Buoyancy Rise - Stable Conditions. The final rise of buoyancy-dominated plumes in stable conditions is

$$\Delta h_{\text{prf}} = 2.6 \left[\frac{F_b}{U(h_s) S} \right]^{1/3} \quad (4.32)$$

This rise is assumed for all distances greater than

$$x_f = 2.0715 \frac{U(h_s)}{\sqrt{S}} \quad (4.33)$$

When the wind is near calm, the final rise of buoyancy-dominated plumes in stable atmospheric conditions can be estimated using

$$\Delta h_{\text{prf}} = 4 F_b^{1/4} S^{-3/8} \quad (4.34)$$

Equations (4.32) and (4.34) can be used to define a critical wind speed for use in selecting the appropriate equation. This wind speed is

$$U_c = 0.2746 (F_b \sqrt{S})^{1/4} \quad (4.35)$$

Equation (4.32) is used to calculate final plume rise when the wind speed at stack height is greater than the critical speed. Otherwise, the final plume rise is calculated by Equation (4.34). Typically, the critical wind speed is less than 1 m/s.

Critical Temperature Difference. The critical temperature difference for determining whether a plume is dominated by momentum or buoyancy is determined using Equations (4.31) and (4.32). Assuming that the wind speed is greater than U_c , the critical temperature difference is

$$\Delta T_c = 0.01958 w_o S^{1/2} T_a \quad (4.36)$$

Equations (4.31) and (4.34) can be used to estimate a critical temperature difference during calm, stable conditions. This difference is

$$\Delta T_c = 0.0138 w_o S^{1/2} T_a \quad (4.37)$$

Except for the value of the leading coefficient, Equations (4.36) and (4.37) are identical. Equation (4.36) gives the larger critical temperature of the two equations. Therefore, the code only uses Equation (4.36).

Elevated Inversions. Briggs (1975, 1984) discuss the effect of elevated inversion on plume rise. The equations provided in these discussions include parameters related to the strength of the inversion that would be difficult to estimate from routine meteorological data. In the code, the plumes are assumed to be bent-over and are confined to the mixing layer initially unless released above the mixing layer because, according to Briggs (1984), they have limited ability to penetrate inversions.

Transition Plume Rise. Only in the plume models are the transition plume rise equations used to determine plume rise for dispersion calculations for receptors that are near the source. During the transition phase, plume rise is independent of atmospheric stability. The transition rise equation for jets is

$$\Delta h_{\text{prt}} = \left(\frac{3 F_m x}{\beta_m^2 U^2} \right)^{1/3} \quad (4.38)$$

where β_m is an entrainment constant for jets. The entrainment constant for jets given by Briggs (1975, 1984) is

$$\beta = 0.4 + \frac{1.2 U}{w_o} \quad (4.39)$$

The transition rise for buoyant plumes is given by

$$\Delta h_{\text{prt}} = \left(\frac{3 F_m}{\beta_m^2 U^2} x + \frac{3 F_b}{2 \beta_b^2 U^3} x^2 \right)^{1/3} \quad (4.40)$$

where β_b is the entrainment factor for buoyant plumes. Briggs (1984) suggest a value of 0.6 be used for β_b .

Within a few meters of the source the momentum term may dominate the transition plume rise. However, generally the buoyancy term will be dominant at distances of 100 m or more. At these distances the momentum term may be dropped and Equation (4.40) may be simplified to

$$\Delta h_{prt} = \frac{1.6 F_b^{1/3} x^{2/3}}{U} \quad (4.41)$$

Whenever transition plume rise is calculated in the codes, the transition rise is compared with the final plume rise. The lesser plume rise is used in dispersion calculations.

In the case where the Schulman and Scire building downwash model is being used, the transitional rise associated with this model is used instead of the above transitional rise equations. The transition rise equation for Schulman and Scire downwash model is given in Section 5.3.4.1.

4.2.2 Wind Profile

Frequently, wind speeds at heights other than the height at which they were measured are required by the atmospheric models. Many wind measurements are made at 10 meters above the ground or lower. For elevated releases, measured winds at these heights are not available. Thus, the models must estimate them from the surface-wind data. If the release height is below 12 meters, the wind speed at 10 meter is used.

A diabatic wind-profile model is used to adjust the wind speed as needed. No attempt is made to model the variation of wind direction with height above the ground. Diabatic profiles account for the effect of surface roughness and atmospheric stability on the variation of wind speed with height.

The diabatic profile model is derived from the atmospheric boundary layer similarity theory proposed by Monin and Obukhov (1954). The basic hypothesis of similarity theory is that a number of parameters in the atmospheric layer near the ground, including the wind profiles, should be universal functions of the friction velocity, a length scale, and the height above ground. The length scale, L , is referred to as the Monin-Obukhov length and the ratio z/L is related to atmospheric stability. When z/L is negative and large (e.g., < -2), the atmosphere is extremely unstable (convective). When z/L is near zero, the atmosphere is neutral, and when it is positive and large (e.g., > 1), the atmosphere is extremely stable. A large body of experimental data supports Monin-Obukhov similarity theory.

The diabatic wind profile is

$$U(z) = \frac{u_*}{k} \left[\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right) \right] \quad (4.42)$$

where	$U(z)$	=	wind speed at height z (m/s)
	u_*	=	friction velocity (boundary-layer turbulence scaling velocity) (m/s)
	k	=	von Karman constant, which has a value of about 0.4 (no units)
	z	=	height (m)
	z_0	=	measure of local surface roughness (roughness length) (m)
	ψ	=	stability correction factor

L = Monin-Obukhov Length (m)

The term $\psi(z/L)$ accounts for the effects of stability of the wind profile. In stable atmospheric conditions, $\psi(z/L)$ has the form $-\alpha z/L$, where α is a value between 4.7 and 5.2. For the models, a value of 5 is used for α . In neutral conditions $\psi(z/L)$ is zero, and the diabatic profile simplifies to a logarithmic profile.

In unstable air, $\psi(z/L)$ is more complicated. According to Panflosky and Dutton (1984), the most common form of $\psi(z/L)$ for unstable conditions is based on the work by Businger et al. (1971) and Paulson (1970). It is

$$\psi\left(\frac{z}{L}\right) = \ln\left(\left[\frac{1+x^2}{2}\right]\left[\frac{1+x}{2}\right]^2\right) - 2 \tan^{-1} x + \frac{\pi}{2} \quad (4.43)$$

where $x = (1 - 16z/L)^{1/4}$. Equation (4.42) is used to estimate the friction velocity (u_*) from wind speed, surface roughness, and the Monin Obukhov Length. In unstable and neutral conditions, the use of Equation (4.42) is limited to the lowest 100 meters of the atmosphere. In stable conditions, the upper limit of application of Equation (4.42) is the smaller of 100 meters or three times the Monin-Obukhov length. Skibin and Businger (1985) provide the rationale for limiting application of Equation (4.43) to three times the Monin-Obukhov length in stable conditions.

The Monin-Obukhov length is a measure atmospheric stability. It varies from small negative values (a few meters) in extremely unstable atmospheric conditions to negative infinity as the atmospheric stability approaches neutral from unstable. In extremely stable conditions, the Monin-Obukhov length is small and positive. As neutral conditions are approached from stable conditions, the Monin-Obukhov length approaches infinity. Thus, there is a discontinuity in the Monin-Obukhov length at neutral. However, this discontinuity is not a problem because the Monin-Obukhov length is found in the denominator of expressions.

Golder (1972) provides a means for converting from stability class estimates to Monin-Obukhov lengths. Figure 4.1, derived from Golder (1972, Figure 5), shows the range for $1/L$ as a function of stability classes and surface roughness. Mid-range values for $1/L$ from this figure are used by the model to estimate $1/L$.

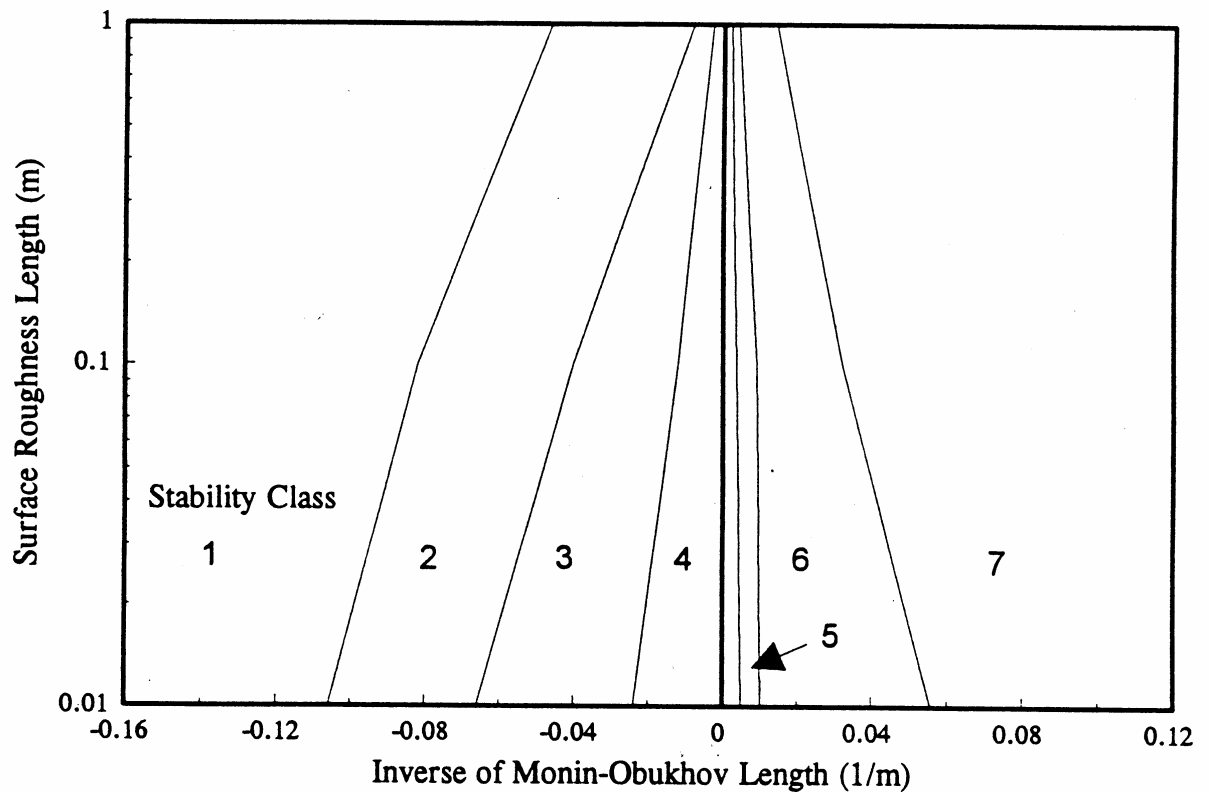


Figure 4.1. Relationship between Stability Class and Monin-Obukhov Length as a Function of Surface Roughness Length

4.2.3 Dispersion coefficients

The spread of effluents in plumes is described by dispersion coefficients. In Gaussian models these coefficients are standard deviations of the concentration distributions. Theoretically, these coefficients are related to atmospheric turbulence and the time since release.

In practice many schemes are used to estimate dispersion coefficients. Historically, most of the schemes have been based on atmospheric stability classes and distance from the source. More modern schemes use information on atmospheric turbulence and time since release.

The code includes several schemes for calculating dispersion coefficients. The user selects the scheme of their choice. In the GENII V2 NESHAPS edition, only the EPA's ISC-3 values are available, therefore, only that scheme included in the code is described here.

Pasquill-Gifford (ISC3)

The Pasquill-Gifford (ISC3) equations are an approximate fit to the Pasquill-Gifford curves (Turner, 1970) as described in the User's Guide for the Industrial Source Complex (ISC3) Model, Volume II (EPA 1995) assuming rural conditions. For urban conditions, the equation used in the ISC3 model for the dispersion coefficients are the same as the Briggs Urban Condition equations. The equation used to calculate the horizontal dispersion coefficient is (with the downwind distance in kilometers):

$$\sigma_y = 465.11628(x) \tan(\text{TH}) \quad (4.44)$$

where

$$\text{TH} = 0.017453293[c - d \ln(x)] \quad 4.45$$

The coefficients c and d are dependent upon atmospheric stability and are given in Table 4.4. The vertical dispersion coefficient is calculated using:

$$\sigma_z = a x^b \quad (4.46)$$

where the coefficients a and b depend upon downwind distance, x (in kilometers), and atmospheric stability. The coefficients a and b are given in Table 4.5.

Table 4.4 Coefficients for Pasquill-Gifford (ISC3) horizontal dispersion coefficient formula

Pasquill Stability Category	Coefficient c	Coefficient d
A	24.1670	2.5334
B	18.3330	1.8096
C	12.5000	1.0857
D	8.3330	0.72382
E	6.2500	0.54287
F	4.1667	0.36191

Table 4.5 Coefficients for Pasquill-Gifford (ISC3) vertical dispersion coefficient formula

Pasquill Stability Category	x (km)	Coefficient a	Coefficient b
A *	< 0.10	122.800	0.94470
	0.10 - 0.15	158.080	1.05420
	0.16 - 0.20	170.220	1.09320
	0.21 - 0.25	179.520	1.12620
	0.26 - 0.30	217.410	1.26440
	0.31 - 0.40	258.890	1.40940
	0.41 - 0.50	346.750	1.72830
	0.50 - 3.11	453.850	2.11660
	>3.11	**	**
B *	<0.20	90.673	0.93198
	0.21 - 0.40	98.483	0.98332
	> 0.40	109.300	1.09710
C *	ALL	61.141	0.91465
D	<0.30	34.459	0.86974
	0.31 - 1.00	32.093	0.81066
	1.01 - 3.00	32.093	0.64403
	3.01 - 10.00	33.504	0.60486
	10.01 - 30.00	36.650	0.56589
	> 30.00	44.053	0.51179
E	< 0.10	24.260	0.83660
	0.10 - 0.30	23.331	0.81956
	0.31 - 1.00	21.628	0.75660
	1.01 - 2.00	21.628	0.63077
	2.01 - 4.00	22.534	0.57154

Pasquill Stability Category	x (km)	Coefficient a	Coefficient b
E continued	4.01 - 10.00	24.703	0.50527
	10.01 - 20.00	26.970	0.46713
	20.01 - 40.00	35.420	0.37615
	> 40.00	47.618	0.29592
F	< 0.20	15.209	0.81558
	0.21 - 0.70	14.457	0.78407
	0.71 - 1.00	13.953	0.68465
	1.01 - 2.00	13.953	0.63227
	2.01 - 3.00	14.823	0.54503
	3.01 - 7.00	16.187	0.46490
	7.01 - 15.00	17.836	0.41507
	15.01 - 30.00	22.651	0.32681
	30.01 - 60.00	27.074	0.27436
	> 60.00	34.219	0.21716

* If the calculated value of σ_z exceeds 5000 m, then σ_z is set to 5000 m

** σ_z is equal to 5000 m

4.2.4 Dispersion Coefficient Corrections

Atmospheric dispersion in the vicinity of buildings is generally treated by modifying the dispersion coefficients used in the straight-line Gaussian plume model [Equation (4.1)]. The modified dispersion coefficients are denoted by σ_y and σ_z rather than σ_y and σ_z . Several methods of calculating σ_y and σ_z have been proposed. The code includes several options for calculating σ_y and σ_z .

4.2.4.1 Building Wakes and Low Wind Speed Meander

There are two different models for building wake, the model based on the work by Ramsdell and Foscire (1995; 1998a; 1998b) and those used in the EPA's ISC3 model (1995). The Ramsdell and Foscire model also includes a dispersion coefficient correction for low wind

speed meander that is separate from building wakes. The two different models are described in the following sections.

Ramsdell and Foscire Model

Ramsdell and Foscire (1995; 1998a; 1998b) suggest that the maximum concentration in the vicinity of a building can be calculated using

$$\Sigma_y^2 = (\sigma_y^2 + \Delta\sigma_{y1}^2 + \Delta\sigma_{y2}^2)^{1/2} \quad (4.47)$$

where σ_y is the usual dispersion coefficient, $\Delta\sigma_{y1}$ is a low wind speed correction, and $\Delta\sigma_{y2}$ is a high wind speed, wake correction. An identical relationship defines σ_z . The low-speed corrections are given by

$$\begin{aligned} \Delta\sigma_{y1}^2 &= A_y \left[1 - \left(1 + \frac{x}{1000 U} \right) \exp\left(-\frac{x}{1000 U}\right) \right] \\ \Delta\sigma_{z1}^2 &= A_z \left[1 - \left(1 + \frac{x}{100 U} \right) \exp\left(-\frac{x}{100 U}\right) \right] \end{aligned} \quad (4.48)$$

where A_y and A_z are constants that depend, in part, on the parameterization used for the normal dispersion coefficients. Table 4.6 contains the constants A_y and A_z for the various dispersion coefficient parameterization schemes.

The high speed wake corrections are given by

$$\begin{aligned} \Delta\sigma_{y2}^2 &= B_y U^2 A \left[1 - \left(1 + \frac{x}{10 \sqrt{A}} \right) \exp\left(-\frac{x}{10 \sqrt{A}}\right) \right] \\ \Delta\sigma_{z2}^2 &= B_z U^2 A \left[1 - \left(1 + \frac{x}{10 \sqrt{A}} \right) \exp\left(-\frac{x}{10 \sqrt{A}}\right) \right] \end{aligned} \quad (4.49)$$

where B_y and B_z are constants that depend, in part, on the parameterization chosen for the normal dispersion coefficients and A is the cross-sectional area of the building. In Ramsdell and Foscire (1998b), it was determined that current open-terrain dispersion parameters already overestimated diffusion in high wind speed conditions. Thus, the constants B_y and B_z are zero for the various dispersion parameterizations used in these codes.

Table 4.6. Coefficient for Low Wind Speed Meander Model^a

Diffusion Parameterization	A_y	A_z
Briggs Open Country	1.78×10^4	1.45×10^5
Briggs Urban Condition	6.15×10^4	1.44×10^4
Pasquill-Gifford (ISC3)	2.05×10^4	1.34×10^5
Pasquill-Gifford (NRC)	1.75×10^4	1.41×10^5
Turbulent Statistics	N/A	N/A

a. Source: Ramsdell and Fosmire (1998b)

EPA's ISC3 Wake Models

As an alternative to the Ramsdell and Fosmire models, the plume model allows the user to use the building wake models found in the EPA ISC3 model. The full details of the building wake model can be found in User's Guide for the Industrial Source Complex (ISC3) Model, Volume II (EPA 1995) and are summarized here.

The ISC3 model uses two different procedures to account for building wake. The first procedure is based on the work of Huber (1977) and Huber and Snyder (1976), and will be referred to as the Huber-Snyder building wake. The other procedure follows the suggestions of Schulman and Hanna (1986) based on the work by Scire and Schulman (1980) and will be referred to as the Schulman-Scire building wake. The Schulman-Scire building wake is applied when the stack height is less than the building height plus half the lesser of the building height or width. Otherwise, the Huber-Snyder building wake procedure is used. For both procedures, direction-specific building dimension are specified by the user.

Huber - Snyder Building Wake

The Huber-Snyder building wake procedure is calculated by using a series of steps. The first step is to calculate the transitional plume rise due to momentum (Equation 4.38) at a distance of two building heights. If the effective plume height (with no stack-tip downwash adjustment) is greater than either 2.5 building heights or the sum of the building height and 1.5 times the building width, the plume is assumed to be unaffected by the building wake. Otherwise, the plume is assumed to be affected by the building wake.

If the plume is affected by the building make, the dispersion coefficients are modified. If the ratio of the plume height to the building height is less than or equal to 1.2, both dispersion coefficients, σ_y and σ_z , are modified. Otherwise, only the vertical dispersion coefficient, σ_z , is modified. The same plume height used to determine if the plume is affected by the building wake is used in the ratio.

How the dispersion coefficients are modified depends on the shape of the building. A building can be defined as either squat (width greater than or equal to the height) or tall (height greater than the width). Dispersion coefficients are only modified if the distance from the source to receptor is greater than 3 building heights. Distances shorter than 3 building heights are assumed to be in the building cavity region and the equations are not applicable. In the codes, the concentration is set to zero if the distance is less than 3 building heights (widths) from the source.

The modified vertical dispersion coefficient for a squat or building is given by

$$\begin{aligned}\sigma_{z'} &= 0.7 h_b + 0.067(x - 3h_b) \quad \text{for } 3h_b \leq x < 10h_b \\ &= \sigma_z(x + x_z) \quad \text{for } x \geq 10h_b\end{aligned}\tag{4.50}$$

where h_b is the building height and x_z is calculated by solving the two equations at $x = 10h_b$. For tall buildings, the same equations are used except h_b is replaced by h_w or

$$\begin{aligned}\sigma_{z'} &= 0.7 h_w + 0.067(x - 3h_w) \quad \text{for } 3h_w \leq x < 10h_w \\ &= \sigma_z(x + x_z) \quad \text{for } x \geq 10h_w\end{aligned}\tag{4.51}$$

For both tall and squat buildings, $\sigma_{z'}$ is not permitted to be less than the unmodified σ_z for distance x .

The modified horizontal dispersion coefficient for a squat building with the building width to building height ratio less than or equal to 5 or a tall building is given by

$$\begin{aligned}\sigma_{y'} &= 0.35 h_w + 0.067(x - 3h_w) \quad \text{for } 3h_w \leq x < 10h_w \\ &= \sigma_y(x + x_z) \quad \text{for } x \geq 10h_w\end{aligned}\tag{4.52}$$

where h_w is the building width.

For a building that is much wider than it is tall (width to height is greater than 5), not enough data was collected to provide general equations for σ_y . For a stack located towards the center of the building, only the height scale is considered to be significant. The modified horizontal coefficient is the same as Equation (4.52) except h_w is replaced by h_b or

$$\begin{aligned}\sigma_{y'} &= 0.35 h_b + 0.067(x - 3h_b) \quad \text{for } 3h_b \leq x < 10h_b \\ &= \sigma_y (x + x_z) \quad \text{for } x \geq 10h_b\end{aligned}\tag{4.53}$$

If the stack is located within about 2.5 building heights from the end of the building, the horizontal dispersion coefficient is calculated using

$$\begin{aligned}\sigma_{y'} &= 1.75 h_b + 0.067(x - 3h_b) \quad \text{for } 3h_b \leq x < 10h_b \\ &= \sigma_y (x + x_z) \quad \text{for } x \geq 10h_b\end{aligned}\tag{4.54}$$

The upper bound of the concentration for a squat building with a width to height ratio greater than 5 is given by Equation (4.53), while the lower bound is given by Equation (4.54). The user is given the option to use either the equation that gives the upper or lower bound concentration. By default, the upper bound is used.

Schulman-Scire Building Wake

The Schulman-Scire building wake procedure involves two steps. First, the plume is reduced due to initial plume dilution, and second, the vertical dispersion coefficient is modified. The vertical dispersion coefficient is calculated using either Equation (4.50) or Equation (4.51) depending upon the building dimensions. In addition, a linear decay factor is applied where

$$\sigma_{z'} = A \sigma_z \tag{4.55}$$

where σ_z' is from either Equation (4.50) or (4.51) and A is the linear decay factor determined by

$$\begin{aligned}A &= 1 \quad \text{if } h_e \leq h_b \\ A &= \frac{h_b - h_e}{2L_b} + 1 \quad \text{if } h_b < h_e \leq h_b + 2L_b \\ A &= 0 \quad \text{if } h_e > h_b + 2L_b\end{aligned}\tag{4.56}$$

where h_e is the height of the plume with transitional momentum rise at 2 building heights downwind.

The plume rise is estimated as follows. The initial dimensions of the downwash plume are approximated by a line source of length L_y and a depth $2R_0$ where

$$\begin{aligned}R_0 &= \sqrt{2} A \sigma_z \quad x = 3L_b \\ L_y &= \sqrt{2\pi} (\sigma_y - \sigma_z) \quad x = 3L_b, \sigma_y \geq \sigma_z \\ L_y &= 0 \quad x = 3L_b, \sigma_y < \sigma_z\end{aligned}\tag{4.57}$$

where L_b is the minimum of the building height and building width and A is a linear decay factor given by Equation (4.56). Both σ_y and σ_z are evaluated at $x = 3L_b$, and are taken as the larger of

the building enhanced sigmas and the uncorrected sigmas. The value of σ_z used in the calculation of L_y also includes the linear decay term, A (see Equation [4.55]).

The rise of a downwashed finite line source was solved in the BLP model (Schulman and Scire 1980). The neutral distance-dependent rise (Z) is given by

$$Z^3 + \left(\frac{3L_y}{\pi\beta} + \frac{3R_0}{\beta}\right)Z^2 + \left(\frac{6R_0L_y}{\pi\beta^2} + \frac{3R_0^2}{\beta^2}\right)Z = \frac{3F_b x^2}{2\beta^2 u^3} + \frac{3F_m x}{\beta_j^2 u^2} \quad (4.58)$$

The stable distance-dependent rise is calculated by

$$Z^3 + \left(\frac{3L_y}{\pi\beta} + \frac{3R_0}{\beta}\right)Z^2 + \left(\frac{6R_0L_y}{\pi\beta^2} + \frac{3R_0^2}{\beta^2}\right)Z = \frac{3F_b x^2}{2\beta^2 u^3} + \frac{3F_m \sin\left(\frac{x\sqrt{s}}{u}\right)}{\beta_j^2 u \sqrt{s}} \quad (4.59)$$

with a maximum stable buoyant rise given by

$$Z^3 + \left(\frac{3L_y}{\pi\beta} + \frac{3R_0}{\beta}\right)Z^2 + \left(\frac{6R_0L_y}{\pi\beta^2} + \frac{3R_0^2}{\beta^2}\right)Z = \frac{6F_b}{\beta^2 u s} \quad (4.60)$$

where

F_b	=	buoyancy flux term (Equation 4.23) (m^4/s^3)
F_m	=	momentum flux term (Equation 4.22) (m^4/s^2)
x	=	downwind distance (m)
u	=	wind speed at release height (m/s)
β	=	entrainment coefficient (=0.6)
β_j	=	jet entrainment coefficient (= $1/3 + u/w_0$, where w_0 is the stack exit velocity in m/s)
s	=	stability parameter (Equation 4.30) ($1/s^2$)

The larger of the momentum and buoyant rise, determined separately by alternately setting F_b and $F_m = 0$ and solving for Z, is selected for plume height calculations for Schulman-Scire building wake procedure. In this code, Z is solved directly assuming the real root is the solution of interest. It should be noted that during unstable conditions, the neutral distance-dependent rise is used. For stable conditions the neutral and stable solutions are compared and the smaller of the two is used.

4.2.4.2 Buoyancy Induced Diffusion

Buoyancy induced diffusion is the correction to the initial dispersion to account for turbulent motions and the subsequent entrainment of ambient air during the plume rise. Using

the methods of Pasquill and Smith (1983), the effective vertical dispersion corrected for buoyancy induced dispersion is

$$\sigma_{ze} = \sqrt{\sigma_z^2 + \left(\frac{\Delta h}{3.5}\right)^2} \quad (4.61)$$

where Δh is the plume rise and σ_z is the vertical dispersion due to ambient turbulence. The horizontal dispersion is parameterized using a similar equation:

$$\sigma_{ye} = \sqrt{\sigma_y^2 + \left(\frac{\Delta h}{3.5}\right)^2} \quad (4.62)$$

where σ_y is the horizontal dispersion due to ambient turbulence.

It should be noted that Δh is the distance-dependent plume rise. So, if the receptor is located at a distance less than that for the final plume rise, the transitional rise is used. For receptor located beyond the distance to the final rise, the final rise is used. The buoyancy-induced dispersion is not used when the Schulman-Scire building wake procedure is used.

4.2.5 Deposition

Deposition calculations are included with the atmospheric transport and diffusion calculations because the deposited material contributes to dose through ground shine and the ingestion pathway and deposition of material reduces the concentration of material in the air. Two primary deposition mechanisms are modeled. These mechanisms are dry deposition and wet deposition by rainout. Wet deposition by in-cloud scavenging of material is not treated.

4.2.5.1 Dry Deposition

The flux of material to the ground resulting from dry deposition is assumed to be proportional to the material's concentration in the air near the ground. Deposition velocity is the term given to the constant of proportionality. Thus,

$$\omega_{1ij}(t) = v_{dd} \chi_{ij}(1, t) \quad (4.63)$$

where $\omega_{1ij}(t)$ = the dry deposition rate at position i,j at time t
 v_{dd} = the dry deposition velocity
 $\chi_{ij}(1, t)$ = the concentration at a height of 1 m at position i,j at time t.

It is important to note that the deposition velocity is a function of the height at which the concentration is measured or calculated. A reference height of 1 m is assumed for deposition velocities in the atmospheric model.

Noble gases are inert. The literature contains some discussion of solubility of noble gases that might lead to deposition on wet surfaces. This deposition is not considered to be significant for dose calculations. As a result, it is assumed that they do not deposit. Therefore, the deposition velocity for noble gases is defined to be zero.

Dry deposition velocities have been calculated from experimental data for particles and gases. In general, the deposition velocities observed for any particular material have a wide range of values. Nevertheless, the deposition velocity is frequently assumed to be constant. More realistically, the dry deposition velocity may be modeled using an analogy to electrical resistance. Resistances are associated with atmospheric conditions, physical and chemical characteristics of the material, and the physical, chemical and biological properties of the surface. Seinfeld (1986) describes the resistance analogy.

For small particles ($\sim 1 \mu$) and gases the resistance model for dry deposition velocities is

$$v_{dd} = (r_a + r_s + r_t)^{-1} \quad (4.64)$$

where $r_a =$ aerodynamic resistance (s/m)
 $r_s =$ surface resistance (s/m)
 $r_t =$ transfer resistance (s/m).

The aerodynamic and surface resistances are generally calculated from near surface wind data. In contrast, the transfer resistance is generally a function of the depositing surface. For example, transfer resistances have been associated with the stomatal openings of plant leaves (Wesley and Hicks 1977).

The aerodynamic resistance is calculated directly from the wind speed and a parameter that is characteristic of the turbulence in the lowest layer of the atmosphere. The usual parameterization for the aerodynamic resistance is

$$r_a = U(z) / u_*^2 \quad (4.65)$$

where z = the height at which the concentration is estimated
 u_* = the characteristic turbulence velocity, called the friction velocity.
 $U(z)$ = wind speed at height z

The concentration is approximately constant for $z < 0.2\sigma_z$ as long as x is sufficiently large that σ_z is greater than or equal to the height of release. Thus, for most elevated release cases, the 10 m wind speed may be used directly in calculating r_a .

The surface resistance is only a function of the friction velocity. It is

$$r_s = 2.6 / (0.4 u_*) = 6.5 / u_* \quad (4.66)$$

where 2.6 is a dimensionless empirical constant and 0.4 is von Karman's constant.

The transfer resistance is used as a mathematical device to establish an upper limit on the deposition velocity. The user can enter transfer resistance, but as a default, 10 and 100 s/m are assumed for gas (iodine) and particles, respectively (Ramsdell et al. 1994).

Equation (4.63) is appropriate for small particles where the settling velocity of the particles may be neglected. A gravitational settling term should be added for larger particles when the settling velocity is not negligible. In this case, the deposition velocity is

$$v_{dd} = (r_a + r_s + r_t + r_a r_s v_s)^{-1} + v_s \quad (4.67)$$

where v_s is the gravitational settling velocity, which is a function of particle size and density. The settling velocity used in the codes is the same as that for the EPA ISC3 model (EPA 1995) and is given by

$$v_s = \frac{(\rho - \rho_{AIR}) g d_p^2 c_2 S_{CF}}{18\mu} \quad (4.68)$$

where ρ = the particle density (g/cm^3)
 ρ_{AIR} = the air density ($= 1.2 \times 10^{-3} \text{ g/cm}^3$)
 d_p = the particle diameter (μm)
 μ = the absolute viscosity of air ($= 1.81 \times 10^{-4} \text{ g/cm/s}$)
 c_2 = air units conversion constant ($= 1 \times 10^{-8} \text{ cm}^2/\mu\text{m}^2$)
 S_{CF} = the slip correction factor, which is computed as

$$S_{CF} = 1 + \frac{2 x_2 (a_1 + a_2 \exp(-\frac{a_3 d_p}{x_2}))}{10^{-4} d_p} \quad (4.69)$$

where x_2 , a_1 , a_2 , and a_3 are constants with values of 6.5×10^{-6} , 1.257, 0.4, and 0.55×10^{-4} , respectively.

4.2.5.2 Wet Deposition

Wet deposition of gases is treated the same as dry deposition in Equation (5.88) with ω_{2ij} replacing ω_{1ij} and v_{dw} , a wet deposition velocity, replacing v_{dd} . The model used assumes that the exchange of gas between the air and precipitation is sufficiently rapid that an equilibrium is maintained between the concentrations in the air and in the precipitation. With this assumption, the flux of gas to the surface is proportional to the concentration of the gas in the air at ground level, the precipitation rate, and a solubility coefficient related to the Henry's law constant for

the gas. A wet deposition velocity, similar to the dry deposition velocity, combines the precipitation rate and solubility coefficient. It is

$$v_{dw} = c S P_r \quad (4.70)$$

where S = the solubility coefficient
 P_r = the precipitation rate in mm/hr
 c = a conversion factor to convert P_r to m/s.

The wet deposition model for gases assumes that the gases are dissolved rapidly by the precipitation. Implicit in this assumption is the assumption that the precipitation is liquid or at least has a liquid exterior because the rate of exchange of gases between air and ice is sufficiently low to be negligible. As a result, the wet deposition velocity for snow is zero if temperature data are available and the temperature is less than -3°C . If temperature data are not available, the wet deposition velocity is zero for all forms of frozen precipitation.

The wet deposition of particles is modeled using a washout coefficient. This model assumes that the particles are collected by impaction as the precipitation falls through the plume. The model also assumes that the scavenging process is irreversible, i.e. once collected the particles remain with the precipitation. The general model for wet deposition of particles is

$$\omega 3_{ij}(t) = \Lambda \int_0^\infty \chi_{ij}(z, t) dz \quad (4.71)$$

where Λ is the washout coefficient. Washout coefficients are assumed to be functions of the type of precipitation (liquid or frozen), the precipitation rate, and the collection efficiency of the precipitation.

For liquid precipitation (rain, drizzle, etc), henceforth referred to as rain, the washout coefficient is calculated by the expression discussed in Slinn (1984), which is

$$\Lambda_r = \frac{C E P_r}{0.35 P_n^{1/4}} \quad (4.72)$$

where Λ_r = the washout coefficient for rain
 C = empirical constant with value of 0.5
 E = average collection efficiency, assumed to be 1.0
 P_r = precipitation rate in mm/hr
 P_n = normalized precipitation rate ($P_r / 1 \text{ mm/hr}$).

During period of frozen precipitation (snow, hail), henceforth referred to as snow, the washout coefficient will be calculated by

$$\Lambda_s = 0.2 P_r \quad (4.73)$$

where Λ_s = the washout coefficient for snow
 0.2 = empirical constant with units of mm^{-1}
 P_r = the precipitation rate in mm/hr, liquid water equivalent.

The integral in Equation (4.71) can be solved based on equations used to calculate the concentration, as only the reflection term, $G(z)$, is dependent upon z . If only the first terms of the reflection terms are used, the wet deposition of particles can be estimated as follows.

The sector averaged point and area source for the plume is given by

$$\omega_3 = \frac{\Lambda Q'}{U \theta_w} \quad (4.74)$$

The non-sector averaged point source for a plume is given by

$$\omega_3 = \frac{\Lambda Q' \exp[-0.5(\frac{y}{\sigma_y})^2]}{\sqrt{2\pi} U \sigma_y} \quad (4.75)$$

The non-sector averaged area source for a plume is given by

$$\omega_3 = \frac{\Lambda Q' 0.5 [\text{erf}(\frac{a+y}{\sqrt{2} \sigma_y}) + \text{erf}(\frac{a-y}{\sqrt{2} \sigma_y})]}{U} \quad (4.76)$$

In the puff model, the washout is calculated by

$$\omega_3 = \frac{\Lambda Q \exp[-0.5(\frac{r}{\sigma_r})^2]}{2\pi \sigma_r} \quad (4.77)$$

where Q' is the release rate corrected for depletion and decay and Q is the mass of the puff.

4.2.5.3 Total Deposition

Given the dry and wet deposition velocities, the surface contamination that accumulated at any point during the short period is computed as

$$D(x, y, T) = \sum_0^T [\omega_{1ij}(t) + \omega_{2ij}(t) + \omega_{3ij}(t)] \Delta t \quad (4.78)$$

where $D(x, y, T)$ is the total surface contamination (Ci/m^2) at position (x, y) and for time period T . The deposition rate, which is calculated in the chronic models, is given by

$$D'(x, y, T) = \frac{1}{T} D(x, y, T) \quad (4.79)$$

4.2.6. Radioactive Decay

Both the plume and puff models have been developed to handle in-transit decay. The decay is based on the general algorithm for radioactive decay with branching found in Streng (1997). The general solution is given by

$$Q_i(t) = \lambda_{ri} \sum_{n=1}^i K_{in} e^{-\lambda_{en} t} \quad (4.80)$$

where $Q_i(t)$ = activity of chain member i at time t
 λ_{ri} = radioactive transition rate constant (half-life) for chain member i (s^{-1})
 λ_{en} = effective lost rate constant for precursor radionuclide n and is given by $\lambda_{en} = L_i + \lambda_{rn}$ where L_i is the total rate constant for all physical transfers of chain member i from the medium (s^{-1})

and K_{in} is defined by

$$K_{11} = \frac{Q_1(0)}{\lambda_{r1}} \quad (4.81)$$

$$K_{in} (n = 1 \rightarrow i - 1) = \frac{\sum_{j=n}^{i-1} d_{ji} \lambda_{rj} K_{jn}}{\lambda_{ei} - \lambda_{en}} \quad (4.82)$$

$$K_{ii} = \frac{Q_i(0)}{\lambda_{ri}} - \sum_{n=1}^{i-1} K_{in} \quad (4.83)$$

where d_{ji} is the fraction [branching factor] of precursor radionuclide transitions (chain member j) that result in production of the chain member i .

In the models, the solution for radioactive decay is used to determine factors for decay and ingrowth for each member of the chain. The following method is used to determine these factors. First, the first member of the chain is assumed to have an activity of 1 and the fraction of decay of material and the ingrowth into the other chain members is calculated using Equation (4.79) assuming a specific time step. For the plume model, the time step is 900 seconds (15 minutes). Next, the second member of the chain is assumed to have an activity of 1 (all the other members have an activity of zero), and the decay and ingrowth factors are calculated for each member of the chain. The same technique is then applied to each member of the chain. Once all the factors have been calculated, the decay results can be constructed into a table like Table 4.7, where f_{11} is the fraction of chain member 1 left after decay (for the specific time period), f_{12} is the fraction of ingrowth to chain member 2 from chain member 1, f_{1n} is the fraction of ingrowth into chain member n from chain member 1, and so on. As ingrowth does not move up the chain, the fraction of ingrowth to chain 1 from chain 2 would be zero. Thus, the bottom triangle of the table (f_{ij} where the row number (i) is larger than the column number(j)), would contain zeros.

For the plume model, the in-transit decay and ingrowth is determined by applying the fractions (f_{ij}) to each of the time steps (time [distance/wind speed] to reach the receptor/900 seconds) required to reach the receptor.

Table 4.7 Chain Member Decay/Ingrowth Fraction Matrix

	Chain Member 1	Chain Member 2	...	Chain Member n
Chain Member 1	f_{11}	f_{12}	...	f_{1n}
Chain Member 2	f_{21}	f_{22}	...	f_{2n}
...
Chain Member n	f_{n1}	f_{n2}	...	f_{nn}

4.2.7 Depletion

Mass balance is maintained in the atmospheric code. Material deposited on the surface by dry and wet deposition is removed from the material in the plume, which acts to reduce the release rate or mass of the plume. Material is not selectively removed from the bottom of the plume. This approach is a variation of the source-depletion model described in Hanna et al. (1982).

In the atmosphere, deposition results in a mass deficit in the layer of air next to the surface. Source-depletion models instantaneously propagate this deficit through the full vertical

extent of the plume. This propagation is unrealistic, particularly in stable atmospheric conditions. Using the resistance analogy to estimate the deposition velocities does not deal with this problem explicitly. However, using the resistance analogy results in lower deposition velocities during stable conditions, which reduces the magnitude of the error.

For the plume model, the depletion of the source term per unit distance is given by Van der Hoven (1968) as

$$\frac{dQ'}{dx} = - \int_{-\infty}^{\infty} \omega(x, y) dy = - \int_{-\infty}^{\infty} v_d \chi dy \quad (4.84)$$

For a point source, the integral can be solved to give

$$\frac{dQ'}{dx} = - \sqrt{\frac{2}{\pi}} \frac{v_d}{U} \frac{Q'}{\sigma_z} G(z) \quad (4.85)$$

which can be rearranged as

$$\int_{x_1}^{x_2} \frac{dQ'}{Q'} = - \sqrt{\frac{2}{\pi}} \frac{v_d}{U} \int_{x_1}^{x_2} \frac{G(z)}{\sigma_z} dx \quad (4.86)$$

Solving the integral on the left hand side gives

$$\ln \frac{Q'(x_2)}{Q'(x_1)} = - \sqrt{\frac{2}{\pi}} \frac{v_d}{U} \int_{x_1}^{x_2} \frac{G(z)}{\sigma_z} dx \quad (4.87)$$

or

$$Q'(x_2) = Q'(x_1) \exp\left(-\sqrt{\frac{2}{\pi}} \frac{v_d}{U} \int_{x_1}^{x_2} \frac{G(z)}{\sigma_z} dx\right) \quad (4.88)$$

The integral of the reflection term, $G(z)$, and the vertical dispersion coefficient normally can not be solved explicitly. In the code, the integral is approximated numerically using a simple trapezoidal rule. The integral is calculated at each receptor in the order of closest receptor to the source to farthest receptor from the source. Thus, the depletion for a receptor would be the sum of the depletion at the previous receptor and the Equation (4.88), where x_1 is the distance to the previous receptor and x_2 is the distance to the current receptor. If the distance between receptors

is greater than twice the distance from the previous receptor to the source, depletion is calculated at an intermediate point that is twice the distance from the previous receptor to the source. For example, if the two receptors are at 100 and 500 meters, the depletion at two intermediate points, 200 and 400 meters, would be calculated. The depletion at 500 meters would be the sum of the depletion at 400 meters and Equation (4.88) with $x_1 = 400$ meters and $x_2 = 500$ meters. These intermediate points are calculated to prevent unreasonable errors in the estimation of the integral. To prevent errors in estimating the integral, depletion does not occur for distances less than 100 meters from the source.

At a downwind distance where $\sigma_z \geq 1.2 H$ (e.g., the concentration is uniformly mixed through the boundary layer), Equation (4.85) can be solved to give

$$Q'(x_2) = Q'(x_1) \exp\left(-\frac{v_d[x_2 - x_1]}{UH}\right) \quad (4.89)$$

As Equation (4.89) does not involve an integral, at the distances where $\sigma_z \geq 1.2H$, Equation (4.89) is used to estimate the depletion of the plume. If this distance where $\sigma_z = 1.2H$ occurs between two receptors, the depletion is a sum of the depletion calculated by Equation (4.88) up to the distance where $\sigma_z = 1.2H$ and Equation (4.89) for the rest of the distance to the second receptor.

For the area source, depletion is assume to not occur until the plume is far enough distance downwind that the area source is similar to a point source (5a for the sector average model and 10a for the non-sector average model). Under this assumption, the equations used for depletion is the same as for a point source (i.e., Equations 4.88 and 4.89). In cases of very large area source, the model tends to underpredict the amount that is depleted. Thus, the concentration and deposition rates would be overpredicted.

For the washout of particles, the integration of deposition term can be solved to give the following

$$Q'(x_2) = Q'(x_1) \exp(-\Lambda \Delta t) \quad (4.90)$$

where Δt is $(x_2 - x_1)/U$.

4.3 FINITE PLUME SUBMERSION DOSE

Earlier versions of GENII calculated cloud-shine doses using either a semi-infinite cloud model or a finite-plume model based on the model developed for MESORAD (Scherpelz et al. 1986, page 31). The first of these models assumes that activity is uniformly distributed through a large volume, and the second assumes that activity is concentrated in a finite number of points distributed through a volume to represent the actual activity distribution. The use of the semi-infinite cloud model is usually inappropriate in the immediate vicinity of the release point, and application of the MESORAD finite-plume model to cloud-shine dose estimates near the release point did not prove satisfactory. Consequently, the cloud-shine dose models in GENII V2 NESHAPS have been significantly revised from those used in earlier versions. The basic framework is that also implemented in the RASCAL 3.0 emergency response code (Sjoreen et al. 2001).

Cloud-shine models based on line sources and plane sources have been developed that are analogous to the point-source model used in MESORAD. These models are used, along with the point-source model, until plumes grow to sufficient size that the assumptions associated with the semi-infinite cloud model are met. In the MESORAD point-source model, point-source dose rates were calculated as a function of distance for each radionuclide from gamma energies. This calculation, which was repetitive and time consuming, has been deleted. The finite-plume cloud-shine models in GENII make use of precalculated dose rate vs distance curves. These curves are provided in the radionuclide data base for each radionuclide for a 1 Ci (0.01 Sv) point source, and a 1 Ci/m (0.01 Sv/m) infinite line source. The remainder of this section describes the GENII V2 NESHAPS cloud-shine models.

A new set of models has been developed for cloud-shine dose calculations in the GENII plume models. Near the source, the plume is divided into a large number of equal-strength line sources spaced to properly represent the distribution of activity in the plume. The dose rates from these line sources are used to calculate the ground-level dose rate as a function of horizontal distance from the plume axis. This relationship is then used to calculate dose rates and 15-min doses at receptor locations. When the width of the plume is sufficient ($\sigma_y = 400$ m), the GENII plume models switch from the line source model to an infinite slab model. Finally, when the vertical dimensions of the plume are sufficient to make the semi-infinite cloud model appropriate ($\sigma_z = 400$ m or uniformly mixed plume with a thickness of 600 m), the GENII models switch to a semi-infinite cloud model.

Dose rates from line sources are calculated using

$$D'_1(\rho) = \sum_{n=1}^N Q'_{ln} D'_n(\rho) \quad (4.91)$$

where

$D'_1(\rho)$ = dose rate (Sv/s) at a distance ρ from an infinite line source of Q'_{ln} (Ci/m),

Q'_{ln} = line source strength (Ci/m), $Q'_{ln} = Q'_n / u$ where Q'_n is in Ci/s, and

$D'_n(\rho)$ = line source dose rate factor [(Sv/s)/(Ci/m)] for radionuclide n .

The line-source dose rates are combined to get the plume dose rate by summing over all line sources. The number of line sources used is determined by the horizontal dispersion parameter, σ_y . If σ_y is greater than 200 m, 100 lines (10x10) are used to describe the concentration distribution in the plume. Otherwise, the concentration distribution is described by 36 lines (6x6). In either case, the lines are spaced horizontally and vertically such that all lines represent the same fraction of the activity in the plume. The plume dose rate is given by

$$D'(y) = \frac{C_R}{N_l} \sum_i \sum_j D'_l(y_{ij}) \quad (4.92)$$

where

- $D'(y)$ = plume dose rate ,
- y = distance from the ground-level projection of the center of the plume,
- C_R = finite line correction factor,
- N_l = number of line sources (36 or 100),
- i,j = line source indices, and
- $D'_l(y_{ij})$ = infinite line, line-source dose rate.

The finite line source correction factor is included in Eq. (4.92) to account for the fact that the plume does not extend upwind of the release point. A correction factor could be calculated by numerical integration of a rather complex equation. However, an approximate correction factor of adequate accuracy can be calculated using

$$C_R = 0.5 \left[1 + \frac{x}{(R^2 + h_e^2)^{1/2}} \right] \quad (4.93)$$

where

- x = downwind distance (m) to a point beneath the plume centerline at the intersection of the plume centerline and a perpendicular line passing through the receptor,
- R = distance (m) from the release point to the receptor, and
- h_e = effective release height.

In the case of a ground-level release and a receptor on the plume centerline, the correction factor will be one. However, generally the correction factor is less than one. For a 0.7 MeV photon, the correction factor given by Eq. (4.93) corresponds to a receptor at a position approximately 100 m off of the plume centerline. Doses will be slightly over-estimated for receptors that are closer than 100 m and slightly under estimated for receptors that are farther than 100 m from the centerline.

When the horizontal dispersion parameter exceeds 400 m, the GENII plume models shift from a line-source based finite plume model to an infinite plane model. Thus,

$$D'_{sl}(r) = \frac{0.1 \sum_n Q'_n DF_{pn}}{2\pi\sigma_y u} \exp \left[-0.5 \left(\frac{r}{\sigma_y} \right)^2 \right] \sum_{i=1}^{10} (1 + k\mu z_i) \exp(-\mu z_i) \quad (4.94)$$

for plumes.

Finally, when the vertical extent of the plume is sufficient ($\sigma_z = 400$ m, or a uniformly mixed plume with a 600 m vertical extent), the plume models shift to a semi-infinite plume cloud shine model. The cloud-shine dose rate calculated using the semi-infinite cloud model is

$$D'(r) = [\chi(r)/Q'] \sum_n Q'_n DF_{sien} \quad (4.95)$$

where $\chi(r)/Q'$ is calculated using Eq. (4.1) or a variation thereof, as appropriate.

4.4 METEOROLOGICAL DATA

The atmospheric model calculations are based on the use of observed meteorological data. Observed meteorological data can occur in two general forms, hourly meteorological data where the meteorological information is recorded every hour and a joint frequency distribution of wind speed, wind direction, and atmospheric stability, in which the hourly meteorological data has been summarized. Two programs, HRLYPROC and JJFDPROC, were developed that take meteorological data stored in the hourly (HRLYPROC) or joint frequency distribution (JJFDPROC) and manipulate the data into a single format that can be read by the atmospheric models. The users' manual discusses the input data required by the model, adjustments to the data, and calculation of meteorological variables that are not directly measured, such as stability classifications.

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5.0 CHRONIC EXPOSURE MODULE

The chronic exposure module provides estimates of exposure media concentrations resulting from groundwater, surface water, and airborne contamination pathways. Exposures are treated as continuous and constant over an extended time period (a year or longer) with consideration of the time variation in air and water concentrations from year to year. In this section, the communication interfaces are described first, followed by the exposure pathway models for external exposure, ingestion exposure, and inhalation exposure.

The chronic exposure module uses as input radionuclide concentrations in air or water, as generated by the transport models or from user defined input. The output from the module is the radionuclide concentration in various exposure media (air, crops, animal products, soil, aquatic foods, etc.). The exposure pathways considered by the chronic module are indicated in Table 5.1. Because GENII V2 has several versions, only a subset are available in the NESHAPS edition. Model details are given in following sections.

Table 5.1 Exposure Pathways for the Chronic Terrestrial and Aquatic Module

<u>Transport Mode</u>	<u>Exposure Pathways</u>	<u>Exposure Route</u>	<u>In NESHAPS</u>
atmosphere	air	inhalation	Yes
	soil resuspension	inhalation	Yes
	soil ingestion	ingestion	Yes
	immersion in air	external	Yes
	ground exposure	external	Yes
	food crops	ingestion	Yes
	animal products	ingestion	Yes
groundwater	drinking water	ingestion	No
	shower volatilization	inhalation	No
	irrigated food crops	ingestion	No
	irrigation/animal products	ingestion	No
	ground exposure	external	No
surface water	drinking water	ingestion	No
	shower volatilization	inhalation	No
	shower water ingestion	ingestion	No
	irrigated food crops	ingestion	No
	irrigation/animal products	ingestion	No
	ground exposure	external	No
	swimming	external	No
	swimming water ingestion	ingestion	No
	boating	external	No
	shoreline sediment	external	No
soil contamination	aquatic foods	ingestion	No
	soil resuspension	inhalation	Yes
	soil ingestion	ingestion	Yes
	ground exposure	external	Yes

5.1 COMMUNICATION INTERFACES

The input files for the chronic exposure module are the global input data file (GID), the atmospheric concentration file (ACF), the water concentration file (WCF) (not used in NESHAPS edition), and one auxiliary data communication files (radionuclide master data library). The communication interfaces are indicated in Figure 5.1. The atmospheric concentration file (ATO) is generated by the atmospheric transport module. The water concentration file (WCF) is generated by the surface water module (or other external program that is capable of generating the water concentration file information). The GID file section for the chronic exposure module is generated by the user interface program. It contains information describing the scope of the analysis and all user-provided input parameters for an analysis. The structure and content of the files are given in Appendix A and B.

The output from the chronic terrestrial and aquatic pathway module is the concentration in various media to which individuals or populations are exposed. Along with each concentration, the duration of exposure is also provided, representing the period of integration for the particular pathway. This information is provided in a primary data communication file, the exposure pathway media concentration output file (EPF).

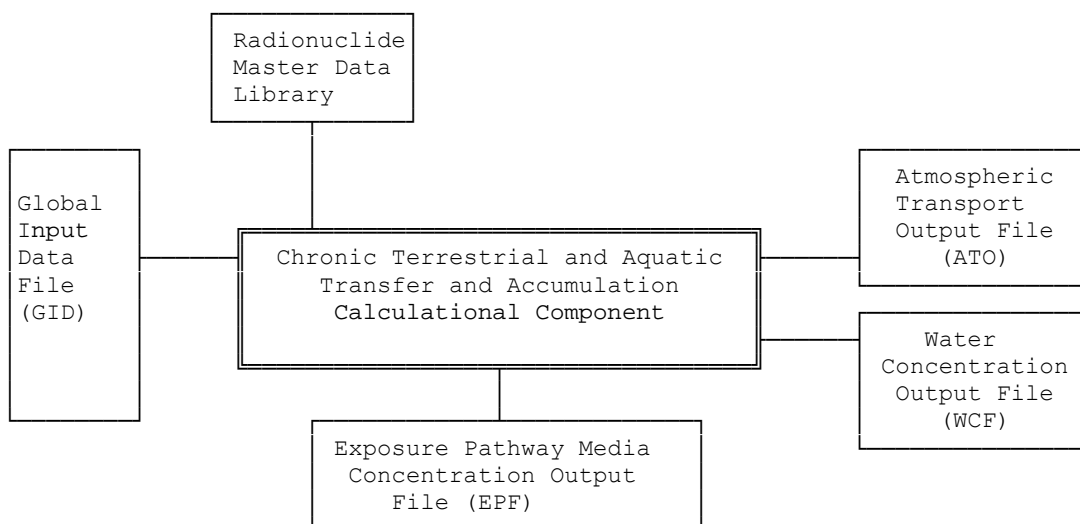


Figure 5.1 Communication Interfaces for the Chronic Pathway Component

5.2 SOIL MODEL

The soil model used with the chronic exposure model is described in this section. This model allows calculation of surface soil concentrations as a function of time with consideration of: 1) leaching from surface soil, 2) deposition from air to surface soil, 3) irrigation deposition from water to surface soil (not used for NESHAPS edition), and 4) loss from surface soil from plant harvest. The soil model is applied separately for each exposure pathway allowing different soil concentrations to be used to evaluate each exposure pathway. For example, different soil concentrations can be defined for leafy vegetable crops consumed directly by humans, and for forage crops used by milk animals.

The general soil model is illustrated in Figure 5.2. This figure shows the compartment considered in the model, the surface zone. The surface soil is the portion on which deposition from the atmosphere and irrigation occurs, and that from which resuspension occurs. Radionuclides may be lost from the surface soil through harvest removal, radiological decay, and leaching out of the surface soil layer. All losses from the surface zone (harvest removal or leaching) are assumed to leave the system.

The soil model allows evaluation of the soil concentration over the intake period, accounting for prior atmospheric deposition and prior irrigation water deposition. It is assumed that the time of prior deposition from air and water is less than or equal to the time of start of intake. The soil model then evaluates the soil concentration at the start of the intake period. After the start of intake, the soil model is used to follow the change in soil compartment concentrations as intake is evaluated.

The deposition from prior years of deposition (air and water) is evaluated using atmospheric deposition and water concentration data provided as a function of time. The analysis is performed on an annual basis, using average atmospheric deposition and water concentrations for each year. The models and sub-models defined in the following section are applied on an annual basis as indicated by the time period parameter, T_{yr} , representing a one-year time period.

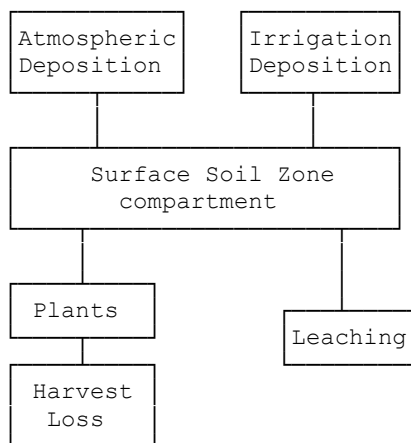


Figure 5.2 Chronic Module Soil Model

The model is defined by a differential equation that describes the change of concentration in surface soil as a function of time. The differential equation for the soil model compartment is defined in terms of the amount of each radionuclide chain member present in units of atoms. This representation is used for ease of understanding and ease of solving the equations. The final solutions are evaluated using the radioactive decay-chain processor described in Appendix C. The general solutions presented in that appendix are given in terms of atom units and activity units. For chronic releases, initial amount in the surface soil is set to zero. The decrease from harvest is modeled as a step function following the time of harvest and does not appear in the differential equation for the surface zone. The differential equation for chronic releases for the surface soil zone is as follows:

$$\frac{d A_i(t)}{d t} = (R_{wi} + R_{ai}) - (\lambda_{Li} + \lambda_i) A_i \quad (5.1)$$

where $A_i(t)$ = amount of radionuclide i in the surface soil zone at time, t (atoms)

R_{wi} = rate of input from irrigation water (atoms /y)

R_{ai} = rate of input from atmospheric deposition (atoms/y)

λ_i = rate constant for radioactive decay of radionuclide i (y^{-1})

λ_{Li} = rate constant for leaching of radionuclide from the surface soil zone (y^{-1}).

Various aspects of the soil model are described in the following subsections. The first section describes definition of air and water deposition during a year for chronic releases. The remaining sections describe estimation methods for the transfer rate constants defined for the soil model.

5.2.1 Activity from Air Deposition

For chronic release analyses the differential equation for surface soil includes terms for deposition from air. The initial concentrations are set to be zero. The amount at the end of a year is evaluated based on the amount present at the beginning of a year plus the amount deposited during the year. In the exposure pathway models that follow, the amount present during a year is composed of two terms: 1) the average amount present during the year from prior years' depositions, and 2) the average amount present from deposited during the year. The average amount present from prior years' contributions is represented by the term $C_{si}(T_{yr})$ with units of Bq/m². This amount is evaluated from the amount present at the end of the prior year (corrected as necessary according to soil model transfers), and accounting for radioactive decay and losses during the year. These evaluations are made using the decay processor described in Appendix C. The deposition during the current year is evaluated as defined for each exposure pathway.

5.2.2 Leaching from the Surface Soil Zone

Removal from the surface soils through leaching into deeper soils is treated by means of a soil removal rate constant. For surface soils the rate constant, λ_{si} , is a correction for long-term leaching of deposited radionuclides out of the surface soil (rooting and resuspension zones). The values for λ_{si} are calculated using the formula of Baes and Sharp (1981):

$$\lambda_{si} = \frac{10^{-2} (P + I - E)}{d_s \theta_s \left[1 + \frac{10^3 10^{-6} \rho_s}{\theta_s} Kd_{si} \right]} \quad (5.2)$$

where λ_{si} = removal rate constant for activity of radionuclide i in the surface soil layer (y^{-1})

P = total annual precipitation (cm/y)

I = total irrigation rate (cm/y)

E = total evapotranspiration rate (cm/y)

ρ_s = surface soil bulk density (kg/m^3)

θ_s = surface soil volumetric water content (mL/cm^3)

Kd_{si} = surface soil distribution coefficient for radionuclide i (mL/g)

10^{-2} = units conversion factor (m/cm)

10^3 = units conversion factor (g/kg)

10^{-6} = units conversion factor (m^3/ml)

5.2.3 Loss by Harvest

Loss of activity from the surface soil zone is modeled as a step function applied at the end of each calculational year. The amount of loss is calculated from the plant concentration at harvest, the annual plant yield, and the soil concentrations at harvest. The calculation is represented by the following equation.

$$C_{si}(t_+) = C_{si}(t_-) \left[(C_{si} - C_{ci}(Th_c) Y_c) / C_{si} \right] \quad (5.3)$$

where $C_{si}(t_+)$ = surface soil concentration at soil location s for radionuclide i after correction for harvest removal at time t (Bq/m^2)

$C_{si}(t_-)$ = surface soil concentration at soil location s for radionuclide i before correction for harvest removal at time t (Bq/m^2)

$C_{ci}(Th_c)$ = crop c concentration for radionuclide i at time of harvest (Bq/kg)

Y_c = annual yield of crop c (kg/m^2)

The multiplicative term represents the average fraction of the contaminant in soil to that in crops over the year; this term is used rather than a simple subtraction of amount harvested because, for short-lived radionuclides, the amount harvested over the year may actually be larger than the amount remaining in the soil at the end of the year.

5.3 EXTERNAL EXPOSURE PATHWAYS

External exposures from atmospheric transport include immersion in air and exposure to contaminated ground following deposition from air. Models for evaluating these exposure pathways are provided here.

5.3.1 External Plume Immersion

External exposure from immersion in a plume is evaluated in the atmospheric transport component and provided to subsequent components as the radiation dose (Sv) received during plume passage at specific locations. As such, no models need to be described in this section. The evaluation of radiation dose is performed using the finite dimensions of the plume. However, an alternate method for evaluating external exposure is described here using the semi-infinite plume model, which does not require knowledge of plume dimension. The model uses the average air concentration over the exposure period to estimate dose.

The input parameter for estimation of external exposure to the plume using the semi-infinite plume model is the average air concentration of a radionuclide in the plume, as estimated by the atmospheric transport component, $\chi_{nv} = C_{ai}$ = air concentration for radionuclide i at usage location a (Bq/m^3) from Equation 4.19.

5.3.2 External Ground Exposure

External exposure to contaminated ground is considered for atmospheric transport and deposition, and deposition from these sources from prior years' activity. The annual average value is used (requiring a time integral equation).

The exposure parameter for this pathway is the average soil concentration over the year of exposure in units of Bq/m^2 . If the exposure parameter is divided by the soil areal density, then the units are in Bq/kg. The soil concentration used in evaluation of the external exposure is given by the following expression that includes integral contributions from the two deposition routes (air, and water) plus the concentration present at the start of the year.

$$C_{esi}(T_{yr}) = \left[C_{si}(T_{yr}) + [R_{ait}] \frac{1}{\lambda_i T_{yr}} \left[T_{yr} - \frac{1 - e^{-\lambda_i T_{yr}}}{\lambda_i} \right] \right] / (d_s \rho_s) \quad (5.4)$$

where $C_{esi}(T_{yr})$ = average surface soil concentration at soil location s for radionuclide i including deposition during the year (Bq/kg)

$C_{si}(T_{yr})$ = average surface soil concentration at soil location s for radionuclide i during the current year from material present at the start of the year (Bq/m²)

R_{ait} = constant deposition rate of radionuclide i from air for year t (Bq/m²·y)

d_s = thickness of soil (m)

ρ_s = density of soil (kg/m³)

T_{yr} = one year integration period (y).

The terms at the right of Equation (5.4), following the deposition rate, represent evaluation of the time integral in soil from deposition at a constant rate with accumulation over a one year period. Division by the one-year period provides the average soil concentration during the year. This equation is appropriate when the exposure occurs relatively uniformly over the one-year period.

The deposition rates are defined for each transport route for the current year. The deposition rate from atmospheric deposition (R_{ait}) is taken directly from the atmospheric transport output file.

5.4 INGESTION EXPOSURE PATHWAYS

Ingestion exposures from atmospheric transport include ingestion of farm products and inadvertent ingestion of soil. Farm products include leafy vegetables, other vegetables, cereal grains, fruit, cow's milk, beef/meat, poultry, and eggs (poultry).

5.4.1 Terrestrial Farm Product Ingestion

The terrestrial farm product pathways include leafy vegetables, other vegetables, cereal grains, fruit, cow's milk, beef/meat, poultry, and eggs (poultry). The output parameter for these pathways is the average concentration of radionuclides in the food product at the time of consumption.

The terrestrial farm products may be contaminated by atmospheric deposition onto plants and soil, resuspension and deposition onto plant surfaces, or by animal consumption of contaminated forages. The plants may also be contaminated from root uptake of residual surface

soil contamination. The discussion of terrestrial farm product pathways begins with a discussion of methods for determining the air and soil concentrations that form the starting point for the calculation. The farm crops are then discussed, followed by the farm animal products.

5.4.1.1 Terrestrial Media Concentrations

Evaluation of farm product concentrations requires use of radionuclide depositions from air and soil. The air deposition used for the terrestrial farm product pathways is the deposition at the location of production of the farm product. This deposition is represented by an average value based on output of the atmospheric transport component. The annual average deposition rate is evaluated as the time integral of the deposited activity for deposition at a constant rate. The differential equation describing the deposition and accumulation is as follows.

$$\frac{d C_{ai}(t)}{dt} = R_{ait} - \lambda_i C_{ai}(t) \quad (5.5)$$

where $C_{ai}(t)$ = deposited amount from air to soil or plants at location a for radionuclide i as a function of time (Bq/m²)

R_{ait} = constant deposition rate of radionuclide i from air at location a (Bq/m² y)

λ_i = radiological decay constant for radionuclide i (y⁻¹).

The atmospheric deposition rate is the total deposition rate and is the sum of the dry deposition and wet deposition components (R_{aitd} and R_{aitw} , respectively).

The double time-integral of this equation is evaluated and divided by one year to give the annual average deposition per unit area. (The single integral results in the concentration at a point in time; the double integral divided by time provides the average over the time period.) This parameter is used to evaluate the total amount deposited on plants and soil. The deposition is taken directly from the atmospheric transport output file summing over the wet and dry deposition components.

The soil concentration is used for estimation of resuspension and re-deposition of activity onto plant surfaces, and for estimation of root uptake to plants. The concentration during the year is calculated as the sum of the surface soil concentration from the soil model (see Section 5.2), $C_{si}(T_{yr})$, and contributions from the three deposition pathways just mentioned. The soil concentration can be expressed as follows, in which the contribution from deposition is represented by a time integral of deposition over the current one-year period.

$$C_{ci}(T_{yr}) = C_{si}(T_{yr}) + \frac{R_{ait}}{\lambda_i T_{yr}} \left[T_{yr} - \frac{1 - e^{-\lambda_i T_{yr}}}{\lambda_i} \right] \quad (5.6)$$

where $C_{ci}(T_{yr})$ is the average concentration of radionuclide i in farmland soil for crop type c during the current year (Bq/m^2), $C_{si}(T_{yr})$ is the average concentration during the current year of radionuclide i in surface soil at location s (where crop c is grown) for deposition from prior years (Bq/m^2), and other terms are as previously defined.

5.4.1.2 Terrestrial Farm Crop Concentrations

The concentration in plants at the time of harvest is evaluated as the sum of contributions from deposition onto plant surfaces, plus uptake through the roots. The contribution from deposition includes deposition directly onto plant surfaces from the air (dry and wet deposition), deposition from material resuspended from soil, and material deposited from irrigation water. Weathering losses from plant surfaces prior to harvest is also included. The plant concentration at harvest from deposition pathways is evaluated as follows.

$$C_{dci}(T_{yr}) = \left[R_{aitd} r_{dc} + R_{aitw} r_{wc} + 3.15E7 C_{ci}(T_{yr}) RF_c Vd_i r_{dc} \right] \frac{Tv_c}{B_c} \left[\frac{1 - e^{-\lambda_{ei} Tg_c 2.74E-3}}{\lambda_{ei}} \right] \quad (5.7)$$

where $C_{dci}(T_{yr})$ = concentration of radionuclide i on plant type c at harvest from deposition processes for a one year period (Bq/kg wet weight)

T_{yr} = one year exposure period (y)

r_{dc} = interception fraction from airborne dry deposition for plant type c (dimensionless)

r_{wc} = interception fraction for airborne wet deposition to plant type c (dimensionless)

$C_{ci}(T_{yr})$ = average concentration of radionuclide i in farmland soil for crop type c for the current one year period (Bq/m^2)

RF_c = resuspension factor for crop soil (m^{-1})

Vd_i = deposition velocity of radionuclide i (m/s)

Tv_c = translocation factor for plant type c (dimensionless)

B_c = total standing biomass for plant type c (kg wet weight/ m^2)

λ_{ei} = effective loss rate constant from plant surfaces representing weathering and radioactive decay for radionuclide i (y^{-1})

$$\lambda_{ei} = \lambda_{wi} + \lambda_i$$

λ_{wi} = weathering rate constant for crops for radionuclide i (y^{-1})

Tg_c = crop growing period for plant type c (d)

3.15E7 = units conversion factor (sec/y)

2.74E-3 = units conversion factor (y/d).

The plants are also contaminated from root uptake from surface soil. The plant concentration at harvest from root uptake pathways is evaluated as follows.

$$C_{rci}(T_{yr}) = \frac{C_{ci}(T_{yr}) RP_{sc} Bv_{ci} f_c}{P_3} \quad (5.8)$$

where $C_{rci}(T_{yr})$ = concentration of radionuclide i in crop type c from root uptake pathways for a one year period (Bq/kg wet weight)

Bv_{ci} = concentration ratio for root uptake of radionuclide i in crop type c (Bq/kg dry plant per Bq/kg dry soil)

f_c = dry-to-wet ratio for plant type c (kg dry plant/kg wet plant)

P_3 = areal soil density of farmland soil (kg/m^2)

RP_{sc} = fraction of plant type c roots in surface soil zone (dimensionless).

The total concentration in the plant at the time of harvest is the sum of the contributions from deposition pathways and root uptake pathways.

$$C_{hci}(T_{yr}) = C_{dci}(T_{yr}) + C_{rci}(T_{yr}) \quad (5.9)$$

where $C_{hci}(T_{yr})$ is the concentration in plant type c at harvest for a one year period (Bq/kg wet weight) and other terms are as previously defined.

The concentration in crops at the time of consumption is evaluated by accounting for decay between harvest and consumption. The holdup delay time defines this time period. The calculation is performed using the decay processor (see Appendix C). The calculation is represented for the parent radionuclide as follows.

$$C_{csi}(T_{yr}) = C_{hci}(T_{yr}) e^{-\lambda_i T_{hc} 2.74E-3} \quad (5.10)$$

where $C_{csi}(T_{yr})$ = concentration of radionuclide i in crop type c at location s at the time of consumption over a one year period (Bq/kg wet weight)

Th_c = holdup delay time between harvest and consumption for crop type c (d)

λ_i = radiological decay constant for radionuclide i (y^{-1})

2.74E-3 = conversion factor years day^{-1} .

5.4.1.3 Terrestrial Farm Animal Product Concentrations

Pathways by which animal products may become contaminated include animal ingestion of plants and soil (the animals' inhalation is neglected as contributing little to the total). The concentration in feed plants is evaluated in a similar manner to the food crop calculations as defined in Equations (5.7) through (5.10), with parameters defined for animal feed crops in place of human food crops. The feed crop concentration at the time of animal feeding, $C_{cfi}(T_{yr})$, is evaluated using Equation (5.10) with the holdup delay time representing the time between harvest and consumption by animals. The soil concentration is the average surface soil concentration for the year given by the parameter, $C_{ai}(T_{yr})$, for animal product, a, and radionuclide i in units of Bq/m^2 , evaluated using Equation (5.6). The concentration in an animal product at the time of harvest (slaughter, milking, or egg collection), is evaluated as follows.

$$C_{hai}(T_{yr}) = Fa_i \left[C_{ai}(T_{yr}) d_{as} U_{as} + \sum_{f=1}^{N_{af}} C_{cfi}(T_{yr}) d_{af} U_{af} \right] \quad (5.11)$$

where $C_{hai}(T_{yr})$ = concentration of radionuclide i in animal product a at harvest of the animal product for a one year period (Bq/kg)

T_{yr} = one year exposure period (y)

Fa_i = transfer coefficient that relates daily intake rate by an animal to the concentration in an edible animal product a (Bq/L milk per Bq/d for milk and Bq/kg meat per Bq/d for meat)

$C_{ai}(T_{yr})$ = average concentration of radionuclide i in soil consumed by animals for a year (Bq/kg dry soil)

$C_{cfi}(T_{yr})$ = concentration of radionuclide i in animal feed type f at time of consumption for a one year period (Bq/kg wet weight)

d_{as} = fraction of animal type a soil intake that is contaminated (dimensionless)

U_{as} = daily soil intake rate for animal type a (kg/d) [currently set to zero]

N_{af} = number of feed types, f, fed to animal type a

d_{af} = fraction of animal type a feed type f intake that is contaminated
(dimensionless)

U_{af} = daily feed intake rate for animal type a of feed type f (kg/d)

and other terms are as previously defined.

The concentration in animal products at the time of consumption is evaluated by accounting for decay between harvest and consumption. The holdup delay time defines this time period. The calculation is performed using the decay processor (see Appendix C). The calculation is represented for the parent radionuclide as follows.

$$C_{asi}(T_{yr}) = C_{hai}(T_{yr}) e^{-\lambda_i Th_a 2.74E-3} \quad (5.12)$$

where $C_{asi}(T_{yr})$ = concentration of radionuclide i in animal product a at usage location s at the time of consumption for a one year period (Bq/kg wet weight)

Th_a = holdup delay time between harvest and consumption for animal product a (d)

λ_i = radiological decay constant for radionuclide i (y^{-1})

$2.74E-3$ = conversion factor years day^{-1} .

5.4.1.4 Initial Interception Fraction

The initial interception fraction for a given vegetation type is a factor that accounts for the fact that not all of the material deposited within a unit area will end up on vegetation surfaces. The fraction of the total deposition that initially resides on plants is the interception fraction. Interception fractions are needed for dry and wet deposition from air.

The interception of material in water, r_{ic} , is not well studied. Thus, a default value of 0.25 is used for all materials deposited on all plant types by irrigation.

An empirical relationship between biomass and interception fraction from atmospheric dry deposition was originally suggested by Chamberlain (1967). This model has been expanded by Pinder, Ciravolo, and Bowling (1988) for grasses and other species. The following form of the equation is used for grasses, leafy vegetables, and grains, where the constant 2.9 is empirically derived:

$$r_{dc} = 1 - e^{-2.9 Y_c f_c} \quad (5.13)$$

where r_{dc} = interception fraction for atmospheric dry deposition to crop type c
(dimensionless)

Y_c = standing biomass of the growing vegetation for crop type c (kg wet weight/m²)

f_c = dry-to-wet weight biomass ratio for crop type c (kg dry weight per kg wet weight).

A similar equation, with an empirical constant of 3.9, is used for fruits and other vegetables:

$$r_{dc} = 1 - e^{-3.6 Y_c f_c} \quad (5.14)$$

where terms are as previously defined. The dry-to-wet ratio is required because the Pinder formulations are given in terms of dry biomass. This formulation results in the need to define the growing biomass, as well as the harvested yield (for use with the harvest removal term defined in Section 6.2.7). The values for biomass and dry-to-wet ratio are given in Table 5.2.

The interception fraction for wet deposition is evaluated as a function of the rainfall rate and standing biomass based on experimental observations of Proel and Hoffman (1993). The data by Proel and Hoffman were used to develop empirical relationships for anions, cations, and for insoluble particles. For anions, such as iodide and sulfate, the interception fraction is evaluated as follows:

$$r_{wc} = 2.3 Y_c f_c R^{-0.92} \quad (5.15)$$

where r_{wc} = interception fraction from wet deposition to crop type c (dimensionless)

Y_c = standing biomass of the growing vegetation for crop type c (kg wet weight/m²)

f_c = dry-to-wet weight biomass ratio for crop type c (kg dry weight per kg wet weight).

R = rainfall rate (mm/d).

For particles, Proel and Hoffman presented the following empirical relationship based on experiments using microspheres:

$$r_{wc} = 2.95 Y_c f_c R^{-0.191} \quad (5.16)$$

where terms are as previously defined.

Table 5.2. Harvested Yield, Standing Biomass, and Ratio of Dry to Wet Vegetation Used in Interception and Harvest Removal Models

<u>Category</u>	Harvested ^(a) Yield (wet) <u>for Soil Removal</u>	Standing ^(b) Biomass (wet) <u>for Interception</u>	Dry-to-Wet ^(c) Ratio for <u>Interception</u>
Leafy Vegetables	2.0	2.0	0.10
Other Vegetables	4.0	2.0	0.25
Grain	0.6	0.8	0.18
Fruit	2.0	3.0	0.18
Meat: Forage/Hay	2.0 ^(d)	1.0	0.20
Meat: Grain	0.6	0.8	0.18
Poultry & Eggs:			
Grain	0.6	0.8	0.18
Milk: Fresh Forage	3.0 ^(d)	1.5	0.20
Milk: Hay	2.0 ^(d)	1.0	0.20

- (a) Adapted from data in Shor, Baes, and Sharp (1982) for the Washington counties of Benton, Franklin, and Yakima; these represent highly-productive agriculture.
- (b) Derived from data in Shor, Baes, and Sharp (1982), Strenge, Bander, and Soldat (1987), or Napier et al. (1980).
- (c) Adapted from Till and Meyer (1983), Section 5.
- (d) Multiple cuttings

5.4.1.5 Resuspension Factor

The resuspension factor relates the radionuclide concentration in soil (per unit area) to the concentration in air. The resuspension factor for food crop and animal product pathways is representative of conditions on farmland, which may be different from the resuspension factor for the inhalation exposure pathway. Farmland would be expected to be tilled and have soil generally looser than soil for the general residential exposure situations.

5.4.1.6 Translocation Factor and Weathering Loss

Material deposited on plant surfaces is subject to absorption and removal processes. The translocation factor indicates the fraction of total deposition to plant surfaces that is incorporated into edible parts of the plant. A value of 1 is assumed for leafy vegetables and forage crops, and 0.1 for all other vegetation.

Losses from plant surfaces are represented by a weathering rate constant, λ_{wi} . The rate constant is based on a weathering half time of 14 days (as used by many sources; originally derived by Soldat et al. 1974).

5.4.2 Inadvertent Soil Ingestion

The inadvertent ingestion of soil is evaluated for all media (atmospheric deposition to soil, groundwater as a contaminated medium for irrigation, and surface water as a contaminated medium for irrigation). The average concentration in soil over the current one year period is evaluated as described in Section 9.2. The exposure parameter for ingestion of soil is the average soil concentration (Bq/kg soil) evaluated as follows.

$$C_{dsi}(T_{yr}) = \frac{10^3}{10^4 \rho_s d_s} \left[C_{si}(T_{yr}) + \frac{R_{ait}}{\lambda_i T_{yr}} \left(T_{yr} - \frac{1 - e^{-\lambda_i T_{yr}}}{\lambda_i} \right) \right] \quad (5.17)$$

where $C_{dsi}(T_{yr})$ = average concentration at soil location s for radionuclide i in soil consumed during the current year (Bq/kg)

$C_{si}(T_{yr})$ = average surface soil concentration at soil location s for radionuclide i during the current year (Bq/m²)

ρ_s = density of surface soil (g/cm³)

d_s = thickness of surface soil layer (cm)

10^4 = units conversion factor (cm²/m²)

10^3 = units conversion factor (g/kg)

and other terms are as previously defined. The inclusion of deposition terms from air is evaluated for each location as appropriate to the defined exposure scenario.

5.5 INHALATION EXPOSURE PATHWAYS

Inhalation exposure pathways include direct inhalation of contaminated plumes and inhalation of resuspended activity from soil. These exposure pathways are described in this section. The output parameter for each pathway is the average air concentration over the exposure period (current year).

5.5.1 Inhalation of Air

The output from the atmospheric transport component is the air concentration at specific locations. This concentration represents the average air concentration for exposure via inhalation, Equation 4.19.

5.5.2 Inhalation of Resuspended Soil

The model for inhalation exposure from resuspended activity uses the resuspension factor approach (as described in Section 5.4.1.2). The resuspension factor relates the soil concentration (per unit area) to the air concentration (per unit volume) and has units of m^{-1} . The use of resuspension factors is based on the assumption that the particulate matter in the air has the same activity as the soil at the location. This is represented mathematically as follows.

$$C_{\text{sai}}(T_{\text{yr}}) = \text{RF}_a \left[C_{\text{si}}(T_{\text{yr}}) + \frac{R_{\text{ait}}}{\lambda_i T_{\text{yr}}} \left(T_{\text{yr}} - \frac{1 - e^{-\lambda_i T_{\text{yr}}}}{\lambda_i} \right) \right] \quad (5.18)$$

where $C_{\text{sai}}(T_{\text{yr}})$ = air concentration of radionuclide i at soil resuspension exposure location a for a year (Bq/m^3)

RF_a = resuspension factor for soil exposure locations (m^{-1})

$C_{\text{si}}(T_{\text{yr}})$ = average surface soil concentration over the current year at the soil exposure location s from material deposited in prior years (Bq/m^2)

and other terms are as previously defined. The inclusion of deposition terms from air is evaluated for each location as appropriate to the defined exposure scenario.

The resuspension factor may be estimated in one of two ways - either by using a time-dependent function developed by Anspaugh et al. (1975) or by means of a mass loading factor. The Anspaugh resuspension factor is given as follows.

$$\text{RF}_a = 10^{-4} e^{-0.15 \sqrt{t}} + 10^{-9} \quad (5.19)$$

where 10^{-4} = resuspension factor at the time of initial deposition to soil (m^{-1})

t = time after initial deposition of material to soil (d)

0.15 = effective decay constant controlling the availability of material for resuspension ($\text{d}^{1/2}$)

10^{-9} = resuspension factor after 17 years (m^{-1}).

The second term in this equation is added based on the assumption that no further measurable decrease in the resuspension factor process occurs after about 17 years, the longest period for which there are data available.

In the implementation, an assumption is made that only the top thin layer of soil is available for resuspension using the Anspaugh method.

The second method for estimating the resuspension factor is to use the atmospheric mass loading of soil in air, as follows.

$$RF_a = \frac{S}{\rho_s d_{rs} 10^6} \quad (5.20)$$

where S = mass loading of soil in air (g/m^3)

ρ_s = surface soil density (g/cm^3).

d_{rs} = thickness of surface soil layer at resuspension location (m). In the code, this is assumed to be the full general surface soil layer; a modification as for the Anspaugh model is not needed.

10^6 = units conversion factor (cm^3/m^3).

5.5.3 Indoor Inhalation

Indoor air is assumed to contain contaminants that have infiltrated from outdoors. The outdoor air concentration calculated using Equation 4.19 is used to give the total indoor air concentration.

5.6 SPECIAL RADIONUCLIDE MODELS: TRITIUM AND CARBON-14

The behavior of the radionuclides tritium and carbon-14 in exposure pathways is handled in a special manner. The concentrations of tritium or carbon-14 in environmental media (soil, plants, and animal products) are assumed to be related to the specific activity (Becquerels of radionuclide per kilogram of soluble element) in the contaminating medium (air or water). The fractional content of hydrogen or carbon in a plant or animal product is then used to compute the concentration of tritium or carbon-14 in the food product under consideration. The hydrogen contents in both the water and the nonwater (dry) portion of the food product are used when calculating the tritium concentration. The creation of organically-bound tritium in plant and animal products from intake of HTO is also addressed.

For airborne releases, it is assumed that plants obtain all their carbon from airborne carbon dioxide and that animals obtain all their carbon through ingestion of plants.

The special models for ^3H as water vapor (HTO) and elemental tritium gas (HT) are described first. The models described are a variant of the model proposed by Peterson and Davis (2002). The ^{14}C models are then described.

5.6.1 Special Tritium Models

Tritiated Water (HTO)

For HTO releases, concentrations in air moisture C_{am} ($Bq\ L^{-1}$) are found by dividing the concentration in air ($Bq\ m^{-3}$) by the absolute humidity ($kg\ or\ L\ m^{-3}$).

To estimate HTO concentrations in plant products, it is assumed conservatively that the concentration of HTO in plant water equals $0.9\ C_{am}$ for leafy vegetables and pasture and $0.8\ C_{am}$ for fruit, root crops and other vegetables, and grain. These reduction factors account for dilution from soil water, which has a lower tritium concentration than does air moisture for atmospheric releases and which affects fruit and root crops more than leaves (Table 5.3). OBT concentrations are estimated from a plant water concentration of $0.9\ C_{am}$ for all plant types, since OBT is assumed to form exclusively in the leaves and to be translocated to other plant parts. Then, isotopic discrimination occurring in the formation of OBT (Table 5.4) is assumed conservatively to result in an OBT concentration 0.9 times the concentration of HTO in plant water.

The equation for calculating concentrations of HTO in plant products ($Bq\ kg^{-1}\ fw$) is:

$$C_{pp_HTO} = RF_{pp} C_{am} F_{fw_pp} \quad (5.21)$$

where

RF_{pp} = reduction factor that accounts for low soil water concentrations relative to concentrations in air moisture and varies by vegetable type

The equation for calculating concentrations of OBT in plant products ($Bq\ kg^{-1}\ fw$) is:

$$C_{pp_OBT} = RF_1 ID_{pp} C_{am} F_{dm_pp} W_{eq_pp} \quad (5.22)$$

where RF_1 = reduction factor for plant leaves

ID_{pp} = isotopic discrimination factor for plant products

Values and definitions for the parameters appearing in Eqns (5.21) and (5.22) for leafy vegetables, fruit, root and other vegetables, grain and pasture are shown in Table 5.3. Values for fresh and dry matter fractions and water equivalent factors were obtained from Geigy (1981).

HTO concentrations in animals are assumed to equal the weighted average tritium concentration of ingested water based on the fraction of water supplied by each source. These sources comprise food (from plant water and digested organically bound molecules) and drinking water.

The concentration of tritium in animal products is calculated from the concentrations in feed and water, as follows.

$$C_{\text{HTOap}}(T_{\text{yr}}) = F_{\text{wa}} \frac{C_{\text{wH}}(T_{\text{yr}}) U_{\text{wa}} d_{\text{aw}} + \sum_{f=1}^{N_{\text{fa}}} C_{\text{cfH}}(T_{\text{yr}}) U_{\text{af}} d_{\text{af}}}{U_{\text{wa}} + \sum_{f=1}^{N_{\text{fa}}} (F_{\text{fw_pp}} U_{\text{af}} + F_{\text{dm_pp}} W_{\text{eq_pp}} U_{\text{af}})} \quad (5.23)$$

where $C_{\text{HTOap}}(T_{\text{yr}})$ = concentration of tritiated water in animal product a at time of consumption by humans over a one year period (Bq/kg)

F_{wa} = fraction of water in animal product a (dimensionless)

$C_{\text{wH}}(T_{\text{yr}})$ = average concentration of tritium i in water consumed by animal type a over a one year period (Bq/L)

U_{wa} = daily water intake rate for animal type a (L/d)

d_{aw} = fraction of animal type a water intake that is contaminated (dimensionless)

$C_{\text{cfH}}(T_{\text{yr}})$ = concentration of tritium (the sum of the water and organic portions, estimated as described above) in animal feed type f at time of consumption for a one year period (Bq/kg wet weight)

U_{af} = daily intake rate for animal type a of feed type f (kg/d)

d_{af} = fraction of animal type a feed type f intake that is contaminated (dimensionless)

N_{fa} = number of feed crops eaten by animal type a

and the other constants are as previously defined. The concentration of tritium in animal feed is evaluated using Equations (5.21) and (5.22) with values defined for the animal feed crops.

The equation to calculate OBT in animal products assumes the specific activity in organic material equals the specific activity in the aqueous phase apart from a discrimination factor. This equation is adapted from the derivation of Peterson and Davis (2002).

$$C_{\text{ap_OBT}} = C_{\text{ap_HTO}} F_{\text{dm_ap}} W_{\text{eq_ap}} / F_{\text{fw_ap}} \quad (5.24)$$

Default values for parameters in eqns (5.23) and (5.24), as recommended by Peterson and Davis (2002), are presented in Table 5.4. Values for fresh and dry matter fractions and for water equivalent factors are from Geigy (1981).

Elemental tritium (HT)

Releases of elemental tritium gas (HT) are a special case. Hydrogen in the elemental form is not readily taken up into vegetation. However, HT is slowly oxidized into tritiated water (HTO) by microbes in soil. Based on data from a release of HT at Chalk River that ran to equilibrium, Peterson and Davis (2002) found that an empirical relationship of $8 \text{ Bq L}^{-1} / (\text{Bq m}^{-3})$ for the ratio of HTO in air moisture to HT in air. This allows a simple addition to the model described above, in which most terms remain the same if C_{am} is approximated as $8 C_{\text{caHT}}$. Peterson and Davis recommend that, for HT releases, the reduction factor for HTO, RF_{pp} , be replaced with a “supplement factor” numerically equal to 1.5.

Table 5.3 Parameter values for calculating HTO and OBT concentrations in plant products (adapted from Peterson and Davis 2002).

	Leafy vegetables	Fruit	Root and other vegetables	Grain	Pasture
Reduction factor (RF_{pp})	0.9	0.8	0.8	0.8	0.9
Reduction factor for leaves (RF_1)	0.9	0.9	0.9	0.9	0.9
Isotopic discrimination factor (ID_{pp})	0.9	0.9	0.9	0.9	0.9
Fresh matter fraction ($\text{F}_{\text{fw_pp}}$)	0.906	0.853	0.824	0.117	0.8
Dry matter fraction ($\text{F}_{\text{dm_pp}}$)	0.094	0.147	0.176	0.883	0.2
Water equivalent factor ($\text{W}_{\text{eq_pp}}$)	0.6	0.59	0.58	0.577	0.616

Table 5.4. Parameter values for calculating HTO and OBT concentrations in animal products (adapted from Peterson and Davis 2002).

	Eggs	Milk	Meat	Pork	Poultry
Fresh weight fraction ($\text{F}_{\text{fw_ap}}$)	0.74	0.897	0.668	0.50	0.67
Dry matter fraction ($\text{F}_{\text{dm_ap}}$)	0.26	0.103	0.332	0.50	0.33
Water equivalent factor ($\text{W}_{\text{eq_ap}}$)	0.835	0.669	0.795	0.904	0.796

5.6.2 Special Carbon-14 Models

The models for ^{14}C are similar to these for ^3H . The concentration of ^{14}C in crops from atmospheric contamination is calculated, assuming carbon behaves as CO_2 , as follows.

$$C_{\text{hcaC}}(T_{\text{yr}}) = \frac{C_{\text{aaC}}(T_{\text{yr}}) F_{\text{Cc}}}{P_{\text{C}}} \quad (5.25)$$

where $C_{\text{hcaC}}(T_{\text{yr}})$ = concentration of ^{14}C in crop type c at harvest from atmospheric deposition at year t (Bq/kg wet weight)

$C_{\text{aaC}}(T_{\text{yr}})$ = annual average air concentration of carbon-14 at usage location a (Bq/m^3)

F_{Cc} = fraction of carbon in crop type c (dimensionless)

P_C = concentration of carbon in air (kg/m³).

The concentration of ¹⁴C in crops from contamination in the surface soil from initial or previous depositions is calculated from the annual average soil concentration, $C_{cC}(T_{yr})$.

$$C_{hcsC}(T_{yr}) = \frac{0.1 F_{Cc} C_{sC}(T_{yr})}{0.01 P_3} \quad (5.26)$$

where $C_{hcsC}(T_{yr})$ = concentration of ¹⁴C in crop type c at harvest from soil root uptake for one year (Bq/kg wet weight)

F_{Cc} = fraction of carbon in crop type c (kg carbon/kg plant)

P_3 = areal soil density of farmland soil (kg/m²)

0.1 = assumed uptake of 10% of plant carbon from soil (dimensionless)

0.01 = average fraction of soil that is carbon (kg carbon/kg soil)

The total concentration in food crops is evaluated as the sum of the contributions from the routes air and soil as follows.

$$C_{hcC}(T_{yr}) = C_{hcaC}(T_{yr}) + C_{hcsC}(T_{yr}) \quad (5.27)$$

where $C_{hcC}(T_{yr})$ = concentration of ¹⁴C in crop type c at harvest for one year (Bq/kg wet weight).

and other terms are as previously defined. The concentration at harvest is the same as the concentration at the time of consumption by humans because of the long radiological half life of ¹⁴C.

The concentration of ¹⁴C in animal products is calculated as follows.

$$C_{caC}(t) = F_{Ca} \frac{\sum_{f=1}^{N_{fa}} C_{cfC} U_{af} d_{af}}{\sum_{f=1}^{N_{fa}} F_{Ca} U_{af}} \quad (5.28)$$

where $C_{caC}(T_{yr})$ = concentration of ¹⁴C in animal product a at time of consumption by humans (Bq/kg)

F_{Ca} = fraction of carbon in animal product a (dimensionless)

$C_{cfC}(T_{yr})$ = concentration of ^{14}C in animal feed type f at time of consumption for a year (Bq/kg wet weight)

U_{af} = daily feed intake rate for animal type a of feed type f (kg/d)

d_{af} = fraction of animal type a feed type f intake that is contaminated (dimensionless)

F_{Cf} = fraction of carbon in animal feed type f (dimensionless)

N_{fa} = number of feed crops eaten by animal type a.

This equation is simplified by noting that the carbon content in plants is much higher than in water.

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6.0 INDIVIDUAL INTAKE MODULE

This section presents the models used to estimate intake of radionuclides by each ingestion and inhalation exposure pathway, and exposure to radionuclides from external exposure pathways. The models are the same for exposure of individuals and members of a population; the difference in the analysis is in the definition of parameter values. For an individual exposure analysis, the parameter values are generally selected to represent the reasonable maximum exposed (RME) individual. When a population analysis is performed, average values could be used to represent the average member of the population. The two types of calculations may also have parameters defined for specific individuals or groups of individuals. For example, exposure of workers may involve definition of a limited set of exposure routes, with exposure occurring only a fraction of the time (e.g, inhalation for 8 hours per day).

The estimation of intake from media concentrations involves multiplication of the medium concentration by an intake or exposure factor, an exposure duration, and other parameters as appropriate to each exposure pathway. This can be represented as the product of several terms, as indicated in Table 6.1.

Another consideration for the exposure models is age of the exposed individual. Each exposure route has parameters defined as a function of age. For example, water ingestion includes the rate of drinking water intake, usually expressed as liters per day. If the exposure assessment is being performed for a child, a different value would be assigned than for an analysis being performed for adults.

Table 6.1 General Intake Equation Terms

General Term	Description	Example Units
Medium concentration	radionuclide concentration in the exposure medium	Bq/m ³ air Bq/kg soil
Intake/contact rate	ingestion, inhalation, or exposure rate	m ³ air/d
Exposure duration	number of years over which the exposure is defined	Y
Daily activity factor	daily activity pattern parameter (e.g. exposure events per day, hours of exposure per day)	hr/d events/d · h/event
Annual activity factor	annual activity pattern parameter (e.g. days per year that exposure occurs)	days/year

The starting point parameter in the intake component analysis depends on the exposure pathway considered. For ingestion and inhalation pathways, the parameter is the medium average concentration. For external exposure pathways the parameter is the time-integrated media concentration. The parameters for each exposure pathway for chronic releases are indicated in Table 6.2, along with the reference to the equation number describing their generation.

The exposure time, T , is represented as a general term in the equations. The time is the chronic time period of one year (T_{yr}).

Table 6.2 Input Parameters for Intake Analyses

Exposure Route	Exposure Pathway	Chronic Releases		
		Parameter	Units	Eq.
External	Plume	$C_{eai}(T_{yr})$	Bq/m ³	4.1
	Ground	$C_{esi}(T_{yr})$	Bq/kg	5.4
Ingestion	Farm Crops	$C_{csi}(T_{yr})$	Bq/kg	5.10
	Animal Products	$C_{asi}(T_{yr})$	Bq/kg	5.12
	Soil	$C_{dsi}(T_{yr})$	Bq/kg	5.18
Inhalation	Outdoor Air	$C_{aai}(T_{yr})$	Bq/m ³	4.1
	Resuspended Soil	$C_{sai}(T_{yr})$	Bq/m ³	5.18
	Indoor Air	$C_{vwi}(T_{yr})$	Bq/m ³	4.1

6.1 COMMUNICATION INTERFACES

The input files for the individual intake module are the global input data file (GID) and the exposure pathway media concentration output file (EPF). No auxiliary data communication files are needed. The exposure pathway media concentration output file (EPF) is generated by the chronic exposure module (or other external program that is capable of generating the proper file information). The GID file section for the individual intake module is generated by the user interface program. It contains information describing the scope of the analysis and all user-provided input parameters for an analysis. The structure and content of the files are given in Appendix A.

The output from the individual intake module is the annualized intake of contaminants from various media to which individuals or populations are exposed. For some pathways (those with dose rates associated rather than intakes), the dose rate information is passed instead, modified by the fraction of the time the individual was in the dose field. This information is provided in a primary data communication file, the receptor intake output file (RIF).

6.2 EXTERNAL EXPOSURE ESTIMATES

The time-average exposure parameter from the exposure component is used to determine the corresponding time-averaged exposure parameter for the intake component. The latter parameter includes consideration of daily and annual individual activity patterns, and includes dependence on age of the exposed individual. This parameter and the total exposure time (1 year for chronic exposures and the time of plume passage for acute exposures) are carried forward to the Health Risk calculation in Section 7.

6.2.1 External Plume Immersion

The evaluation of the plume-immersion intake external-exposure parameter is performed as follows:

$$I_{eai}(T) = C_{eai}(T) U_{eag} TC_p \quad (6.1)$$

where I_{eai} = average exposure factor for external plume immersion exposure for radionuclide i for an individual in age group g (Bq/m³)

C_{eai} = average air concentration at the location of the exposed individual for radionuclide i (Bq/m³)

U_{eag} = daily exposure factor giving hours of plume immersion exposure per day for individuals in age group g (h/d)

TC_p = time correction set equal to $T_{eag}/(8760 \text{ h/y})$ for chronic releases, where

T_{eag} = annual exposure factor giving days of external plume immersion for individuals in age group g (d/yr).

6.2.2 External Ground Exposure

The evaluation of the external ground exposure intake parameter is performed as follows.

$$I_{esig}(T) = C_{esi} U_{esg} [SH_h FT_{hg} + SH_o FT_{og}] T_{esg} / 8760 \quad (6.2)$$

where $I_{esig}(T)$ = average exposure factor over time period T for external exposure to ground for radionuclide i for individuals in age group g (Bq/kg)

$C_{esi}(T)$ = average soil concentration at the location of individual exposure for radionuclide i for time period T (Bq/kg)

U_{esg} = daily exposure factor giving hours of exposure to contaminated ground per day for individuals in age group g (h/d)

SH_h = shield factor for exposure to soil while inside a home (dimensionless)

FT_{hg} = fraction of time spent inside a home for individuals in age group g (dimensionless)

SH_o = shield factor for exposure to soil while outside (dimensionless)

FT_{og} = fraction of time spent outside for individuals in age group g (dimensionless)

T_{esg} = annual exposure factor giving for external ground exposure for individuals in age group g (d/yr).

8760 = unit correction (hr/yr).

6.3 INGESTION INTAKE ESTIMATES

The input parameter for ingestion exposure pathways is the radionuclide concentration in the medium that contributes to the exposure. The output parameter for ingestion pathways is the total intake of each radionuclide by an individual in each age group over the exposure period. Evaluation of the intake amounts is described in the following sections for ingestion pathways.

6.3.1 Terrestrial Farm Product Ingestion

Terrestrial farm products include food crops and animal products. Food crops include leafy vegetables, other vegetables, cereal grains, and fruit. Animal products include cow's milk, beef/meat, poultry, and eggs (poultry).

The evaluation of the food crop intake parameter is performed as follows.

$$I_{csig} = C_{csi}(T) U_{csg} T_{csg} E D_{csg} \quad (6.3)$$

where $I_{csig}(T)$ = total intake radionuclide i in food crop c over the period T from ingestion at agricultural location s for individuals in age group g (Bq)

$C_{csi}(T)$ = average concentration in food crop c at agricultural location s for radionuclide i (Bq/kg)

U_{csg} = ingestion rate of food crop c at agricultural location s by an individual in age group g (kg/d)

T_{csg} = annual intake factor giving the days per year that food crop c is eaten at agricultural location s by individuals in age group g (d/y)

ED_{csg} = exposure duration for consumption of food crop c at agricultural location s for individuals in age group g (y).

The evaluation of the animal product intake parameter is performed as follows.

$$I_{asig}(T) = C_{asi}(T) U_{asg} T_{asg} E D_{asg} \quad (6.4)$$

where $I_{asig}(T)$ = total intake radionuclide i in animal product a over the period T from ingestion at agricultural location s for individuals in age group g (Bq)

$C_{asi}(T)$ = average concentration in animal product a at agricultural location s for radionuclide i (Bq/kg)

U_{asg} = ingestion rate of animal product a at agricultural location s by an individual in age group g (kg/d)

T_{asg} = annual intake factor giving the days per year that animal product a is eaten at agricultural location s by individuals in age group g (d/y)

ED_{asg} = exposure duration for consumption of animal product a at agricultural location s for individuals in age group g (y).

6.3.2 Inadvertent Soil Ingestion

Evaluation of the inadvertent soil ingestion intake parameter is performed as follows.

$$I_{dsig}(T) = 10^{-6} C_{dsi}(T) U_{dsg} T_{dsg} E D_{ds} \quad (6.5)$$

where $I_{dsig}(T)$ = total intake of radionuclide i from inadvertent soil ingestion over the period T at soil usage location s for individuals in age group g (Bq)

$C_{dsi}(T)$ = average soil concentration for radionuclide i at soil usage location s for time period T (Bq/m²)

U_{dsg} = ingestion rate for soil at soil usage location s for individuals in age group g (mg/d)

T_{dsg} = annual intake factor giving days per year that soil ingestion occurs at soil usage location s for individuals in age group g (d/y)

ED_{ds} = exposure duration for the soil ingestion pathway at soil usage location s for individuals in age group g (y)

10^{-6} = units conversion factor (mg/kg)

6.4 INHALATION INTAKE ESTIMATES

The input parameter for inhalation exposure pathways is the radionuclide concentration in the medium that contributes to the exposure. For example, the soil resuspension inhalation pathway uses the annual average air concentration above the area of contaminated soil. The output parameter for inhalation pathways is the total intake of each radionuclide by an individual in each age group over the exposure period. Evaluation of the intake amounts is described in the following sections for inhalation pathways.

6.4.1 Inhalation of Outdoor Air

Evaluation of the air inhalation intake parameter is performed as follows.

$$I_{aai g}(T) = C_{aai}(T) U_{aag} T_{aag} F_{aag} ED_{aag} \quad (6.6)$$

where $I_{aai g}(T)$ = total intake of radionuclide i from air inhalation over the period T at air usage location a for individuals in age group g (Bq)

$C_{aai}(T)$ = average air concentration for radionuclide i at air usage location a over time period T (Bq/m^3)

U_{aag} = inhalation rate for air at air usage location a for individuals in age group g (m^3/d)

T_{aag} = annual intake factor giving days per year that air inhalation occurs at air usage location a for individuals in age group g (d/y)

F_{aag} = fraction of a day that outdoor inhalation occurs at location a for individuals in age group g (dimensionless)

ED_{aag} = exposure duration for the air inhalation pathway at air usage location a for individuals in age group g (y).

6.4.2 Inhalation of Resuspended Soil

Evaluation of the resuspended soil inhalation intake parameter is performed as follows.

$$I_{sai g}(T) = C_{sai}(T) U_{sag} F_{sag} T_{sag} E D_{sag} \quad (6.7)$$

where $I_{sai}(T)$ = total intake of radionuclide i from resuspension inhalation over the period T at soil usage location a for individuals in age group g (Bq)

$C_{sai}(T)$ = average concentration of radionuclide i in soil over time period T at soil usage location s (Bq/m^2)

U_{sag} = inhalation rate of air for the resuspension pathway at soil usage location s for individuals in age group g (m^3/d)

F_{sag} = fraction of a day that resuspension inhalation exposure occurs at soil usage location s for individuals in age group g (dimensionless)

T_{sag} = annual intake factor giving days per year that resuspension inhalation occurs at soil usage location s for individuals in age group g (d/y)

ED_{sag} = exposure duration for the resuspension inhalation at soil usage location s for individuals in age group g (y)

6.4.3 Indoor Inhalation of Contaminants Including Radon

Evaluation of the indoor air inhalation intake parameter for contaminants is performed as follows.

$$I_{vwig}(T) = C_{aai}(t) U_{vwg} F_{vwg} T_{vwg} ED_{vwg} \quad (6.8)$$

where $I_{vwig}(T)$ = total intake of radionuclide i from indoor air inhalation over the period T at usage location w for individuals in age group g (Bq)

$C_{aai}(T)$ = average outdoor air concentration for radionuclide i at air usage location a over time period T (Bq/m^3)

U_{vwg} = inhalation rate for indoor air at usage location w for individuals in age group g (m^3/d)

F_{vwg} = fraction of a day that indoor inhalation occurs at usage location w for individuals in age group g (dimensionless)

T_{vwg} = annual intake factor giving days per year that indoor air inhalation occurs at usage location w for individuals in age group g (d/y)

ED_{vwg} = exposure duration for the indoor air inhalation pathway at usage location w for individuals in age group g (y).

A special radon model is incorporated at this point. If the radionuclide in consideration is radon-222 (^{222}Rn), which has several short-lived progeny, the concentrations of the progeny may be set equal to some fraction of the radon activity. This is a radon equilibrium fraction model, designed to account for the partial buildup of radon progeny in indoor air. In essence, this model bypasses the chain decay processor calculation, and sets each of the progeny to a specific fraction of the parent activity. Thus, the parent radon concentration indoors is a function of the outdoor air, and the progeny are directly associated with that parent concentration.

The radon and progeny air concentrations are reported in the normal fashion via the RIF file, as well as reported in a separate output file. The output file has the designation *.WLM and contains estimates of radon Working Levels and Working Level Months for each age group and time period. The Working Level is a convention for measuring the concentration of radon progeny, defined as any combination of the short-lived progeny of radon in 1 L of air that results in the ultimate release of 1.30×10^8 MeV of potential alpha energy. This calculation is based on the airborne concentrations of ^{222}Rn (always assumed to be in equilibrium with ^{218}Po), ^{214}Pb , and ^{214}Bi (assumed to be in equilibrium with ^{214}Po). Working levels are calculated as (ICRP Publication 65):

$$\text{WL} = \frac{(0.104 \text{ RN} + 0.514 \text{ PB} + 0.382 \text{ BI}) 55.6 \times 10^{-10} \text{ J/Bq}}{(1.30 \times 10^8 \text{ MeV/m}^3 \text{ per WL}) (1.602 \times 10^{-13} \text{ J/MeV})} \quad (6.9)$$

where RN, PB, and BI are the average (estimated using both the indoor and outdoor concentrations and exposure fractions) concentrations of these radionuclides in Bq/m^3 as calculated using the transport model or assigned using the indoor equilibrium fraction approach, and their coefficients are related to the potential alpha energy in J/Bq for each nuclide.

Individual exposures in Working Level Months (WLM) are estimated using the Working Levels, and the overall times spent indoors and outdoors at the relevant concentrations.

7.0 DOSIMETRY AND HEALTH RISK MODULE

Estimates of radiation dose and health risk are performed based on the intake and external exposure parameters generated by the intake component. Radiation dose is expressed as either committed equivalent dose to a specific organ, or as the committed effective dose to an individual. The health risk is expressed as the incremental risk of cancer incidence or mortality. The methods for estimation of radiation dose and health risk are discussed in the following sections.

The input parameters for the dose and health risk evaluation are the intake parameters (for ingestion and inhalation) or the medium concentration average parameters and exposure times (for external exposure pathways) as generated by the intake component (defined in Section 6). Table 7.1 summarizes these parameters.

7.1 COMMUNICATION INTERFACES

The input files for the individual intake module are the global input data file (GID) and the receptor intake output file (RIF). Several auxiliary data communication files are needed if Federal Guidance Report 13 doses or risks are requested (index file, two ingestion dose and risk factor files, two inhalation dose and risk factor files, and external dose factor files for air, soil, and water). Other dosimetry data are taken from the FRAMES database via the GID file. The receptor intake output file (RIF) is generated by the individual intake module (or other external program that is capable of generating the proper file information). The GID file section for the impacts module is generated by the user interface program. It contains information describing the scope of the analysis and all user-provided input parameters for an analysis. The structure and content of the files are given in Appendices A and B.

Table 7.1 Input Parameters for Dosimetry and Health Risk Evaluation

Exposure Route	Exposure Pathway	Parameter	Units	Equation
External	Plume	$I_{eaig}(T)$	Bq/m ³	6.1
	Ground	$I_{esig}(T)$	Bq/kg	6.2
Ingestion	Farm Crops	$I_{csig}(T)$	Bq	6.3
	Animal Products	$I_{asig}(T)$	Bq	6.4
	Inadvertent Soil	$I_{dsig}(T)$	Bq	6.5
Inhalation	Air	$I_{aaig}(T)$	Bq	6.6
	Resuspended Soil	$I_{saig}(T)$	Bq	6.7
	Indoor Air	$I_{vwig}(T)$	Bq	6.8

The output from the impacts module is the annualized dose and risk from contaminants in various media to which individuals or populations are exposed. This information is provided in a primary data communication file, the health impacts output file (HIF).

7.2 RADIATION DOSE ASSESSMENT

The endpoints for radiation dose depend on the dose factors used as the basis of the analysis. Three sources of dose factors are in general use: 1) EPA supported values published in Federal Guidance Reports 11 and 12, 2) DOE supported values published in DOE reports, and 3) age dependent dose factors in reports of the International Commission on Radiological Protection (ICRP). All of these sources are based on recommendations of the ICRP. Each set of dose factors is described in the following sections.

Differences in parameter assumptions exist for some radionuclides between the EPA, DOE, and ICRP dosimetry, which have resulted in numerical differences between dose factors. The EPA and DOE sources are essentially equivalent (rounding error); the differences between these and the more-recent ICRP sources relate primarily to changes in the weighting factors used for effective dose equivalent versus effective dose coefficients (a change in definition).

The dose parameter for specific organs is represented as the "committed equivalent dose" and is the sum of the average absorbed dose over all radiation types, as follows.

$$H_T(\tau) = \sum_R w_R D_{T,R}(\tau) \quad (7.1)$$

where $H_T(\tau)$ = committed equivalent dose to target organ T over integrating period τ (Sv)

w_R = radiation weighting factor to derive the equivalent dose from the absorbed dose averaged over a tissue or organ and is based on the quality of radiation (dimensionless)

$D_{T,R}(\tau)$ = average absorbed dose to target organ T over integrating period τ from radiation of type R (Gy).

Both the absorbed dose and the equivalent dose have units of $J\ kg^{-1}$. Separate names are defined for the unit for each term to indicate the application of the radiation weighting factor. The absorbed dose unit is gray (Gy) and the committed equivalent dose unit is the sievert (Sv).

The dose parameter representing the total effect to the body is the committed effective dose, $E(\tau)$. This parameter is estimated as the sum of the products of the committed organ or tissue equivalent doses and the appropriate organ or tissue weighting factors (w_T), over the integrating time, τ . The committed effective dose is calculated from the committed equivalent dose as follows.

$$E(\tau) = \sum_T w_T H_T(\tau) \quad (7.2)$$

where $E(\tau)$ = committed effective dose over integrating period τ (Sv)

w_T = tissue weighting factor, by which the equivalent dose in a tissue or organ is weighted to represent the relative contribution of that tissue or organ to the total detriment resulting from uniform irradiation of the body (dimensionless)

and $H_T(\tau)$ is calculated as per Equation (7.1). The units of the committed effective dose are the same as the units of the committed equivalent dose (Sv).

The time period of integration for worker dose coefficients is 50 years. The integration period for age-dependent dose coefficients is from the time of intake to 70 years. The age-dependent dose coefficients are provided for the age groups listed in Table 7.2.

Table 7.2 Age-dependent Dose Coefficient Age Groups

Age at Intake	Age Range	Integrating Time, τ
3 mo	0 - 12 mo	69.75 y
1 y	1 - 2 y	69 y
5 y	>2 - 7 y	65 y
10 y	>7 - 12 y	60 y
15 y	>12 - 17 y	55 y
Adult	> 17 y	50 y

A change in dose terminology occurred with release of ICRP Publication 60. Prior to this publication the effective dose, $E(\tau)$, was called the committed effective dose equivalent (CEDE). Also, the equivalent dose was previously called the dose equivalent. In the following discussions, the current terms are used: the CEDE is referred to as effective dose and the dose equivalent is referred to as the equivalent dose.

The dose coefficients are defined for several exposure routes and media and, in some cases, as a function of age. The nomenclature for representation of the dose coefficients is indicated in Table 7.3.

7.2.1 Federal Guidance Report Dose Coefficients

The EPA dose coefficients are provided in Federal Guidance Reports (FGR) 11 and 12 (EPA 1988 and EPA 1993). Coefficient values of organ-specific dose equivalent and effective dose equivalent are provided for inhalation and ingestion in FGR 11, and for external exposure to

Table 7.3 Dose and Risk Coefficient Nomenclature

Dose Coefficient	General Symbol	Subscript Description	
		Position	Uses
Effective Dose (and Effective Dose Equivalent)	EC ₁₂₃	1	radionuclide - i
		2	age group g - general a - adult
		3	exposure route/medium a - external, <u>a</u> ir g - external, <u>g</u> round o - ingestion, <u>o</u> ral r - inhalation, <u>r</u> espiration w - external, <u>w</u> ater
Equivalent Dose (and Dose Equivalent)	HC ₁₂₃₄	1,2,3	same as above
		4	inhalation or ingestion class – c inhalation (F,M,S) ingestion (f1)
		5	organ - T

air, water, and soil in FGR 12. The internal dose coefficient values are based primarily on recommendations in ICRP Publications 26 and 30, and are to be used for evaluation of dose to adults (workers). The integration period for internal dose conversion factors is 50 years. The external dose conversion factors are also based on ICRP Publication 30 tissue weighting factors. These are included in the GENII V2 NESHAPS libraries under the general heading of “ICRP-30/48.”

7.2.2 Department of Energy Dose Coefficients

The DOE (1988a and 1988b) values are for workers and are based on ICRP Publications 26 and 30. They provide estimates of dose equivalent for specific organs in addition to the effective dose equivalent. There are some differences in the numerical evaluation of dose coefficients between the DOE publication and the EPA FGR publications and differences in numerical values can be found. Dose coefficients are provided for inhalation and ingestion intakes in DOE (1988b) and for external exposure to air, ground, and water in DOE (1988a). These are similar enough to the EPA guidance that the ICRP-30/48 values are used for both.

7.2.3 Current ICRP Dose Coefficients

The ICRP has published dose coefficients for estimation of dose to workers and to members of the public. Worker committed effective dose factors are based on a 50 year work period with the target individual being an adult. Worker dose coefficients are given in ICRP Publications 68. The ICRP age-dependent committed equivalent dose coefficients are for estimation of dose to the public. Age-dependent committed equivalent dose and committed effective dose coefficient values for ingestion are given in ICRP Publications 56, 67, and 69, and values for inhalation are given in ICRP Publication 71. ICRP Publication 72 presents committed effective dose coefficients as a function of age for ingestion and inhalation (organ specific committed equivalent dose coefficients are not presented in this publication). Table 7.4 summarizes the content of each of these reports. These values form the underlying basis for Federal Guidance Report 13; they are included in the GENII V2 NESHAPS libraries under the general heading of “ICRP-60.”

7.2.4 External Exposure Pathway Dose Assessment

Radiation dose from external exposure pathways is evaluated using the average medium concentrations, the exposure times, and the external dose coefficient appropriate to the medium. The external dose coefficients are provided for exposure of adults in FGR 12 (EPA 1993) in terms of equivalent dose to specific organs and the effective dose for an individual. The dose coefficients are presented as dose rate factors that are multiplied by the medium average

Table 7.4 Summary of ICRP Publication Dose Coefficients

Publication No. Target Group	Dose Type	Intake Route	Lung Model	Elements	Basis for w_T
56 (1989) Public, Part 1	$E(\tau)$ $H_T(\tau)$	Ingestion	NA	H, C, Sr, Zr, Nb, Ru, I, Cs, Ce, Pu, Am, Np	ICRP 26
67 (1993) Public, Part 2	$E(\tau)$ $H_T(\tau)$	Ingestion	NA	S, Co, Ni, Zn, Sr, Mo, Tc, Ag, Te, Ba, Pb, Po, Ra	ICRP 60
68 (1994) Workers	$E(50)$	Inhalation Ingestion	ICRP 66	Most	ICRP 60
69 (1995) Public, Part 3	$E(\tau)$ $H_T(\tau)$	Ingestion	NA	Fe, Se, Sb, Th, U	ICRP 60
71 (1995) Public, Part 4	$E(\tau)$ $H_T(\tau)$	Inhalation	ICRP 66	H, C, S, Ca, Fe, Co, Ni, Zn, Se, Sr, Zr, Nb, Mo, Tc, Ru, Ag, Sb, Te, I, Cs, Ba, Ce, Pb, Po, Ra, Th, Np, Pu, Am, Cm	ICRP 60
72 (1996a) Public, Part 5	$E(\tau)$	Inhalation Ingestion	ICRP 66	Most	ICRP 60

concentration and exposure time to give the total radiation dose for the defined exposure period. The following equations describe estimation of the equivalent dose and effective dose from external exposure pathways.

External Exposure from Air Immersion The evaluation of radiation dose from a plume of radioactivity may be evaluated using the finite plume model or the semi-infinite plume model. When the finite plume model is used the dose is evaluated by the atmospheric transport component (Section 4.3) because the dose is a function of plume dimensions. When the semi-infinite plume model is used, the atmospheric transport analysis provides the time-integral of plume concentration at the exposure locations, which is used in the analysis described here. For the semi-infinite plume model, the equivalent dose from external exposure is evaluated as follows.

$$IH_{\text{eaigT}}(T) = I_{\text{eaig}}(T) HC_{\text{iaaT}} TE_a \cdot 3.15 \times 10^7 \quad (7.3)$$

where $IH_{\text{eaigT}}(T)$ = equivalent dose to organ or tissue T from external exposure to radionuclide i from plume immersion at air usage location a for an individual in age group g (Sv)

$I_{\text{eaig}}(T)$ = external exposure average air concentration for radionuclide i for plume immersion at air usage location a for individuals in age group g (Bq/m^3)

HC_{iaaT} = equivalent dose coefficient for air immersion to an organ T, radionuclide i, for an adult (Sv m^3 per Bq s)

TE_a = time of exposure, T_{yr} , for chronic releases (y)

3.15×10^7 = units correction (s/y).

The effective dose from external exposure from immersion in an airborne plume is evaluated as follows.

$$IE_{\text{eaig}}(T) = I_{\text{eaig}}(T) EC_{\text{iaa}} TE_a \cdot 3.15 \times 10^7 \quad (7.4)$$

where $IE_{\text{eaig}}(T)$ = effective dose from external exposure to radionuclide i from plume immersion at air usage location a for an individual in age group g (Sv)

$I_{\text{eaig}}(T)$ = external exposure average air concentration for radionuclide i for plume immersion at air usage location a for individuals in age group g (Bq/m^3)

EC_{iaa} = effective dose coefficient for external exposure from plume immersion for radionuclide i for an adult (Sv m^3 per Bq s).

TE_a = time of exposure, T_{yr} , for chronic releases (y)

3.15×10^7 = units correction (s/y).

As indicated in these equations, the adult equivalent dose (HC_{iaaT}) and effective dose coefficients (EC_{iaa}) are used for all age groups, as represented by the subscript "a" (adult) in place of the general age group subscript "g". This is a necessary approximation because age-dependent effective dose coefficients are not available for external exposures, although ICRP indicates that external doses to adults and children do not differ greatly at most photon energies of concern (ICRP 1996b).

External Exposure from Ground Contamination The equivalent dose from external exposure to contaminated ground is evaluated as follows.

$$IH_{esigT}(T) = I_{esig}(T) HC_{iagT} TE_g 3.15 \times 10^7 \rho_s d_s \quad (7.5)$$

where $IH_{esigT}(T)$ = equivalent dose to organ T from external exposure to radionuclide i from plume immersion at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{esig}(T)$ = external exposure average soil concentration for radionuclide i at soil usage location s for individuals in age group g for exposure over time period T (Bq/kg)

HC_{iagT} = equivalent dose coefficient to organ T for external exposure to ground for radionuclide i for an adult (Sv m² per Bq s)

TE_g = time of exposure, T_{yr} , for chronic releases (y)

ρ_s = surface soil bulk density (kg/m³)

d_s = thickness of surface soil layer (m)

3.15×10^7 = units correction (s/y).

The effective dose from external exposure to contaminated ground is evaluated as follows.

$$IE_{esig}(T) = I_{esig}(T) EC_{iag} TE_g 3.15 \times 10^7 \rho_s d_s \quad (7.6)$$

where $IE_{esig}(T)$ = effective dose from external exposure to radionuclide i in contaminated soil at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{esig}(T)$ = external exposure average of soil concentration for radionuclide i for soil at soil usage location s for individuals in age group g for exposure over time period T (Bq/kg)

EC_{iag} = effective dose equivalent factor for external exposure from ground exposure (g) for radionuclide i for an adult (Sv m² per Bq s)

TE_g = time of exposure, T_{yr} , for chronic releases (y)

ρ_s = surface soil bulk density (kg/m³)

d_s = thickness of surface soil layer (m)

3.15×10^7 = units correction (s/y).

7.2.5 Ingestion Exposure Pathway Dose Assessment

The equivalent dose and effective dose are evaluated for each ingestion exposure pathway using the ingestion dose coefficients as defined in Sections 7.1.1 through 7.1.3. The evaluation is similar for all ingestion pathways; the medium concentration intake parameter (e.g. $I_{csig}(T)$) is multiplied by the appropriate dose coefficient (i.e., HC_{12oc5} or EC_{12oc} as defined in Table 7.3). The following equations describe calculation of radiation doses for food crops, animal products, and soil ingestion pathways.

Ingestion of Food Crops The equivalent dose from ingestion of food crops (leafy vegetables, other vegetables, fruit, and cereal grains) is evaluated as follows.

$$IH_{csigT}(T) = I_{csig}(T) HC_{igo c T} \quad (7.7)$$

where $IH_{csigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in food crop c at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{csig}(T)$ = ingestion intake of radionuclide i in food crop c at soil location s for individuals in age group g for exposure over time period T (Bq)

HC_{igocT} = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from ingestion of food crops is evaluated as follows.

$$IE_{csig}(T) = I_{csig}(T) EC_{igo c} \quad (7.8)$$

where $IE_{csig}(T)$ = effective dose from ingestion intake of radionuclide i in food crop c at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{csig}(T)$ = ingestion intake of radionuclide i in food crop c at soil location s for individuals in age group g for exposure over time period T (Bq)

EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide I of class c for an individual in age group g (Sv/Bq).

Ingestion of Animal Products The equivalent dose from ingestion of animal products (beef/meat, cow's milk, poultry, and eggs) is evaluated as follows.

$$IH_{asigT}(T) = I_{asig}(T) HC_{igocT} \quad (7.9)$$

where $IH_{asigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in animal product a at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{asig}(T)$ = ingestion intake of radionuclide i in animal product a at soil location s for individuals in age group g for exposure over time period T (Bq)

HC_{igocT} = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from ingestion of animal products is evaluated as follows.

$$IE_{asig}(T) = I_{asig}(T) EC_{igoc} \quad (7.10)$$

where $IE_{asig}(T)$ = effective dose from ingestion intake of radionuclide i in animal product a at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{asig}(T)$ = ingestion intake of radionuclide i in animal product a at soil location s for individuals in age group g for exposure over time period T (Bq)

EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq).

Ingestion of Soil The equivalent dose from inadvertent ingestion of soil is evaluated as follows.

$$IH_{dsigT}(T) = I_{dsig}(T) HC_{igocT} \quad (7.11)$$

where $IH_{dsigT}(T)$ = equivalent dose to organ T from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{dsig}(T)$ = ingestion intake of radionuclide i in soil at soil location s for individuals in age group g for exposure over time period T (Bq)

HC_{igocT} = equivalent dose coefficient to organ T for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from inadvertent ingestion of soil is evaluated as follows.

$$IE_{dsig}(T) = I_{dsig}(T) EC_{igoc} \quad (7.12)$$

where $IE_{dsig}(T)$ = effective dose from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{dsig}(T)$ = ingestion intake of radionuclide i in soil at soil location s for individuals in age group g for exposure over time period T (Bq)

EC_{igoc} = effective dose coefficient for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

7.2.6 Inhalation Exposure Pathway Dose Assessment

The equivalent dose and effective dose are evaluated for each inhalation exposure pathway using the inhalation dose coefficients as defined in Sections 7.1.1 through 7.1.3. The evaluation is similar for all inhalation pathways; the medium concentration intake parameter (e.g. $I_{csig}(T)$) is multiplied by the appropriate dose coefficient (i.e., HC_{12rc5} or EC_{12rc} as defined in Table 7.3). The following equations describe calculation of radiation doses for inhalation of air, resuspended soil, and indoor air contaminants. NOTE: inhalation of tritium gas (HT) is a special case – the code assumes fractional conversion to HTO, which is inhaled (see Section 5.6.1).

Inhalation of Air The equivalent dose from inhalation of air is evaluated as follows.

$$IH_{aaigT}(T) = I_{aaig}(T) HC_{igr c T} \quad (7.13)$$

where $IH_{aaigT}(T)$ = equivalent dose to organ T from inhalation intake of radionuclide i in air at air usage location a for an individual in age group g for exposure over time period T (Sv)

$I_{aaig}(T)$ = inhalation intake of radionuclide i in air at air usage location a for individuals in age group g for exposure over time period T (Bq)

$HC_{igr c T}$ = equivalent dose coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from inhalation of air is evaluated as follows.

$$IE_{aaig}(T) = I_{aaig}(T) EC_{igr c} \quad (7.14)$$

where $IE_{aaig}(T)$ = effective dose from inhalation intake of radionuclide i in air at air usage location a for an individual in age group g for exposure over time period T (Sv)

$I_{aaig}(T)$ = inhalation intake of radionuclide i in air at air usage location a for individuals in age group g for exposure over time period T (Bq)

$EC_{igr c}$ = effective dose coefficient for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

Inhalation of Resuspended Soil The equivalent dose from inhalation of resuspended soil is evaluated as follows.

$$IH_{saigT}(T) = I_{saig}(T) HC_{igr c T} \quad (7.15)$$

where $IH_{saigT}(T)$ = equivalent dose to organ T from inhalation intake of radionuclide i in resuspended soil at air usage location a for an individual in age group g for exposure over time period T (Sv)

$I_{saig}(T)$ = inhalation intake of radionuclide i in resuspended soil at air usage location a for individuals in age group g for exposure over time period T (Bq)

$HC_{igr c T}$ = equivalent dose coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from inhalation of resuspended soil is evaluated as follows.

$$IE_{saig}(T) = I_{saig}(T) EC_{igr c} \quad (7.16)$$

where $IE_{saig}(T)$ = effective dose from inhalation intake of radionuclide i in resuspended soil at air usage location a for an individual in age group g for exposure over time period T (Sv)

$I_{saig}(T)$ = inhalation intake of radionuclide i in resuspended soil at air usage location a for individuals in age group g for exposure over time period T (Bq)

$EC_{igr c}$ = effective dose coefficient for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

Inhalation of Indoor Air The equivalent dose from inhalation of contaminants in indoor air is evaluated as follows.

$$IH_{vwigT}(T) = I_{vwig}(T) HC_{igr c T} \quad (7.17)$$

where $I_{H_{vwigT}}(T)$ = equivalent dose to organ T from inhalation intake of radionuclide i in indoor air at location w for an individual in age group g for exposure over time period T (Sv)

$I_{vwig}(T)$ = inhalation intake of radionuclide i in indoor air at location w for individuals in age group g for exposure over time period T (Bq)

$HC_{igr cT}$ = equivalent dose coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

The effective dose from inhalation in indoor air is evaluated as follows.

$$IE_{vwig}(T) = I_{vwig}(T) EC_{igr c} \quad (7.18)$$

where $IE_{vwig}(T)$ = effective dose from inhalation intake of radionuclide i in indoor air at location w for an individual in age group g for exposure over time period T (Sv)

$I_{vwig}(T)$ = inhalation intake of radionuclide i in indoor air at location w for individuals in age group g for exposure over time period T (Bq)

$EC_{igr c}$ = effective dose coefficient for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq).

7.3 HEALTH RISK ASSESSMENT

Three primary methods are available to perform the assessment of health impacts: 1) use of effective dose estimates multiplied by health effects conversion factors, 2) use of intake estimates multiplied by cancer incidence slope factor published in EPA Health Effects Assessment Summary Tables, 3) calculation using organ-dependent health effect conversion factors. Each of these methods is discussed in the following sections.

7.3.1 Use of Effective Dose

An estimate of the health impacts, expressed as risk of a defined health effect, can be made from the effective dose and appropriate health effect conversion factors. The health effect conversion factors ("Risk coefficients") must be defined for each age group or for adults and must be representative of the exposed population (i.e., workers or the public). General health effect conversion factors are presented in ICRP Publication 60 (1990) for exposure of workers and the adult population for health effects expressed as fatal cancer, non-fatal cancer, and severe hereditary effects.

Estimation of the health impacts is performed as follows for exposure pathway 1, medium 2, radionuclide i, age group g, and health effect h.

$$IR_{12igh}(T) = IE_{12ig}(T) HC_{gh} \quad (7.19)$$

where $IR_{12igh}(T)$ = health effects h risk, for age group g, radionuclide i, exposure pathway 1, medium 2, (lifetime risk from exposure during period T)

$IE_{12ig}(T)$ = effective dose from exposure to pathway 1, usage location 2, for radionuclide i and an individual in age group g over exposure time period T (Sv)

HC_{gh} = health effects conversion factor for effect h and an individual in age group g (risk/Sv)

The subscripts 1 and 2 are as defined in Table 7.1 for the intake parameter, $I_{12ig}(T)$.

Use of the ICRP Publication 60 health effects conversion factors could be represented in Equation (7.19) by replacing the age group subscript "g" with an "a" to represent adults, as suggested in Table 7.3.

The health impact parameter, $IR_{12igh}(T)$, can be summed in various ways to estimate the total impact as a function of pathway, location, or age group. For example, the total health risk to an individual from food crop ingestion is given as follows, with summations over food crop types and radionuclides, at location s.

$$IR_{CsIgh}(T) = \sum_{c=1}^{N_c} \sum_{i=1}^{N_i} IR_{csigh}(T) \quad (7.20)$$

where $IR_{CsIgh}(T)$ = health effects h risk, for an individual in age group g, over exposure time period T, at soil usage location s, summed over all farm crop types and radionuclides (risk)

N_c = number of farm crop types consumed by the individual at the usage location (dimensionless)

N_i = number of radionuclides considered at usage location s (dimensionless)

and other terms are as previously defined. In this equation, summations are indicated by a capitalized subscript, e.g., the C (farm crop) and I (radionuclide) are capitalized in the risk parameter, $IR_{CsIg}(T)$, indicating the value is the sum over farm crop types and radionuclides.

7.3.2 Use of EPA Slope Factors

The EPA has developed slope factors [originally reported separately in the Health Effects Assessment Summary Tables (HEAST) but now derived directly from FGR 13 (Eckerman et al.

1999)] for exposure to radionuclides via inhalation, ingestion, and external direct radiation from contamination on a ground plane (available online at <http://www.epa.gov/radiation/heast/>). This method may be used only to estimate lifetime cancer incidence because the slope factors are specific to total cancer incidence in the general population. The slope factors for ingestion and inhalation are expressed in units of risk per pCi intake, and the external slope factors are expressed as a rate in units of risk/y per pCi/g soil. The following equations indicate use of these factors, with unit conversions, for estimation of total cancer incidence from exposure of the population. This approach is essentially equivalent to the FGR 13 approach (Section 7.3.3)

The ingestion slope factors are to be applied to the ingestion intake estimates for an adult, as follows.

$$IR_{12iah}(T) = 27 I_{12ia}(T) SF_{io} \quad (7.21)$$

where $IR_{12iah}(T)$ = lifetime cancer incidence risk (effect h) from ingestion exposure via pathway 1, medium 2, radionuclide i, for the general population (a), for exposure over the period T (risk)

$I_{12ia}(T)$ = ingestion intake of radionuclide i via exposure pathway 1, at usage location 2, for the adult age group (a) over exposure time period T (Bq)

SF_{io} = slope factor for ingestion (o) of radionuclide i (risk/Bq)

27 = units conversion factor (pCi/Bq).

The exposure and location pathways include all those involving ingestion intake (i.e., subscript pairs cs, as, fw, dw, and ds as per Table 7.1).

The inhalation slope factors are applied in a similar manner to the inhalation intake estimates for an adult, as follows.

$$IR_{eliah}(T) = 27 I_{elia}(T) SF_{ir} \quad (7.22)$$

where $IR_{eliah}(T)$ = lifetime cancer incidence risk (effect h) from inhalation exposure via pathway e, medium l, radionuclide i for the general population (a), for exposure over the period T (risk)

$I_{elia}(T)$ = inhalation intake of radionuclide i via exposure pathway e, for medium l, for the adult age group (a) over exposure time period T (Bq)

SF_{ir} = slope factor for inhalation (r) of radionuclide i (risk/pCi)

27 = units conversion factor (pCi/Bq).

The exposure and location pathways include all those involving inhalation intake (i.e., subscript pairs aa, sa, and vw as per Table 7.1).

The EPA external slope factors for ground exposure can be applied to the ground external exposure pathway . For the ground exposure pathway the risk is evaluated as follows.

$$IR_{esiah}(T) = (27) 10^{-3} I_{esia}(T) SF_{ig} TE \quad (7.23)$$

where $IR_{esiah}(T)$ = lifetime cancer incidence risk (effect h) from external exposure to ground (pathway e), at soil usage location s for radionuclide i for the general population (a), for exposure over the period T (risk)

$I_{esia}(T)$ = external exposure ground concentration average for radionuclide i via at soil usage location s, for the adult age group (a) over exposure time period T (Bq/kg)

SF_{ig} = slope factor for external exposure to ground (g) of radionuclide i (risk/y per pCi/g soil)

27 = unit conversion factor (pCi/Bq)

10^{-3} = unit conversion factor (kg/g)

TE = exposure time (y)

7.3.3 Use of Age- and Organ-Dependent Risk Factors

The supporting material (EPA 2002) for Federal Guidance Report 13 (Eckerman et al. 1999) provides radionuclide health conversion factors for external (ground-plane, soil volume, and semi-infinite plume only) and internal (inhalation and ingestion) exposures. The risk factors are based on a hypothetical stationary U.S. population, and are provided as a function of age for internal emitters, and only for adults for external exposures. Risk factors are provided for both cancer morbidity (incidence) and mortality. For inhalation, the risk factors are provided for the lung absorption rates (F-fast, M-medium, S-slow) of ICRP Publication 66 (ICRP 1994). For ingestion, factors are provided for materials ingested with water and for materials ingested with foods. In GENII Version 2 NESHAPS, risks are estimated with the Federal Guidance Report 13 parameters where applicable, and parallel calculations are made using the dose/risk factor approach described in Section 7.3.1 where necessary for completeness.

7.3.3.1 External Exposure Pathway Risk Assessment

Radiation risk from external exposure pathways is evaluated using the average medium concentrations, the exposure times, and the external risk coefficient appropriate to the medium where this is possible. The external risk coefficients are provided for exposure of adults in FGR

13 (Eckerman et al. 1999) in terms of risk to specific organs and the total risk for an individual. The risk coefficients are presented as rate factors that are multiplied by the medium average concentration and exposure time to give the total radiation risk for the defined exposure period. The following equations describe estimation of the risks from external exposure pathways.

External Exposure from Air Immersion The evaluation of risk from a plume of radioactivity may be evaluated using the finite plume model or the semi-infinite plume model. When the finite plume model is used the dose is evaluated by the atmospheric transport component because the dose is a function of plume dimensions, and a dose-to risk conversion is applied as described in Section 11.3.1. When the semi-infinite plume model is used, the atmospheric transport analysis provides the time-integral of plume concentration at the exposure locations, which is used in the analysis described here. For the semi-infinite plume model, the risk from external exposure is evaluated as follows.

$$IR_{eaigT}(T) = I_{eaig}(T) RC_{igaT} TE_a 3.15 \times 10^7 \quad (7.24)$$

where $IR_{eaigT}(T)$ = risk to organ or tissue T from external exposure to radionuclide i from plume immersion at air usage location a for an individual in age group g (risk)

RC_{igaT} = risk coefficient for air immersion to an organ T, radionuclide i, for an individual in age group g (m^3 per Bq s)

TE_a = time of exposure, T_{yr} , for chronic releases (y)

3.15×10^7 = units correction (s/y).

External Exposure from Ground Contamination The risk from external exposure to contaminated ground is evaluated as follows.

$$IR_{esigT}(T) = I_{esig}(T) RC_{iggT} TE_g 3.15 \times 10^7 \rho_s d_s \quad (7.25)$$

where $IR_{esigT}(T)$ = risk to organ T from external exposure to radionuclide i from at soil usage location s for an individual in age group g for exposure over time period T (risk)

$I_{esig}(T)$ = external exposure average soil concentration for radionuclide i for plume immersion at soil usage location s for individuals in age group g for exposure over time period T (Bq/kg)

RC_{iggT} = risk coefficient to organ T for external exposure to ground for radionuclide i for an adult (m^2 per Bq s)

TE_g = time of exposure, T_{yr} , for chronic releases (y)

ρ_s = surface soil bulk density (kg/m³)

d_s = thickness of surface soil layer (m)

3.15×10^7 = units correction (s/y).

7.3.3.2 Ingestion Exposure Pathway Risk Assessment

The ingestion risks are evaluated for each ingestion exposure pathway using the ingestion risk coefficients. The evaluation is similar for all ingestion pathways; the medium concentration intake parameter (e.g. $I_{csig}(T)$) is multiplied by the appropriate risk coefficient (i.e., RC_{12oc5} as defined in Table 7.3). The following equations describe calculation of radiation doses for food crops, animal products, aquatic foods, drinking water, and soil ingestion pathways.

Ingestion of Food Crops The risk from ingestion of food crops (leafy vegetables, other vegetables, fruit, and cereal grains) is evaluated as follows.

$$RH_{csigT}(T) = I_{csig}(T) RC_{igocT} \quad (7.26)$$

where $RH_{csigT}(T)$ = risk to organ T from ingestion intake of radionuclide i in food crop c at soil usage location s for an individual in age group g for exposure over time period T (risk)

$I_{csig}(T)$ = ingestion intake of radionuclide i in food crop c at soil location s for individuals in age group g for exposure over time period T (Bq)

RC_{igocT} = risk coefficient to organ T for food ingestion intake of radionuclide I of class c for an individual in age group g (/Bq).

Ingestion of Animal Products The risk from ingestion of animal products (beef/meat, cow's milk, poultry, and eggs) is evaluated as follows.

$$RH_{asigT}(T) = I_{asig}(T) RC_{igocT} \quad (7.27)$$

where $RH_{asigT}(T)$ = risk to organ T from ingestion intake of radionuclide i in animal product a at soil usage location s for an individual in age group g for exposure over time period T (risk)

$I_{asig}(T)$ = ingestion intake of radionuclide i in animal product a at soil location s for individuals in age group g for exposure over time period T (Bq)

RC_{igocT} = risk coefficient to organ T for food ingestion intake of radionuclide i of class c for an individual in age group g (/Bq).

Ingestion of Soil The equivalent dose from inadvertent ingestion of soil is evaluated as follows.

$$RH_{dsigT}(T) = I_{dsig}(T) RC_{igocT} \quad (7.28)$$

where $RH_{dsigT}(T)$ = risk to organ T from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (Sv)

$I_{dsig}(T)$ = ingestion intake of radionuclide i in soil at soil location s for individuals in age group g for exposure over time period T (Bq)

RC_{igocT} = risk coefficient to organ T for foods ingestion intake of radionuclide I of class c for an individual in age group g (/Bq).

7.3.3.3 Inhalation Exposure Pathway Risk Assessment

The risks are evaluated for each inhalation exposure pathway using the inhalation riskcoefficients. The evaluation is similar for all inhalation pathways; the medium concentration intake parameter (e.g. $I_{csig}(T)$) is multiplied by the appropriate risk coefficient (i.e., RC_{12rc5} as defined in Table 7.3). The following equations describe calculation of risks for inhalation of air, resuspended soil, and indoor air contaminants.

Inhalation of Air The risk from inhalation of air is evaluated as follows.

$$RH_{aaigT}(T) = I_{aaig}(T) RC_{igr c T} \quad (7.29)$$

where $RH_{aaigT}(T)$ = risk to organ T from inhalation intake of radionuclide i in air at air usage location a for an individual in age group g for exposure over time period T (risk)

$I_{aaig}(T)$ = inhalation intake of radionuclide i in air at air usage location a for individuals in age group g for exposure over time period T (Bq)

$RC_{igr c T}$ = risk coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (/Bq).

Inhalation of Resuspended Soil The risk from inhalation of resuspended soil is evaluated as follows.

$$RH_{saigT}(T) = I_{saig}(T) RC_{igr c T} \quad (7.30)$$

where $RH_{saigT}(T)$ = risk to organ T from inhalation intake of radionuclide i in resuspended soil at air usage location a for an individual in age group g for exposure over time period T (risk)

$I_{saig}(T)$ = inhalation intake of radionuclide i in resuspended soil at air usage location a for individuals in age group g for exposure over time period T (Bq)

$RC_{igr c T}$ = risk coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (/Bq).

Inhalation of Indoor Air The risk from inhalation of contaminants in indoor air is evaluated as follows.

$$RH_{vwigT}(T) = I_{vwig}(T) RC_{igr c T} \quad (7.31)$$

where $RH_{vwigT}(T)$ = risk to organ T from inhalation intake of radionuclide i in indoor air at location w for an individual in age group g for exposure over time period T (risk)

$I_{vwig}(T)$ = inhalation intake of radionuclide i in indoor air at location w for individuals in age group g for exposure over time period T (Bq)

$RC_{igr c T}$ = risk coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (/Bq).

7.4 REFERENCES FOR SECTION 7

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APPENDIX A

APPENDIX A: PRIMARY DATA COMMUNICATION FILE SPECIFICATIONS

This appendix provides details of content and structure of each of the primary communication interface files used by the GENII V2 NESHAPS software package. These files are generated by specific components of GENII V2 NESHAPS, or by external programs run to interface with GENII V2 NESHAPS. The general structure of the primary data communication files is described first, followed by detailed information for each file. The file specifications provided here are requirements of the FRAMES software package.

Primary data communication files (PDCFs) are communication interfaces between calculational components operating under the FRAMES system. The content of these files is related to radionuclide transfer rates, amounts, concentrations, intakes, or doses for particular points in the risk assessment. The content of each PDCF is dependent on the components that write and read the file. There are currently eight PDCFs defined for the GENII V2 NESHAPS software package. A summary description of each is given in Table A.1, with details of each given in the following subsections. Standard file extensions are defined for each PDCF type.

Table A.1 Summary Description of PDCFs

Components Involved		File Extension	Description
Writing File	Reading File		
Source	Atmospheric Transport	AFF	Atmospheric flux file: release rates of radionuclides to the atmosphere at the source
Atmospheric Transport	Acute and Chronic Exposure	ATO	Air concentration file: air concentration, deposition rates, and external exposure rates to airborne radionuclides, at specific points in the environment
Exposure	Receptor Intake	EPF	Exposure pathway file: concentration of radionuclides in exposure media
Receptor Intake	Health Impacts	RIF	Receptor intake file: estimated intakes for the exposed individual
Health Impacts	Report Generator	HIF	Health impacts file: health impact results

A.1 GENERAL STRUCTURE OF PDCFS

Each PDCF has a unique structure, defined for transmission of information between two specific components of the system. Because the PDCFs are to be used by any calculational component (not just the GENII V2 NESHAPS components) to be included under the control of the Framework UI, it is necessary that the PDCF structure be compatible with many programming languages (e.g., C++ and FORTRAN). The structure of each PDCF is outlined in the following sections. These structures are subject to change as experience is gained in attempts to implement the methodology.

A general feature of each PDCF is a heading area that is defined by each module/code developer. Information included here is variable (or nothing), however, the GENII V2 NESHAPS components provide an indication of the module and transport pathways included in the analysis, as well as the date and time of the generation of the file.

As with the global input data file (GID), the information in the PDCF is contained in data sets, with one set for each calculation defined for the analysis. The first line for each set contains the name of the data set and the number of lines of information that follow in the set. This line is referred to as the "marker" line.

The first line of the data set (following the marker line) for a component gives the number of lines of heading information that follow. The data for the file starts in the line after the last line of heading information. The heading information may be read (or skipped) and then the data section is read.

Within each PDCF structure, substructures are defined for definition of particular types of information. A minimum of one substructure is defined for each PDCF type. As an example of substructures, consider the "atmospheric transport medium" PDCF (defined below). This file provides information on the concentration in air and deposition rate to soil. Cases involving acute releases may be expected to require some information different than cases involving chronic exposures. Substructures to the PDCF are defined for acute and chronic exposures. A standard parameter identifier (e.g. "acute" or "chronic") at the start of a substructure defines the type of substructure present.

A.1.2 PDCF Character and Numeric Syntax

To ensure file data readability by several programming languages, the following primary standards are used for PDCFs.

- The files are visually readable (ASCII/Text).
- The files are readable by major programming languages (FORTRAN, C, Basic).
- The line syntax is compatible with FORTRAN free-field read conventions.

- Each data value (string, integer, or float) is separated by a comma (.). Character fields are fully contained within quote (') or double quote (") marks.
- Floating point numbers are entered as integers, floating point values, or in scientific notation.

When PDCF files are generated by FORTRAN programs, the character fields are printed using format statements (rather than the * free-field format specification). Use of a free-field write will not properly handle character strings that have embedded commas or blanks. Quote marks and commas can easily be inserted in output lines following each parameter value (string, integer, or float), as appropriate.

A.1.3 PDCF Primary Interface Parameters

Each PDCF file contains information specific to the interface components involved. Some general information will always be included, such as radionuclide names and media locations. Each PDCF will also have information specific to the interface considered. The specific information is defined in Table A.2.

Table A.2. PDCF Interface Parameters

Component	File	Interface Parameters
Source Definition	AFF	Release rate to a transport medium, time history. Example, Bq/sec to air, time pairs
Transport to Transport Medium	ATO	Medium concentration, time history. Example, Bq/m ³ in air, time pairs
Transport Medium to Exposure Medium	EPF	Exposure medium concentration, time history. Example, Bq/kg in vegetables, over specified time periods
Exposure Medium to Intake	RIF	Exposed Human/Biota intake or exposure as appropriate to each exposure route and pathway. Examples, Bq intake from crop ingestion, or radiation dose Sv over the exposure duration.
Intake to Impacts	HIF	Endpoint parameter values appropriate to pollutant and exposure pathway. Examples, lifetime cancer incidence from inhalation of a radionuclide, or radiation dose (Sv effective dose) from ingestion or inhalation exposures. These endpoint are for exposure of an individual.

A.1.4 Error file (ERR)

An error message file (extension ERR) is to be opened by each component. If the file has not been used by the end of the run (i.e., no error messages were generated), then the file is deleted. The Framework UI will look for the file, and if present, warn the user of possible problems with the execution of that component. All executables will create the ERR file before processing is started and delete it only after all processing is complete. The file contains text information describing errors encountered during the run. The contents of the file are displayed to the user by the Framework UI.

A.2 ATMOSPHERIC RELEASE PDCF (AFF)

The air flux file (AFF) is a spatial average through an exit area into unconstrained air passing by the area. The exit area is normally defined by physical characteristics of the source. In all cases, the exit area is the area used to define the spatial average of the air flux. The air fluxes are in pCi/yr or g/yr depending on whether the constituent is a radionuclide or chemical. These flux values are the instantaneous values at a specified time (i.e. the value is not a time-average). There are no limits on number of constituents, progeny, fluxes. The number of contaminant types is unlimited. The structure and content of the AFF files is shown in Exhibit A.3.

Exhibit A.1 Structure and Content of the AFF File

```
For each 'Module' a line with:
Module Name -(string)
Number of Lines that follow for this module's section
A line with:
    Number of Header Lines -(integer)
For each 'Header Line' a line with:
    Header line information -(string)
Next 'Header Line'
A line with:
    Number of Data Sets-(integer)
For each 'Data Set'
A line with:
    Data Set name -(string)
A line with:
    Source Type Name -(string)
    ;If Stack, vent, etc. - "POINT"
    ;If Landfill, pond, etc. - "AREA"
A line with:
    Exit Area of Source -(float)
    Exit Area Unit -(string) - "m2"
A line with:
    Exit Height -(float)
    ;If 'Source Type' = AREA then 'Exit Height' = 0
```

Exhibit A.1 Structure and Content of the AFF File (Continued)

Exit Height units -(string) - "m"
A line with:
Adjacent Structure Height -(float)
;If 'Source Type' = AREA then 'Adjacent Structure Height' = 0
Adjacent Structure Height unit -(string) - "m"
A line with:
Exit Velocity -(float)
;If 'Source Type' = AREA then 'Exit Velocity' = 0
Exit Velocity units -(string) - "m/s"
A line with:
Exit Temperature -(float)
Exit Temperature units -(string) - "deg C"
A line with:
Ambient Air Temperature -(float)
Ambient Air Temperature units -(string) - "deg C"
A line with:
Number of Flux Types-(integer)
For each 'Flux Type' a line with:
Flux Type Name - (string)
;If Gas, then "Gas 1"
;If particle then "Particle " followed by the particle count
; "Particle 1", "Particle 2", "Particle 3", ...
If Type Name = "Gas #" then
Reactive Gas fraction - (float)
Reactive Gas fraction unit - (string) - "fraction"
Else
Particle Radius - (float)
Particle Radius unit - (string) - "um"
End If
Flux Type Density - (float)
Flux Type Density unit - (string) - "g/cm3"
Next 'Flux Type'
A line with:
Number of Constituents -(integer)
For each 'Constituent' a line with:
Constituent name-(string)
Constituent ID-(string)
Time unit -(string) - "yr"
Flux unit -(string) - "pCi/y" or "g/y"
Number of Time Flux Pairs -(integer)
Number of Progeny -(integer)
For each 'Time Flux Pair' a line with:
Time -(float)

Exhibit A.1 Structure and Content of the AFF File (Continued)

```
For each 'Flux Type'
  Flux -(float)
Next 'Flux Type'
Next 'Time Flux Pair'
For each 'Progeny' a line with:
  Progeny name -(string)
  Progeny ID -(string)
  Time unit -(string) - "yr"
  Flux unit -(string) - "pCi/y" or "g/y"
  Number of Time Flux Pairs -(integer)
  Parent name -(string)
  Parent ID -(string)
For each 'Time Flux Pair' a line with:
  Time -(float)
  For each 'Flux Type'
    Flux -(float)
  Next 'Flux Type'
Next 'Time Flux Pair'
Next 'Progeny'
Next 'Constituent'
Next 'Data Set'
Next 'Module'
```

A.3 TRANSPORT TO EXPOSURE

The PDCFs for transport analyses contain time histories of concentrations at defined points in the environment where exposure of humans may occur. The locations are referred to as receptor locations. Two PDCFs have been identified related to transport analyses; atmospheric transport and waterborne transport (groundwater, surface water, overland transport). Descriptions of the atmospheric transport file is provided below.

The atmospheric transport output (ATO) file provides data for use by exposure pathway modules for airborne releases and atmospheric transport and deposition of pollutants. The file contents depend on options selected for the atmospheric transport analysis. The analysis may be for an acute or chronic release, or for specific exposure locations or for a grid of locations (e.g., by distance and direction). The basic data sets are provided as point values at specific locations relative to the release point. Keywords are used to define options selected. The content and structure of the ATO file is indicated in Exhibit A.4.

The data in each set within the ATO file is defined according to the data set type, coordinate type, and receptor type defined on the second line for the data set. The program reading the information will process the information as necessary.

The format of the ATO file is particularly complex. Multiple data sets can be included in one file (all related to the heading information). This allows input of acute and chronic information in one file, and use of polar co-ordinates and Cartesian co-ordinates in the same file.

Exhibit A.2 Content and Structure of the ATO File

For each 'Module' a line with:

Module Name (string)

Number of Lines that follow for this module's section

A line with:

Number of Header Lines -(integer)

For each 'Header Line' a line with:

Header line information -(string)

Next 'Header Line'

A line with:

Number of Data Sets -(integer)

For each 'Data Set' a line with:

Number of Flux Types - (integer)

Data Set name - (string)

For each 'Flux Type' a line with:

Flux Type Name - (string)

;If Gas, then "Gas 1"

;If particle then "Particle " followed by the particle count

; "Particle 1", "Particle 2", "Particle 3", ...

If Type Name = "Gas #" then

Reactive Gas fraction - (float)

Reactive Gas fraction unit - (string) - "fraction"

Else

Particle Radius - (float)

Particle Radius unit - (string) - "um"

End If

Flux Type Density - (float)

Flux Type Density unit - (string) - "g/cm3"

Next 'Flux Type'

Line with:

Release type - (string) - "acute" / "chronic"

Co-ordinate grid type - (string) - "polar" / "cartesian"

Spatial type - (string) - "grid" / "points"

Number of Constituents (parent) - (integer)

For each 'Constituent' a line with:

Constituent Name - (string)

Constituent ID - (string)

Number of Time Periods - (integer)

Exhibit A.2 Content and Structure of the ATO File (Continued)

Number of Progeny - (integer)
For each 'Time Period' line with:
Time - (float)
If 'Release type' = "acute" then
Time unit - (string) - "hr"
Else 'Release type' = "chronic"
Time unit - (string) - "yr"
End if
Number of Output Products - (integer)
For each 'Output Product' line with:
Output Product Name - (string)-"Air Concentration" / "Deposition Rate" / "External Dose"
If 'OutPut Product Name' = "Air Concentration" or "Deposition Rate" then
Output Product Source 'Flux Type' - (string)
Else
Blank entry - (string) - ""
End If
If 'Output Product Name' = "Deposition Rate" then
Relative Moisture of Output Product - (string) - "wet" / "dry" / "total"
Else
Blank entry - (string) - ""
End If
If 'OutPut Product Name' = "Air Concentration"
If 'Constituent' is a Radionuclide then
Output Product unit - (string) - "Bq/m3"
Else
Output Product unit - (string) - "kg/m3"
End If
ElseIf 'OutPut Product Name' = "Deposition Rate"
If 'Constituent' is a Radionuclide then
Output Product unit - (string) - "Bq/m2/yr"
Else
Output Product unit - (string) - "kg/m2/yr"
End If
Else 'OutPut Product Name' = "External Dose" then
Output Product unit - (string) - "Sv"
End If
If 'Co-ordinate grid type' = "polar" and 'Spatial type' = "grid" then
Number of Radial Distances - (integer)
ElseIf 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "grid" then
Number of x Co-ordinates - (integer)
Else 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "points" then
Number of x,y coordinate points - (integer)

Exhibit A.2 Content and Structure of the ATO File (Continued)

```
End If
Unit of Radial Distances or x Co-ordinates - (string) - "m"
If 'Co-ordinate grid type' = "polar" and 'Spatial type' = "grid" then
    Number of Directions - (integer)
ElseIf 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "grid" then
    Number of y Co-ordinates - (integer)
Else 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "points" then
    Number - (integer) - 1
End If
If 'Co-ordinate grid type' = "polar" then
    Unit of Directions - (string) - "deg"
Else 'Co-ordinate grid type' = "cartesian"
    Unit of y Co-ordinate - (string) - "m"
End If
If 'Spatial type' = "grid" then line with:
    All Radial Distances or x Co-ordinates - (set of float)
    If 'Co-ordinate grid type' = "polar" then
        For each 'Direction' line with:
            Direction - (float)
            Output Product Value for the 'Radial Distance' and 'Direction' - (float)
        Next 'Direction'
    Else 'Co-ordinate grid type' = "cartesian" then line with:
        For each 'y Co-ordinate' line with:
            y Co-ordinate - (float)
            Output Product Value for the 'x,y Co-ordinate' pair - (float)
        Next 'Direction'
    End If
Else 'Spatial type' = "points"
    A line with: Name of Reporting Points - (set of strings)
    A line with: Values of x Co-ordinates for each point - (set of float)
    A line with: Values of y Co-ordinates for each point - (set of float)
    A line with:
        Number - (integer) - 99
        Output Product Values for each point - (set of float)
    End If
Next 'Output Product'
Next 'Time Period'
For each 'Progeny' a line with:
    Progeny Name-(string)
    Progeny ID-(string)
    Number of Time Periods - (integer)
    Parent Name-(string)
    Parent ID-(string)
```

Exhibit A.2 Content and Structure of the ATO File (Continued)

For each 'Time period' a line with:

Time - (float)

Time unit - (string) - "hr" / "yr"

Number of Output Products - (integer)

For each 'Output Product' line with:

Output Product Name-(string)-"Air Concentration" / "Deposition Rate" / "External Dose"

If 'OutPut Product Name' = "Air Concentration" or "Deposition Rate" then

Output Product Source 'Flux Type' - (string)

Else

Blank entry - (string) - ""

End If

If 'Output Product Name' = "Deposition Rate" then

Relative Moisture of Output Product - (string) - "wet" / "dry" / "total"

Else

Blank entry - (string) - ""

End If

If 'OutPut Product Name' = "Air Concentration"

If 'Constituent' is a Radionuclide then

Output Product unit - (string) - "Bq/m3"

Else

Output Product unit - (string) - "kg/m3"

End If

ElseIf 'OutPut Product Name' = "Deposition Rate"

If 'Constituent' is a Radionuclide then

Output Product unit - (string) - "Bq/m2/yr"

Else

Output Product unit - (string) - "kg/m2/yr"

End If

Else 'OutPut Product Name' = "External Dose" then

Output Product unit - (string) - "Sv"

End If

If 'Co-ordinate grid type' = "polar" and 'Spatial type' = "grid" then

Number of Radial Distances - (integer)

ElseIf 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "grid" then

Number of x Co-ordinates - (integer)

Else 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "points" then

Number of x,y coordinate points - (integer)

End If

Unit of Radial Distances or x Co-ordinates - (string) - "m"

If 'Co-ordinate grid type' = "polar" and 'Spatial type' = "grid" then

Number of Directions - (integer)

ElseIf 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "grid" then

Number of y Co-ordinates - (integer)

Exhibit A2. Content and Structure of the ATO File (Continued)

```
Else 'Co-ordinate grid type' = "cartesian" and 'Spatial type' = "points" then
  Number - (integer) - 1
End If
If 'Co-ordinate grid type' = "polar" then
  Unit of Directions - (string) - "deg"
Else 'Co-ordinate grid type' = "cartesian"
  Unit of y Co-ordinate - (string) - "m"
End If
If 'Spatial type' = "grid" then line with:
  All Radial Distances or x Co-ordinates - (set of float)
  If 'Co-ordinate grid type' = "polar" then
    For each 'Direction' line with:
      Direction - (float)
      Output Product Value for the 'Radial Distance' and 'Direction' - (float)
    Next 'Direction'
  Else 'Co-ordinate grid type' = "cartesian" then line with:
    For each 'y Co-ordinate' line with:
      y Co-ordinate - (float)
      Output Product Value for the 'x,y Co-ordinate' pair - (float)
    Next 'Direction'
  End If
Else 'Spatial type' = "points"
  Line with: Name of Reporting Points - (set of strings)
  Line with: Values of x Co-ordinates for each point - (set of float)
  Line with: Values of y Co-ordinates for each point - (set of float)
  Line with:
    Number - (integer) - 99
    Output Product Values for each point - (set of float)
End If
Next 'Output Product'
Next 'Time Period'
Next 'Progeny'
Next 'Constituent'
Next 'Data Set'
Next 'Module'
```

A.4 EXPOSURE PATHWAY TO RECEPTOR INTAKE FILE (.EPF)

The exposure medium component reads files providing transport medium concentrations and determines concentrations in media to which the individuals or population are exposed. The output from the exposure medium component is the concentration of each constituent in the media of interest. For external exposure pathways the output is either radiation dose (finite

plume model) or time integral of medium concentration. This is the input to the intake assessment component (which produces estimates of intake and external exposure). The file extension is .EPF (exposure pathway file). Following the header information, intake information is provided for all receptor locations, exposure pathways, and constituents. The content and structure of the EPF file is indicated in Exhibit A.3.

Concentration units are Bq/unit medium for radionuclides. For finite plume external exposure, dose units are used, Sv. The medium concentration units are: air - m^3 , soil - kg or m^2 , water - L, foods - kg.

A.5 RECEPTOR INTAKE FILE (.RIF)

The output from the receptor intake component is the intake amount for each constituent for each receptor exposure pathway. This is the input to the health impacts component (which produces estimates of health impacts, e.g., risk of developing cancer, hazard quotient, radiation dose, etc.). The input to the health impacts component is provided in this Primary Data Communication File, extension RIF (Receptor Intake File). This file provides intake amounts for each age group (as specified by the user). Following the header information, intake information is provided for all receptor locations, exposure pathways, and constituents. The content and structure of the RIF file is indicated in Exhibit A.4.

Intake units are Bq for radionuclides. For external finite plume exposure, dose units are used, Sv. The number of values is equal to the number of age groups defined for the current data set.

Exhibit A.3 Content and Structure of the EPF File

For each 'Module' a line with:
Module Name -(string)
Number of Lines that follow for this module's section
A line with:
Number of Header Lines -(integer)
For each 'Header Line' a line with:
Header line information -(string)
Next 'Header Line'
A line with:
Number of Data Sets -(integer)
For each 'Data Set' a line with:
Data set type -(string)
;"acute" / "chronic"
Data Set name -(string)
Exposure Medium Type -(string)
;Input Models Qualified type
;"Air" / "Aquifer" / "Surface water" / ...

Exhibit A.3 Content and Structure of the EPF File(Continued)

Number of Exposure Media Points -(integer)
Number of Constituents -(integer)
For each 'Exposure Media Point' a line with:
 X coordinate -(float)
 X coordinate unit -(string) - "km"
 Y coordinate -(float)
 Y coordinate unit -(string) - "km"
Next 'Exposure Media Point'
For each 'Constituent' a line with:
 Constituent Name -(string)
 Constituent ID -(string)
 Number of Progeny -(integer)
 Number of Exposure Start Times -(integer)
 For each 'Exposure Start Time' a line with:
 Exposure Start Time -(float)
 Exposure Start Time unit -(string) - "yr"
 Exposure Duration -(float)
 Exposure Duration unit -(string) - "yr"
 Number of Exposure Pathways -(integer)
 For each 'Exposure Pathway' line with:
 Exposure Pathway Name -(string)
 ;"Air" / "Indoor air" / "Ground" / "Leafy vegetables" /
 ;"Root vegetables" / "Fruit" / "Grain" / "Meat" /
 ;"Poultry" / "Milk" / "Eggs" / "Soil" / "Swimming" /
 ;"Boating" / "Shoreline" / "Water" / "Fish" / "Mollusks" /
 ;"Crustacea" / "Aquatic plants" / "Showering" / ...
 Exposure Route -(string)
 ;"Ingestion" / "Inhalation" / "Dermal" / "External"
 Exposure Concentration unit -(string)
 ;"Bq/kg" / "Bq/l" / "Bq/m3" for radionuclides
 ;"mg/kg" / "mg/l" / "mg/m3" for non-radionuclides
 ;"Sv" for external routes
 A line with:
 Exposure Concentration -(set of float)
 ;a concentration for each 'Exposure Media Point'
Next 'Exposure Pathway'
For each 'Progeny' a line with:
 Progeny Name -(string)
 Progeny ID -(string)
 Number of Exposure Pathways -(integer)
 For each 'Exposure Pathway' line with:
 Exposure Pathway Name -(string)
 ;"Air" / "Indoor air" / "Ground" / "Leafy vegetables" /

Exhibit A.3 Content and Structure of the EPF File(Continued)

```
;"Root vegetables" / "Fruit" / "Grain" / "Meat" /  
;"Poultry" / "Milk" / "Eggs" / "Soil" / "Swimming" /  
;"Boating" / "Shoreline" / "Water" / "Fish" / "Mollusks" /  
;"Crustacea" / "Aquatic plants" / "Showering" / ...  
Exposure Route -(string)  
;"Ingestion" / "Inhalation" / "Dermal" / "External"  
Exposure Concentration unit -(string)  
;"Bq/kg" / "Bq/l" / "Bq/m3" for radionuclides  
;"mg/kg" / "mg/l" / "mg/m3" for non-radionuclides  
;"Sv" for external routes  
A line with:  
Exposure Concentration -(set of float)  
;a concentration for each 'Exposure Media Point'  
Next 'Exposure Pathway'  
Next 'Progeny'  
Next 'Exposure Start Time'  
Next 'Constituent'  
Next 'Data Set'  
Next 'Module'
```

Exhibit A.4 Content and Structure of the RIF File

```
For each 'Module' a line with:  
Module Name -(string)  
Number of Lines that follow for this module's section  
A line with:  
Number of Header Lines -(integer)  
For each 'Header Line' a line with:  
Header line information -(string)  
Next 'Header Line'  
A line with:  
Number of Data Sets -(integer)  
For each 'Data Set' a line with:  
Data set type -(string)  
;"acute" / "chronic"  
Data Set name -(string)  
Exposure Medium Type -(string)  
;Input Models Qualified type  
;"Air" / "Aquifer" / "Surface water" / ...  
Number of Exposure Media Points -(integer)  
Number of Age Groups -(integer)  
Number of Constituents -(integer)  
For each 'Exposure Media Point' a line with:
```

Exhibit A.4 Content and Structure of the RIF File (Continued)

X coordinate -(float)
X coordinate unit -(string) - "km"
Y coordinate -(float)
Y coordinate unit -(string) - "km"
Next 'Exposure Media Point'
For each 'Age Group' a line with:
Starting Age -(float)
Ending Age -(float)
Age group unit -(string) - "yr"
For each 'Constituent' a line with:
Constituent Name -(string)
Constituent ID -(string)
Number of Progeny - (integer)
Number of Exposure Start Times -(integer)
For each 'Exposure Start Time' a line with:
Exposure Start Time - (float)
Exposure Start Time unit -(string) - "yr"
Exposure Duration -(float)
Exposure Duration unit -(string) - "yr"
Number of Exposure Pathways -(integer)
For each 'Exposure Pathway' line with:
Exposure Pathway Population - (float)
Exposure Pathway Name -(string)
; "Air" / "Indoor air" / "Ground" / "Leafy vegetables" /
; "Root vegetables" / "Fruit" / "Grain" / "Meat" /
; "Poultry" / "Milk" / "Eggs" / "Soil" / "Swimming" /
; "Boating" / "Shoreline" / "Water" / "Fish" / "Mollusks" /
; "Crustacea" / "Aquatic plants" / "Showering" / ...
Exposure Route -(string)
; "Ingestion" / "Inhalation" / "Dermal" / "External"
Exposure Intake unit - (string)
; "mg/kg/d" for non-radionuclide ingestion, dermal, inhalation routes
; "mg/m3" for non-radionuclide inhalation routes
; "Bq/kg" for radionuclide external soil routes
; "Bq/m3" for radionuclide external air routes
; "Bq/l" for radionuclide external water routes
; "Bq" for radionuclide ingestion, dermal, inhalation routes
; "Sv" for external route
Exposure type - (string)
; if 'Exposure Intake unit' = "mg/kg/d" or "mg/m3" then
; "carcinogenic" / "noncarcinogenic"
; elseif 'Exposure Intake unit' = "Bq/kg" or "Bq/m3" or "Bq/l" then
; "concentration"

Exhibit A.4 Content and Structure of the RIF File (Continued)

```
;elseif 'Exposure Intake unit' = "Bq" then
; "intake"
;elseif 'Exposure Intake unit' = "Sv" then
; "radiation dose"
A line with:
  Exposure Intake/concentration/dose - (set of float)
  ;one value for each 'Exposure Media Point'
Next 'Exposure Pathway'
For each 'Progeny' a line with:
  Progeny Name -(string)
  Progeny ID -(string)
  Number of Exposure Pathways -(integer)
  For each 'Exposure Pathway' line with:
    Exposure Pathway Name -(string)
    ;"Air" / "Indoor air" / "Ground" / "Leafy vegetables" /
    ;"Root vegetables" / "Fruit" / "Grain" / "Meat" /
    ;"Poultry" / "Milk" / "Eggs" / "Soil" / "Swimming" /
    ;"Boating" / "Shoreline" / "Water" / "Fish" / "Mollusks" /
    ;"Crustacea" / "Aquatic plants" / "Showering" / ...
  Exposure Route -(string)
  ;"Ingestion" / "Inhalation" / "Dermal" / "External"
  Exposure Intake unit - (string)
  ;"mg/kg/d" for non-radionuclide ingestion, dermal, inhalation routes
  ;"mg/m3" for non-radionuclide inhalation routes
  ;"Bq/kg" for radionuclide external soil
  ;"Bq/m3" for radionuclide external air
  ;"Bq/l" for radionuclide external water
  ;"Bq" for radionuclide ingestion, dermal, inhalation routes
  ;"Sv" for external route
  Exposure type - (string)
  ;if 'Exposure Intake unit' = "mg/kg/d" or "mg/m3" then
  ; "carcinogenic" / "noncarcinogenic"
  ;elseif 'Exposure Intake unit' = "Bq/kg" or "Bq/m3" or "Bq/l" then
  ; "concentration"
  ;elseif 'Exposure Intake unit' = "Bq" then
  ; "intake"
  ;elseif 'Exposure Intake unit' = "Sv" then
  ; "radiation dose"
  A line with:
    Exposure Intake/concentration/dose - (set of float)
    ;one value for each 'Exposure Media Point'
  Next 'Exposure Media Point'
```

Next 'Progeny'
Next 'Exposure Start Time'
Next 'Constituent'
Next 'Age Group'
Next 'Data Set'
Next 'Module'

A.6 HEALTH IMPACTS TO OUTPUT REPORTS (.HIF)

The output from the Health Impacts Component is used by the report generators to prepare text reports. This file has an extension of HIF (health impacts file). The health impacts are expressed as the risk of developing cancer, either as total incidence, fatal incidence, or incidence of severe genetic effects, depending on the method used to evaluate health impacts (see Section 11). The input to the impacts report generator component is provided in the Primary Data Communication File, extension .HIF. Following the header information, data is provided for all receptor locations, exposure pathways, constituents, and health endpoints. The content and structure of the HIF file is indicated in Exhibit A.5.

One health impact measure value is given for each age group. Health impact units are "Risk" for carcinogenic effects, "HQ" for hazard quotient values for non-carcinogenic effects, and "Sv" for radiation dose.

Exhibit A.5 Content and Structure of the HIF File

For each 'Module' a line with:
Module Name -(string)
Number of Lines that follow for this module's section
A line with:
Number of Header Lines -(integer)
For each 'Header Line' a line with:
Header line information -(string)
Next 'Header Line'
A line with:
Number of Data Sets -(integer)
For each 'Data Set' a line with:
Data set type -(string)
;"acute" / "chronic"
Data Set name -(string)
Exposure Medium Type -(string)
;Input Models Qualified type
;"Air" / "Aquifer" / "Surface water" / ...
Number of Exposure Media Points -(integer)
Number of Age Groups -(integer)

Exhibit A.5 Content and Structure of the HIF File (Continued)

Number of Constituents -(integer)
Number of Cancer Effect Organs
Number of Radiation Dose Effect Organs
A line with:
 The Names of 'Cancer Effects Organs' - (string)
A line with:
 The Names of 'Radiation Dose Effect Organs' - (string)
For each 'Exposure Media Point' a line with:
 X coordinate -(float)
 X coordinate unit -(string) - "km"
 Y coordinate -(float)
 Y coordinate unit -(string) - "km"
Next 'Exposure Media Point'
For each 'Age Group' a line with:
 Starting Age -(float)
 Ending Age -(float)
 Age group unit -(string) - "yr"
For each 'Constituent' a line with:
 Constituent Name -(string)
 Constituent ID -(string)
 Number of Progeny - (integer)
 Number of Exposure Start Times -(integer)
For each 'Exposure Start Time' a line with:
 Exposure Start Time - (float)
 Exposure Start Time unit -(string) - "yr"
 Exposure Duration -(float)
 Exposure Duration unit -(string) - "yr"
 Number of Exposure Pathways -(integer)
For each 'Exposure Pathway' line with:
 Exposure Pathway Population - (float)
 Exposure Pathway Name -(string)
 ;"Air" / "Indoor air" / "Ground" / "Leafy vegetables" /
 ;"Root vegetables" / "Fruit" / "Grain" / "Meat" /
 ;"Poultry" / "Milk" / "Eggs" / "Soil" / "Swimming" /
 ;"Boating" / "Shoreline" / "Water" / "Fish" / "Mollusks" /
 ;"Crustacea" / "Aquatic plants" / "Showering" / ...
 Exposure Route -(string)
 ;"Ingestion" / "Inhalation" / "Dermal" / "External"
 Exposure Risk unit -(string)
 ;"Risk" / "HI" / "Sv"
 Exposure Endpoint Type - (string)
 ;if 'Constituent' is not a radionuclide then
 ; "carcinogenic" / "noncarcinogenic"

Exhibit A.5 Content and Structure of the HIF File (Continued)

```
;elseif 'Constituent' is a radionuclide then
; "radiation dose" / "cancer incidence"
; "cancer fatalities" / "cancer plus severe hereditary effects"
For each 'Exposure Media Point' a line with:
Health Impacts -(set of float)
; if 'Exposure Risk unit' = "Risk" then
; one value for each 'Cancer Effect Organ'
; elseif 'Exposure Risk unit' = "Sv" then
; one value for each 'Radiation Dose Effect Organ'
; elseif 'Exposure Risk unit' = "HI" then
; one value for HI
Next 'Exposure Media Point'
Next 'Exposure Pathway'
For each 'Progeny' a line with:
Progeny Name -(string)
Progeny ID -(string)
Number of Exposure Pathways -(integer)
For each 'Exposure Pathway' line with:
Exposure Pathway Name -(string)
; "Air" / "Indoor air" / "Ground" / "Leafy vegetables" /
; "Root vegetables" / "Fruit" / "Grain" / "Meat" /
; "Poultry" / "Milk" / "Eggs" / "Soil" / "Swimming" /
; "Boating" / "Shoreline" / "Water" / "Fish" / "Mollusks" /
; "Crustacea" / "Aquatic plants" / "Showering" / ...
Exposure Route -(string)
; "Ingestion" / "Inhalation" / "Dermal" / "External"
Exposure Risk unit -(string)
; "Risk" / "HI" / "Sv"
Exposure Endpoint Type -(string)
; if 'Constituent' is not a radionuclide then
; "carcinogenic" / "noncarcinogenic"
; elseif 'Constituent' is a radionuclide then
; "radiation dose" / "cancer incidence" /
; "cancer fatalities" / "cancer plus severe hereditary effects"
For each 'Exposure Media Point' a line with:
Health Impacts -(set of float)
; if 'Exposure Risk unit' = "Risk" then
; one value for each 'Cancer Effect Organ'
; elseif 'Exposure Risk unit' = "Sv" then
; one value for each 'Radiation Dose Effect Organ'
; elseif 'Exposure Risk unit' = "HI" then
; one value for HI
Next 'Exposure Media Point'
```

Exhibit A.5 Content and Structure of the HIF File (Continued)

Next 'Exposure Pathway'
Next 'Progeny'
Next 'Exposure Start Time'
Next 'Constituent'
Next 'Age Group'
Next 'Data Set'
Next 'Module'

APPENDIX B

APPENDIX B: AUXILIARY DATA COMMUNICATION FILE SPECIFICATIONS

This appendix provides detailed descriptions of content and structure of the auxiliary data communication files used by GENII V2 NESHAPS modules.

B.1 Radionuclide Master Data File Content

The radionuclide master data library (RMDLIB.DAT) contains all radiological decay data in addition to the specification of all radionuclides for which data is included in the GENII V2 NESHAPS software system. The radionuclides are organized into decay chains ordered by atomic number under the radionuclides highest in the chain. The data in this file are used by the chain decay processor to account for radioactive decay and progeny ingrowth with time. RMDLIB.DAT currently contains information on 839 radionuclides.

Each parent radionuclide entry has at least 2 lines of data. If the radionuclide is the head of a decay chain, then there will be as many additional entries as there are additional members of the decay chain, one line per progeny. In some instances (primarily where the decay progeny has a very short half-life with respect to the parent), progeny are included “implicitly” – their decay energy is included with that of the parent in all applications. In these cases, the implicit progeny are included in the chain, but without indication of half-life.

The first line of the file is descriptive information. The second line indicates detail about the structure of the following data: the maximum number of explicit decay progeny in a chain and the maximum number of implicit progeny in any one chain. The remaining records are set up in blocks for each parent radionuclide. This structure allows consideration of chain decay progeny and released progeny separately in the GENII V2 NESHAPS calculations. The structure of the data blocks is given in Table B.1.

B.2 External Radiation Dosimetry Conversion Factor Files

The files F12TIII1.EXT, FGR12F32.DAT, F12TIII3.EXT, and F12TIII7.EXT contain dose rate conversion factors derived from Federal Guidance Report 12 for exposure to immersion in air, immersion in water, soil surface, and soil volume contamination, respectively. Each contains information for 825 radionuclides, and for each factors for 25 organs or tissues in the body.

The files contain three lines of header information, and 828 lines of data, as illustrated in Table B.2. The file format is A7, 25E9.2. The units vary between the four files. For the air submersion, water immersion, and soil volume files, the units are Sv/s per Bq/m³. For the soil surface contamination file, the units are Sv/s per Bq/m².

TABLE B.1. Radionuclide Master Library Record Structure

<u>Field Number</u>	<u>Data Type</u>	<u>Field Size</u>	<u>Description</u>
Record 1:			
1	CHARACTER	8	Radionuclide identifier
2	INTEGER	5	Number of explicit members in the chain
3	INTEGER	5	Number of implicit members in the chain
Record 2:			
1	CHARACTER	8	Radionuclide identifier (all caps)
2	REAL	13	Half-life (days)
3	INTEGER	2	Chain position number
4	INTEGER	2	Position of first parent
5	REAL	7	Branching ratio from first parent
6	INTEGER	2	Position of second parent
7	REAL	7	Branching ratio from second parent
8	INTEGER	4	Atomic mass number
9	CHARACTER	2	Bone seeker classification (not used by GENII V2)
10	CHARACTER	1	ICRP-30 Primary lung class (not used by GENII V2)

TABLE B.2. External Dose Conversion Factor File Record Format

<u>Field Number</u>	<u>Data Type</u>	<u>Field Size</u>	<u>Description</u>
1	CHARACTER	7	Alphabetical symbol as specified in the master radionuclide library
2-26	REAL	9	Organ-specific dose rate conversion factor.

B.3 Ingestion Radiation Dosimetry Conversion Factor Files

The dose conversion factors for ingestion calculated using the latest ICRP methods are provided in the file FGR13ING.GDB. This file includes significantly more data than are currently being used in GENII V2 NESHAPS. The file provides age-dependent radiation doses for radionuclides for various values of the gut-to-blood transfer factor (f₁). The ages for which data are specified are 100 days, 1 year, 5 years, 10 years, 15 years, and 20 years. Data are provided for 33 organs, tissues, or lung compartments in the ICRP models. This information was provided by Dr. K.F. Eckerman of Oak Ridge National Laboratory.

The file contains two lines of header information, followed by blocks of data for each radionuclide. For some radionuclides, information is provided for both low-LET and high-LET radiations; these radionuclides have 2 lines of data as indicated in the fourth field. The format of the information is provided in Table B.3.

TABLE B.3. Ingestion Dose Conversion Factor Library Record Format

Field Number	Data Type	Field Size	Description
1	CHARACTER	7	Alphanumeric symbol as specified in the master radionuclide library
2	INTEGER	5	Age for which data on this line are applicable, days
3	REAL	8	Gut-to-blood transfer fraction (f1), dimensionless
4	INTEGER	2	Number of lines of data (1 or 2)
5-37	REAL	10	Organ/tissue dose factor, Sv/Bq

B.4 Inhalation Radiation Dosimetry Conversion Factor Files

The dose conversion factors for inhalation calculated using the latest ICRP methods are provided in the file FGR13INH.HDB. The file provides age-depended radiation doses for radionuclides for an inhaled particle size of one micrometer, ICRP lung transfer classes (Fast, Medium, or Slow), and gut-to-blood transfer factor (f1). The ages for which data are specified are 100 days, 1 year, 5 years, 10 years, 15 years, and 20 years. Data are provided for 33 organs, tissues, or lung compartments in the ICRP models. This information was provided by Dr. K.F. Eckerman of Oak Ridge National Laboratory.

The file contains two lines of header information, followed by blocks of data for each radionuclide. For some radionuclides, information is provided for both low-LET and high-LET radiations; these radionuclides have 2 lines of data as indicated in the seventh field. The format of the information is provided in Table B.4.

TABLE B.4. Inhalation Dose Conversion Factor Library Record Format

Field Number	Data Type	Field Size	Description
1	CHARACTER	7	Alphanumeric symbol as specified in the master radionuclide library
2	INTEGER	5	Age for which data on this line are applicable, days
3	REAL	5	Particle size aerodynamic median activity diameter, micrometers
4	CHARACTER	2	ICRP lung transfer class, F, M, or S
5	CHARACTER	2	Flag for Equivalent dose or Absorbed dose, unused
6	REAL	8	Gut-to-blood transfer fraction (f1), dimensionless
7	INTEGER	2	Number of lines of data (1 or 2)
8-40	REAL	10	Organ/tissue dose factor, Sv/Bq

B.5 External Radiation Risk Conversion Files

The file FGR13EXT.RBS provides the risk factors for external exposure for the pathways of air submersion, soil ground plane, and soil volume sources. Data are provided for 15 cancer sites for 5 age groups. These age groups differ from those for the dose conversion factors; they are 0-5 years, 5-15, 15-25, 25-70, and lifetime. This information was provided by Dr. K.F. Eckerman of Oak Ridge National Laboratory.

The file contains 3 header lines to identify and organize the material, followed by three blocks of data for each radionuclide. The format of the information is provided in Table B.5.

TABLE B.5. External Risk Conversion Factor Library Record Format

<u>Field Number</u>	<u>Data Type</u>	<u>Field Size</u>	<u>Description</u>
1	CHARACTER	7	Alphanumeric symbol as specified in the master radionuclide library
2	CHARACTER	11	Mode descriptor (air, soil surface, or soil volume)
3	CHARACTER	10	Cancer site descriptor for this line
4-8	REAL	9	Risk of mortality conversion factor for the five age groups, risk per Bq-s
9-13	REAL	9	Risk of morbidity conversion factor for the five age groups, risk per Bq-s
14	CHARACTER	22	Descriptor of source file for ORNL data
15	CHARACTER	10	Date of generation of data

B.6 Ingestion Radiation Risk Conversion Files

The file FGR13ING.RBS provides the risk factors for ingestion exposure. Data are provided for two intake pathways – drinking water and food. Information is provided on the f1 values used, but only one selection is currently available in this file for each radionuclide. Data are provided for 15 cancer sites for 5 age groups. These age groups differ from those for the dose conversion factors; they are 0-5 years, 5-15, 15-25, 25-70, and lifetime. This information was provided by Dr. K.F. Eckerman of Oak Ridge National Laboratory.

The file contains 3 header lines to identify and organize the material, followed by two blocks of data for each radionuclide. The format of the information is provided in Table B.6.

TABLE B.6. Ingestion Risk Conversion Factor Library Record Format

<u>Field Number</u>	<u>Data Type</u>	<u>Field Size</u>	<u>Description</u>
1	CHARACTER	7	Alphanumeric symbol as specified in the master radionuclide library
2	CHARACTER	11	Mode descriptor (Drinking water or dietary)
3	REAL	8	Gut-to-blood transfer (f1)
4	CHARACTER	10	Cancer site descriptor for this line
5-9	REAL	9	Risk of mortality conversion factor for the five age groups, risk per Bq
10-14	REAL	9	Risk of morbidity conversion factor for the five age groups, risk per Bq

B.7 Inhalation Radiation Risk Conversion Files

The file FGR13INH.RBS provides the risk factors for inhalation exposure. Data are provided for two intake pathways – drinking water and food. Information is provided on the f1 values used, but only one selection is currently available in this file for each radionuclide. Data are provided for 15 cancer sites for 5 age groups. These age groups differ from those for the dose conversion factors; they are 0-5 years, 5-15, 15-25, 25-70, and lifetime. This information was provided by Dr. K.F. Eckerman of Oak Ridge National Laboratory.

The file contains 3 header lines to identify and organize the material, followed by two blocks of data for each radionuclide. The format of the information is provided in Table B.7.

TABLE B.7. Inhalation Risk Conversion Factor Library Record Format

<u>Field Number</u>	<u>Data Type</u>	<u>Field Size</u>	<u>Description</u>
1	CHARACTER	7	Alphanumeric symbol as specified in the master radionuclide library
2	REAL	5	Particle size, currently limited to 1 micrometer AMAD
3	CHARACTER	2	ICRP lung transfer class, F, M, or S
4	CHARACTER	2	Flag for Equivalent dose or Absorbed dose, unused
5	REAL	8	Gut-to-blood transfer (f1)
6	CHARACTER	10	Cancer site descriptor for this line
7-11	REAL	9	Risk of mortality conversion factor for the five age groups, risk per Bq
12-16	REAL	9	Risk of morbidity conversion factor for the five age groups, risk per Bq

B.8 Dose and Risk Factor Index File

The files described in Sections B.2 through B.7 are used in the GENII V2 NESHAPS codes as direct access files. Thus, each radionuclide requires an individual address within each file. This address is provided in the file FGR13CD.NDX. This file, provided by Oak Ridge National Laboratory, contains additional information unused by the GENII V2 NESHAPS codes. This file is necessary for the file-reading routines to access the available data quickly.

B.9 Atmospheric Cloud Shine Dose Rate Factor File

The GENII V2 NESHAPS atmospheric transport modules use a separate file of dose rate factors for infinite lines and planes. The data are derived from the larger dose rate factor files described in Section B.2, but are provided for a fixed range of distances. Buildup and shielding by the atmosphere are included. The first line is a listing of distances in meters for which the following data apply. Each radionuclide has a three-line entry. The format of these entries is shown in Table B.8

Table B.8 Atmospheric Plume Dose Rate Factor File Record Format

<u>Field Number</u>	<u>Data Type</u>	<u>Field Size</u>	<u>Description</u>
Record 1			
1	CHARACTER	10	Alphanumeric radionuclide symbol
2	INTEGER	2	Typing identifier (particle, noble gas, reactive gas) (Not used by GENII V2 NESHAPS)
3-23	REAL	11	Infinite line source dose rate factor
Record 2			
1-20	REAL	11	Infinite plane source dose rate factor
Record 3			
1	REAL	11	Infinite plane source factor (Sv per Ci s/m ²)
2	REAL	11	Infinite plume source factor (Sv per Ci s/m ³)

B.10 FRAMES Connection Files

The GENII system works within the FRAMES framework. This requires a large number of “Description” files (*.DES files). These files describe the interconnected relationships of the GENII V2 NESHAPS system to FRAMES.

TABLE B.9. Pseudo-code Description of DES File Contents

A line with:

Modeling Framework Check - [Const STRING] - "mf"

Modeling Framework Version - [Const STRING] "Version 2.1"

End Line

A line with:

Model Icon Type - [STRING]

;[Model:|Database:|System:|Viewer:| ...] ... is assume to behave as a model

Model Icon Category - [STRING]

;Any user supplied category label

Model Icon Category Prefix - [STRING]

;unique three character string to identify the category

Module Name - [STRING]

Module UI executable or batch path - [STRING]

;Extra command line parameters are also to be included space separated

Module Model executable or batch path - [STRING]

;Extra command line parameters are also to be included space separated

;Not used in the Viewer and optional for Database

End Line

Multi-Line text enclosed in double quotes with

;Description of model - [STRING]

;It is recommended that the Description editor be used to complete this section

;The text should contain

; Description of the model

; Typical uses

; Limiting assumptions

; Typical time scale of runs

; Reference to formulation documents

; Reference to verification documents if they exist

; Reference to validation documents if they exist

; Hardware requirements

; Contact point for question regarding the model

End Multi-Line

A line with:

Number of Input Schemes - [INTEGER]

[Const STRING] - "Reads"

End Line

For each 'Input Scheme'

A line with:

Number of Input Boundary Conditions - [INTEGER]

For each Input Boundary Condition

Boundary Condition File Extension - [STRING]

Boundary Condition Qualifier - [STRING]

Minimum number of this file type required

TABLE B.9. Pseudo-code Description of DES File Contents (Continued)

```

    Maximum number of this file type allowed
    Next Input Boundary Condition
    End Line
Next 'Input Scheme'
A line with:
    Number of Outputs - [INTEGER]
    [Const STRING] - "Writes"
    End Line
For each 'Output'
    A line with:
        Boundary Condition File Extension - [STRING]
        Boundary Condition Qualifier - [STRING]
    End Line
Next 'Output'
A line with:
    Number of Module Input Variables
    [Const STRING] - "Variables"
    End Line
For each 'Module Input Variable'
    A line with:
        Variable Name - [STRING]
        Stochastic Flag - [STRING]
        ;One of ["NOT STOCHASTIC"|"STOCHASTIC"]
        Variable Units - [STRING]
        If a minimum is defined then
            [Const STRING] - "Min"
            Minimum value - (float)
        EndIf
        If a maximum is defined then
            [Const STRING] - "Max"
            Maximum value - (float)
        EndIf
        Variable Description - [STRING]
        Number of Label Ques
    End Line
For each 'Label Que'
    A line with:
        If Label Que then
            [Const STRING] - "Label"
            Label - [STRING]
            Index 1-6 - [STRING]
            ;Indicate which variable indice is to be used for this label

```


TABLE B.9. Pseudo-code Description of DES File Contents (Continued)

```

; "Site" is a reserved indice that represents site being assessed
; "Index1" - "Index6" represent the different indices of the variable
Else
[Const STRING] - "Variable"
Variable Name - [STRING]
; Name must be a variable from the FUI or Modules gid section
Index 1-6 - [STRING]
; Indicate which variable indice is to be used for this label
; "Site" is a reserved indice that represents site being assessed
; "Index1" - "Index6" represent the different indices of the variable
; An assumption is made that the order of the given indexing
; variable arrays must match this variables order
EndIf
End Line
Next 'Label Que'
Next 'Module Input Variable'

```

APPENDIX C

APPENDIX C: RADIOLOGICAL CHAIN-DECAY PROCESSOR

A general solution to first-order compartmental models is presented in this appendix for application to systems consisting of one physical medium that contains any number of radionuclide decay chain members. The solution can be applied to any such system involving physical transfers from the medium and radioactive chain decay with branching. The general analytical solution to the problem is described mathematically and extended to evaluation of the time integral of the radionuclide quantities and to cases involving deposition from outside sources. For deposition at a constant rate during a time period, the general solution can be applied to determine the quantity present during the time period and the time integral of the quantity during the time period.

Various methods have been described for evaluating systems involving radioactive decay (Bateman 1910; Friedlander and Kennedy 1955; Hamawi 1971; Scherpelz and Desrosiers 1980) and physical transfers between media (Gear 1971; Skrable et al. 1974; Hindmarsh 1983; Birchall and James 1989; Kirchner 1990). Some of these methods involve simple analytical solutions, such as the Bateman (1910) representation of the radioactive decay process without branching; others involve advanced numerical methods to solve multi-compartment systems such as the numerical differential equation solvers of Gear (1971) and Hindmarsh (1983) and the numerical matrix method described by Birchall and James (1989). The analytical solutions presented by Bateman (1910), Scherpelz and Desrosiers (1980), and Skrable et al. (1974) do not consider branching, but can account for branching by performing multiple applications of the equations to each possible decay path and summing the results appropriately, a method suggested by Friedlander and Kennedy (1955). The general solution presented in this paper includes chain decay with branching explicitly in the equations (Kennedy and Strenge 1992).

The general radioactive-decay-chain problem is illustrated in Figure C.1. In this figure each box represents a radionuclide decay chain member in a medium. Two types of transfers may be represented: radioactive decay between chain members and physical transfer from the medium. Radioactive transitions in this system are represented as flowing from upper boxes to lower boxes; any upper box may contribute material to any lower box. Because radioactive transitions within decay chains are irreversible, upward transfers, representing recycling of material, are not considered. Physical transfers out of the medium are indicated by the downward arrows from each box.

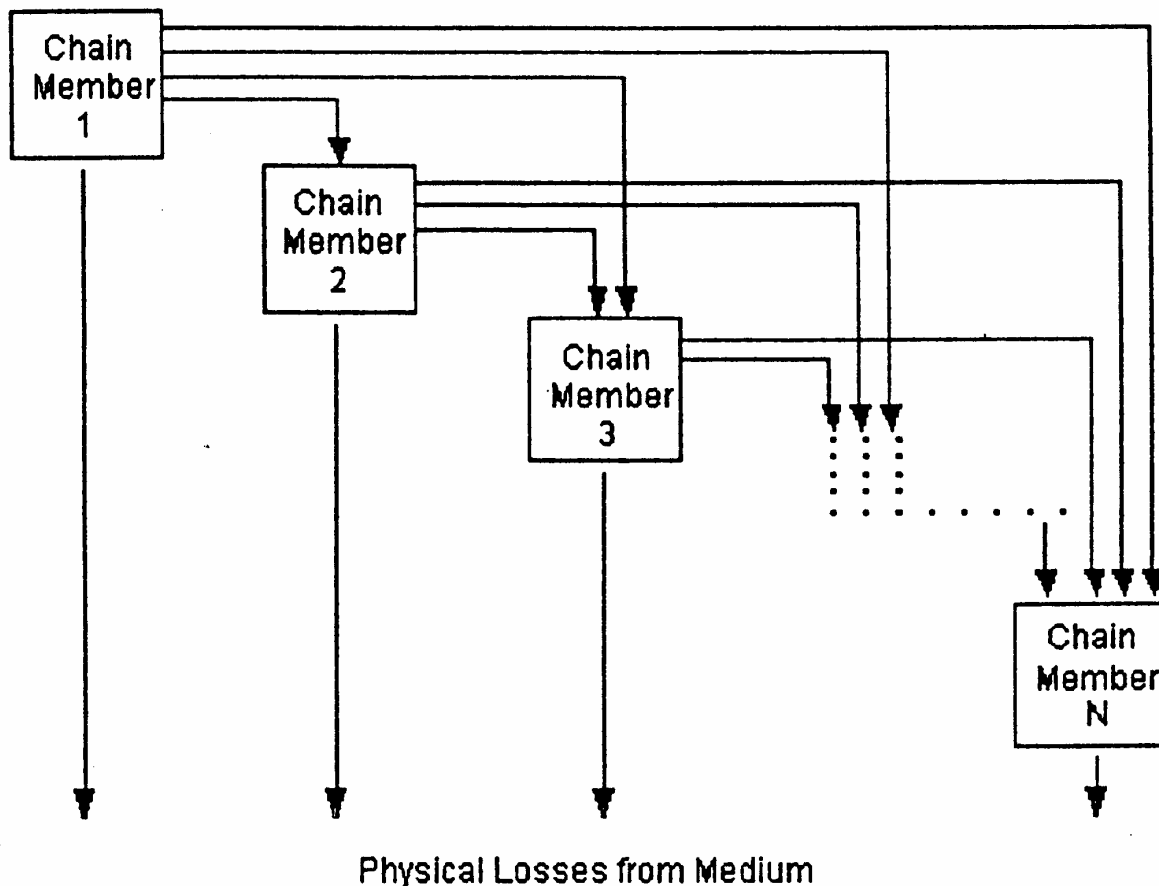


Figure C.1. A Representation of the General Radioactive-Decay-Chain Problem

Four applications are included of the general solution for the compartmental system of Figure C.1. First, the solution is presented for the evaluation of the quantity of radionuclides in each box as a function of time, based on a user-defined initial inventory. The general solution is presented for quantities expressed in units of atoms and activity. The solution then is extended for use to evaluate three additional situations. The first extension covers the evaluation of the time integral of the quantity in each box during a time period. The general solution also is shown to apply to cases involving deposition of radionuclides at a constant rate to a medium when the initial quantity in each box is zero. This application provides the quantity in each box after accumulation during a time period, and can be extended to provide the time integral of the quantity of each chain member from deposition accumulation during a time period.

General Solution

An algorithm for evaluations using the general solution equations is given to demonstrate translation of the method to computer applications. In the system of boxes as shown in Figure C.1, each box may involve 1) transfer to any other box lower in the system and 2) loss by radioactive decay within each box with generation of progeny in a lower box. Transfers between

boxes are described by rate constants. The general differential equation for the change in the quantity of a radionuclide in the medium is described by the following word equation:

(Rate of change of chain member c) =
 - (rate of physical transfer of chain member c out of the medium)
 - (rate of radioactive-transition loss of chain member c)
 + (rate of radioactive-transition ingrowth of chain member c).

Radioactive transitions of precursor radionuclides are represented in the last term.

The equivalent mathematical form of this equation is

$$\frac{d A_c(t)}{d t} = -L_c A_c(t) - \lambda_{rc} A_c(t) + \sum_{n=1}^{c-1} d_{nc} \lambda_{rn} A_n(t) \quad (C.1)$$

where L_c = total rate constant for all physical transfers of chain member from the medium (d^{-1})

$A_c(t)$ = quantity of chain member c at time t (atoms)

λ_{rc} = radioactive transition rate constant for chain member c (d^{-1})

$A_n(t)$ = quantity of chain member n at time t (atoms)

d_{nc} = fraction of precursor radionuclide transitions (chain member n) that result in production of the chain member c (dimensionless)

λ_{rn} = radioactive transition rate constant for chain member n (d^{-1}).

To simplify the solution, the first two terms on the right side of Equation (C.1) can be combined as follows:

$$-L_c A_c(t) - \lambda_{rc} A_c(t) = -\lambda_{ec} A_c(t)$$

where λ_{ec} = effective loss rate constant for radionuclide c from the medium (d^{-1})

$$\lambda_{ec} = L_c + \lambda_{rc}$$

and other terms are as previously defined.

The first term on the right side of Equation (C.1) represents physical transfers of chain member c out of the medium. The rate constant, L_c , is the sum of all physical transfer rate constants from the media (for chain member c). The second term represents loss by radioactive transitions of the radionuclide of chain member c to progeny radionuclides in other boxes. The last term represents production of the chain member c from all precursor radionuclides.

The general solution can be summarized by the following four equations:

$$A_c(t) = \sum_{i=1}^c K_{ci} e^{-\lambda_{ci} t} \quad (C.2)$$

$$K_{11} = A_1(0) \quad (C.3)$$

$$K_{cn} \ (n = 1 \rightarrow c - 1) = \frac{\sum_{i=n}^{c-1} d_{ic} \lambda_{ri} K_{in}}{\lambda_{ec} - \lambda_{en}} \quad (C.4)$$

and

$$K_{cc} = A_c(0) - \sum_{n=1}^{c-1} K_{cn} \quad (C.5)$$

The previous discussion and equations describe quantities of radionuclides expressed in units of atoms. Equations (C.2) through (C.5) can be easily converted to units of activity, such as Bq or Ci, using the general relationship between atom and activity units:

$$Q_c(t) = k A_c(t) \lambda_{rc} \quad (C.6)$$

where $Q_c(t)$ = activity of chain member c at time t (activity units)

k = constant of proportionality between activity units and atoms
(activity·time/atom)

λ_{rc} = radioactive-transition rate constant (inverse time)

and $A_c(t)$ is as previously defined. When activity is expressed in Bq and time in seconds, the constant equals 1.

Substituting the expression in Equation (C.6) into Equations (C.2) through (C.5), with the terms slightly simplified, results in the following general solution with quantities expressed in activity units:

$$Q_c(t) = \lambda_{rc} \sum_{n=1}^c K_{cn} e^{-\lambda_{en} t} \quad (C.7)$$

$$K_{11} = \frac{Q_1(0)}{\lambda_{r1}} \quad (C.8)$$

$$K_{cn} \ (n = 1 \rightarrow c - 1) = \frac{\sum_{i=n}^{c-1} d_{ic} \lambda_{ri} K_{in}}{\lambda_{ec} - \lambda_{en}} \quad (C.9)$$

and

$$K_{cc} = \frac{Q_c(0)}{\lambda_{rc}} - \sum_{n=1}^{c-1} K_{cn} \quad (C.10)$$

The forms of Equations (C.7) through (C.10) suggest some limitations on definition of numerical values for rate constants. First, all boxes must represent a radioactive material, because the radioactive-transition rate constant appears in the denominator of Equations (C.8) and (C.10). Stable elements at the end of a decay chain can be simulated as a material with a long but finite radioactive half-life. This limitation does not apply to the general solution expressed in atom units [Equations (C.2) through (C.5)] although a stable progeny will effectively terminate a radioactive decay chain, because the rate constant for a stable isotope is zero. Another limitation is that the effective rate constant for any two boxes, λ_{ec} and λ_{en} , must not be equal, because their difference appears in the denominator of Equations (C.4) and (C.9). This limitation applies only to pairs of chain members that have radioactive transfers from one to the other.

Use of the general solution given here requires definition of all rate constants and branching fractions. Data on radionuclide half-lives, decay chains, and fractional branching within chains have been published by Lederer and Shirley (1978) and the International Commission on Radiological Protection in ICRP Publication 38 (ICRP 1983).

Extension to Time-Integration

The discussions and equations to this point have centered on evaluation of the quantity of radionuclides present as a function of time. The general solution can be extended easily to provide the time integral of the quantity present during a time period. This extension is demonstrated by observing that the general solution includes the time variable, t , only in the exponential term of Equations (C.2) and (C.7). Obtaining the time-integral expression involves simply integrating the exponential expression and evaluating the integral from time zero to the desired time. The following sequence applied to Equation (C.7) illustrates these steps:

$$\begin{aligned}
\int_0^t Q_i dt &= \int_0^t \lambda_{ri} \left[\sum_{n=1}^i K_{in} e^{-\lambda_{en} t} \right] dt \\
&= \lambda_{ri} \sum_{n=1}^i K_{in} \left[\int_0^t e^{-\lambda_{en} t} dt \right] \\
&= \lambda_{ri} \sum_{n=1}^i K_{in} \left[\frac{e^{-\lambda_{en} t}}{-\lambda_{en}} \right]_0^t,
\end{aligned}$$

The general solution for the time now uses the following formula with Equations (C.8), (C.9), and (C.10):

$$\int_0^t Q_c dt = \lambda_{rc} \sum_{n=1}^c K_{cn} \left[\frac{1 - e^{-\lambda_{en} t}}{\lambda_{en}} \right] \quad (C.12)$$

Extension to Deposition at a Constant Rate

Another extension of the general solution applies to deposition of radionuclides to a medium and accumulation during a time period. The extension assumes that there are initially no radionuclides in the medium. The differential equation for chain member c is based on Equation (C.1) with an added term representing the constant rate of deposition of chain member c to the medium, R_c :

$$\frac{d A_c(t)}{dt} = R_c - \lambda_{ec} A_c(t) + \sum_{n=1}^{c-1} d_{nc} \lambda_{m} A_n(t) \quad (C.13)$$

where R_c = constant deposition rate of chain member c to the medium (atoms/d) and other terms are as previously defined. The general solution to this problem is written as follows, with quantities expressed in activity units:

$$Q_c(t) = \lambda_{rc} \sum_{n=1}^c K_{cn} \left[\frac{1 - e^{-\lambda_{en} t}}{\lambda_{en}} \right] \quad (C.14)$$

$$K_{11} = \frac{D_1}{\lambda_{r1}} \quad (C.15)$$

$$K_{cn} (n = 1 \rightarrow c - 1) = \frac{\sum_{i=n}^{c-1} d_{ic} \lambda_{ri} K_{in}}{\lambda_{ec} - \lambda_{en}} \quad (C.16)$$

and

$$K_{cc} = \frac{D_c}{\lambda_{rc}} - \sum_{n=1}^{c-1} K_{cn} \quad (C.17)$$

where D_c is the constant deposition rate of chain member c expressed in terms of activity (pCi/d), and other terms are as previously defined.

This solution is identical to that for the time-integral problem except for substitution of D_c for $Q_c(0)$, and the integral of the exponential for the exponential as illustrated in Equations (C.11) and (C.12).

Extension to Deposition with Time-Integral

The equations for deposition at a constant rate with accumulation can be integrated to give the time integral of the quantities in each box during a time period. This integration, similar to that described in Equation (C.11), works as follows:

$$A_i(t) = \sum_{n=1}^i K_{in} \left[\frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}} \right],$$

$$K_{11} = R_1,$$

$$K_{in} (n = 1 \rightarrow i - 1) = \frac{\sum_{j=n}^{i-1} d_{ji} \lambda_{rj} K_{jn}}{\lambda_{ei} - \lambda_{en}}, \quad (C.18)$$

or

$$\int_0^t Q_c dt = \lambda_{rc} \sum_{n=1}^c \frac{K_{cn}}{\lambda_{cn}} \left[t - \frac{1 - e^{-\lambda_{cn} t}}{\lambda_{cn}} \right] \quad (C.19)$$

The general solution to the time integral of deposition at a constant rate with accumulation uses Equation (C.19) [in place of Equation (C.14)], and Equations (C.15), (C.16), and (C.17). These equations can be put in terms of atom units by using Equation (C.6), as illustrated earlier.

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APPENDIX D

APPENDIX D: TRANSFER FACTORS

The transfer factor, also known as the concentration ratio or bioaccumulation factor, is the ratio of the concentration of an element in an organism of interest to the concentration in the source medium. The transfer factor applies to long-term, chronic exposure of plants and animals and is ideally measured at equilibrium. Transfer factors relate the concentration of an element in soil to the element's concentration in plant products and the concentration in animal feed to animal products; the fish transfer factor relates the concentration in water to the concentration in fish muscle tissue. Transfer factors are used in risk assessments to estimate the amount of radioactivity that could be present in a food crop or organism based on the calculated concentration in the source medium (i.e., soil or animal feed). By calculating the concentration in the food, the total intake can be estimated and a dose calculated as a result of the annual intake. In terms of radionuclides, the transfer factor is used to calculate how many curies per kilogram of soil are transferred to the edible dry plant product (Bq per kg). For vegetation, the units are kg soil/kg edible dry plants. For animal products, the transfer factor relates the daily intake to that of the animal product. Units for milk are Bq/L per Bq intake/d. For animal and fish meat products, transfer factors are measured in wet weight animal product: Bq/kg muscle per Bq/d intake for meat and Bq/kg muscle per Bq/L for fish.

Numerous studies have been undertaken to quantify transfer factors for specific chemical elements as a function of food type. These studies have been compiled in several publications. This document was written to compile a list of those transfer factors which best describe the commonly accepted factors, and to document the data sources by providing the original as well as the compilation references. In some cases, this listing contains values for elements that are not included in other compilations. Transfer factors for such elements were extrapolated from experimental data based on chemical similarities.

D.1 Selection of Transfer Factors

Transfer factors for this listing were generally selected from recommended values compiled by national or international organizations for use in radiological food chain transport calculations. (In some cases, where newer data were available, very recent references for specific values were preferred to compiled recommendations.) In general, the recommended values from more recent compilations were selected rather than those in older publications. The primary data sources are also cited where identified in the compilation document. In many cases, where neither a primary source of data nor a recommended value in a compilation was available, other methods were used to estimate transfer factors, as described in the following sections.

D.2 Compilations of Data Sources

A hierarchy of data sources was established to select recommended values for transfer factors. The most recent and comprehensive references were given priority. The first reference chosen was the International Atomic Energy Agency's Technical Report Series #364, *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments* (IAEA 1994). This document encompasses a wide variety of plant types and is the result of

extensive background investigations. It is based on data compiled by the International Union of Radioecologists. The second reference given consideration was the NUREG/CR-5512, *Residual Radioactive Contamination From Decommissioning: Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent* (Kennedy and Streng 1992) because of its large set of data and traceable references. Other references used to fill in data were the NCRP Report #123 (1996), *Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground*, the library from the GENII Version 1.485 system of computer codes (Napier et al. 1988), and the series of documents by Coughtrey et al., *Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, Vols. 1-6* (1983). The NCRP Report #123 was chosen because it is a generally accepted reference for a generic model. The GENII V.1.485 values have been in use for a decade to model the semi-arid environment at Hanford and are reasonably well documented. Although the methodology for the Coughtrey and Thorne values was somewhat different, resulting in high values for transfer factors, it was necessary to use their values to fill in data where no other information was available. When no referenceable documents were available, data were derived based on chemical groupings in the periodic table of the elements, as described below.

D.3 Food Types Evaluated

For this compendium of data, foods were grouped into the following types: meat, milk, poultry, eggs, fish, leafy vegetables, other (root) vegetables, fruit, and grain. When more than one food was listed for a given food type (e.g., spinach, cabbage and lettuce listed as leafy vegetable), the transfer factor for each food was weighted by the U.S. Department of Agriculture annual per capita consumption rate (USDA 1983), and a weighted average of transfer factors was reported for that food type.

Plant transfer factors from the IAEA Handbook #364, NUREG/CR-5512, GENII, and Coughtrey et al. are based on dry weight data (Bq per kg dry crop edible product)/(Bq/kg dry soil in the upper 20 cm). When data were presented on a wet weight basis, they were converted to dry weight using conversion factors found in Table D.1. All plant transfer factors presented in this report are based on dry weight. Animal products are presented on a wet weight or volume (milk) basis.

D.4 Methods Used to Estimate Transfer Factors

Experimental data are not available for all elements for all food types. Therefore, several methods were employed to estimate transfer factors for elements and food types where experimental data were lacking. In some cases, parameters from one vegetable type were applied to remaining vegetable types for the same element. In these cases, no adjustments were made for the wet/dry ratios for specific food types, due to the relatively large uncertainty inherent in applying the transfer factor from one food type to another. In other cases, chemical similarities among elements were the basis for estimating the transfer factor. If two or more transfer factors were available for elements in a chemical group, the geometric mean was calculated from the chemical group for the given food type (Figure 1). Where data were available for only one element in a chemical group, the transfer factor for that element was applied to other elements in the same chemical group. Specific cases are listed in the Estimated Transfer

Factors section below. For the actinides, many of the values from americium were applied to other elements for which parameters were not available. Cerium was selected as the surrogate element for other lanthanides for which values were not known.

Table D.1. Dry-to-Wet-Weight Conversion Factors for Food Products ^a

Plant Type		Conversion Factor
Leafy vegetation		0.2
Other vegetables		0.25
Fruit		0.18
Grain		0.91
Meat	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91
Poultry	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91
Dairy	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91
Eggs	Forage	0.22
	Stored hay	0.22
	Stored grain	0.91

^a From Kennedy and Streng (1992)

Tables D.2-D.10 list (a) the recommended transfer factors by food or crop type, (b) the compilation from which the value was taken, and (c) the original sources of data as cited in each compilation document. The following paragraphs describe how transfer factors were estimated for special cases without direct primary references.

D.5 Special Cases Without Primary References

Fish

Most of the water-to-fish transfer factors were available from one of the compilations. However, values for all lanthanides were based on Ce.

Meat

The Ta transfer factor for feed-to-meat was set equal to the Nb value, and all lanthanides were based on Ce. Unknown actinides, Ac, Pa, and Cf values were set equal to Am values for their respective food types. All other values were based on the recommended values in a compilation document.

Fruit

The soil-to-fruit transfer factors for N, Os, Au, and Hg were calculated based on the geometric mean of the transfer factors in their respective groups on the periodic table. Hafnium (Hf) and Ta were assigned values equal to those for Zr and Nb, respectively. All the lanthanide elements were assigned the value for Ce.

Grain

The soil-to-grain transfer factors for Be, N, and Hg were calculated as the geometric mean of the transfer factors in their respective periodic table groups. Silver (Ag), Hf, Ta, and Au transfer factors for grain were based on the single known value in their respective chemical groups. All the lanthanide elements were assigned the value for Ce. The grain transfer factors for Ac, Pa, and Cf were based on Am.

Leafy Vegetation

The soil-to-leafy vegetation transfer factors for N, Hf, Ta, and Au were calculated as the geometric means of the transfer factors in their respective periodic table groups. All the lanthanide elements were assigned the value for Ce. Actinium (Ac), Pa, and Cf were assigned the leafy vegetable transfer factor from Am.

Root Vegetables

The soil-to-root transfer factors for N and Au were calculated as the geometric mean of the transfer factors in their respective periodic table groups. Hafnium (Hf) and Ta were based on a single established value in their respective chemical groups. The root transfer factors for Ac, Pa, and Cf were based on Am. All lanthanide elements were assigned the value for Ce.

D.6 Additional Transfer Factors used in GENII V2 NESHAPS

Three additional types of transfer factors are used in GENII V2 NESHAPS; these are all derived from the earlier GENII 1.485 (Napier et al. 1988) without current updating. These are the transfer factors for saltwater fish, fresh and salt water crustaceans, fresh and salt water molluscs, and fresh and salt water plants. These are listed in Tables D.11, D.12, D.13, and D.14. All transfer factors in these tables come from the GENII 1.485 data files. For marine species, the GENII 1.485 values in Napier et al. (1988) are largely traceable back to *A Model for the Approximate Calculation of Safe Rates of Discharge of Radioactive Wastes into Marine Environments* (Freke 1967). Specifically for freshwater environments, the parameters are ultimately traceable to *Concentration Factors of Chemical Elements in Edible Aquatic Organisms* (Thompson et al. 1972), which in turn is primarily derived from Ng's (1968) *Handbook for Estimating the Maximum Internal Dose from Radionuclides Released to the Biosphere*.

Table D.2. Transfer Factors for Meat (Bq/kg muscle per Bq/d intake)

Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference
04 Be	1.0E-3	KS92	Ng68	52 Te	7.0E-3	IAEA94	Jo88
07 N	7.5E-2	KS92	Ng68	53 I	4.0E-2	IAEA94	Bi89
09 F	1.5E-1	KS92	Ng68	55 Cs	5.0E-2	IAEA94	Co90
11 Na	8.0E-2	IAEA94	Ng82a	56 Ba	2.0E-4	IAEA94	Jo88
12 Mg	2.0E-2	IAEA94	Ng82a	57 La	2.0E-3	NCRP96	NCRP96
14 Si	4.0E-5	KS92	Ng68	58 Ce	2.0E-5	IAEA94	CEC87
15 P	5.0E-2	IAEA94	Ng82a	59 Pr	2.0E-5	Based on Ce	CEC87
16 S	2.0E-1	Na88	IAEA87	60 Nd	2.0E-5	Based on Ce	CEC87
17 Cl	2.0E-2	IAEA94	Bi89	61 Pm	2.0E-5	Based on Ce	CEC87
19 K	2.0E-2	IAEA94	Ng82a	62 Sm	2.0E-5	Based on Ce	CEC87
20 Ca	2.0E-3	IAEA94	Ng82a	63 Eu	2.0E-5	Based on Ce	CEC87
21 Sc	1.5E-2	KS92	Ng68	64 Gd	2.0E-5	Based on Ce	CEC87
24 Cr	9.0E-3	IAEA94	Ng82a	65 Tb	2.0E-5	Based on Ce	CEC87
25 Mn	5.0E-4	IAEA94	Ng82a	66 Dy	2.0E-5	Based on Ce	CEC87
26 Fe	2.0E-2	IAEA94	Ng82a	67 Ho	2.0E-5	Based on Ce	CEC87
27 Co	1.0E-2	IAEA94	Ng82a	68 Er	2.0E-5	Based on Ce	CEC87
28 Ni	5.0E-3	IAEA94	Cr90	72 Hf	1.0E-3	KS92	Ng68
29 Cu	9.0E-3	IAEA94	Ng82a	73 Ta	3.0E-7	Based on Nb	Jo88
30 Zn	1.0E-1	IAEA94	Ng82a	74 W	4.0E-2	IAEA94	Ng82a
31 Ga	5.0E-4	KS92	Ba84	75 Re	8.0E-3	KS92	Ng68
33 As	2.0E-3	KS92	Ng68	76 Os	4.0E-1	KS92	Ng68
34 Se	1.5E-2	KS92	Ng68	77 Ir	1.5E-3	KS92	Ng68
35 Br	2.5E-2	KS92	Ng68	79 Au	5.0E-3	Na88	NCRP86
37 Rb	1.0E-2	IAEA94	Ng82a	80 Hg	2.5E-1	KS92	Ng68
38 Sr	8.0E-3	IAEA94	Co90	81 Tl	4.0E-2	KS92	Ng68
39 Y	1.0E-3	IAEA94	Ng82a	82 Pb	4.0E-4	IAEA94	Ng82a
40 Zr	1.0E-6	IAEA94	Jo88	83 Bi	4.0E-4	KS92	Ng68
41 Nb	3.0E-7	IAEA94	Jo88	84 Po	5.0E-3	IAEA94	Ng82a
42 Mo	1.0E-3	IAEA94	Jo88	88 Ra	9.0E-4	IAEA94	MB90
43 Tc	1.0E-4	IAEA94	Bi89	89 Ac	4.0E-4	Na88	LS85
44 Ru	5.0E-2	IAEA94	Co90	90 Th	4.0E-5	Based on Am	Co90
45 Rh	2.0E-3	KS92	Ng79	91 Pa	4.0E-5	Based on Am	Co90
46 Pd	4.0E-3	KS92	Ng68	92 U	3.0E-4	IAEA94	Cr90
47 Ag	3.0E-3	IAEA94	CEC87	93 Np	1.0E-3	IAEA94	Br79
48 Cd	4.0E-4	IAEA94	Ng82a	94 Pu	1.0E-5	IAEA94	Co90
49 In	8.0E-3	KS92	Ng68	95 Am	4.0E-5	IAEA94	Co90
50 Sn	8.0E-2	KS92	Ng68	96 Cm	4.0E-5	Based on Am	Co90
51 Sb	1.0E-3	Na88	IAEA87	98 Cf	4.0E-5	Based on Am	Co90

g.m. = geometric mean.

Table D.3. Transfer Factors for Eggs (Bq/kg egg per Bq/d intake)

Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference
04 Be	2.0E-2	KS92	Na88	52 Te	5.0E+0	IAEA94	En88a
07 N	2.6E-1	g.m.	g.m.	53 I	4.4E+0	Sn94	Sn94
09 F	2.7E+0	g.m.	g.m.	55 Cs	4.0E-1	IAEA94	Co90
11 Na	6.0E+0	IAEA94	Ng82a	56 Ba	9.0E-1	IAEA94	En88a
12 Mg	2.0E+0	IAEA94	Ng82a	57 La	9.0E-3	IAEA94	Ng82a
14 Si	1.0E+0	Based on P	Na88	58 Ce	4.0E-5	IAEA94	CEC87
15 P	1.0E+0	KS92	Na88	59 Pr	4.0E-5	Based on Ce	CEC87
16 S	7.0E+0	g.m.	g.m.	60 Nd	4.0E-5	Based on Ce	CEC87
17 Cl	2.7E+0	g.m.	g.m.	61 Pm	4.0E-5	Based on Ce	CEC87
19 K	1.0E+0	IAEA94	Ng82a	62 Sm	4.0E-5	Based on Ce	CEC87
20 Ca	4.0E-1	IAEA94	Ng82a	63 Eu	4.0E-5	Based on Ce	CEC87
21 Sc	4.2E-3	g.m.	g.m.	64 Gd	4.0E-5	Based on Ce	CEC87
24 Cr	9.0E-1	Based on Mo	En88a	65 Tb	4.0E-5	Based on Ce	CEC87
25 Mn	6.0E-2	IAEA94	Ng82a	66 Dy	4.0E-5	Based on Ce	CEC87
26 Fe	1.0E+0	IAEA94	Ng82a	67 Ho	4.0E-5	Based on Ce	CEC87
27 Co	1.0E-1	IAEA94	Ng82a	68 Er	4.0E-5	Based on Ce	CEC87
28 Ni	1.0E-1	KS92	Na88	72 Hf	2.0E-4	Based on Zr	Jo88
29 Cu	5.0E-1	IAEA94	Ng82a	73 Ta	1.0E-3	Based on Nb	En88a
30 Zn	3.0E+0	IAEA94	Ng82a	74 W	9.0E-1	Based on Mo	En88a
31 Ga	1.0E+0	Based on P	Na88	75 Re	4.2E-1	g.m.	g.m.
33 As	2.6E-1	g.m.	g.m.	76 Os	7.1E-2	g.m.	g.m.
34 Se	9.0E+0	IAEA94	Ng82a	77 Ir	1.0E-1	Based on Co	Ng82a
35 Br	1.6E+0	KS92	Na88	79 Au	5.0E-1	Based on Cu	Ng82a
37 Rb	3.0E+0	KS92	Na88	80 Hg	5.0E-1	g.m.	g.m.
38 Sr	2.0E-1	IAEA94	Co90	81 Tl	1.0E+0	Based on P	Na88
39 Y	2.0E-3	IAEA94	Ng82a	82 Pb	1.0E+0	Based on P	Na88
40 Zr	2.0E-4	IAEA94	En88a	83 Bi	2.6E-1	g.m.	g.m.
41 Nb	1.0E-3	IAEA94	En88a	84 Po	7.0E+0	g.m.	g.m.
42 Mo	9.0E-1	IAEA94	En88a	88 Ra	3.1E-1	g.m.	g.m.
43 Tc	3.0E+0	IAEA94	En88a	89 Ac	4.0E-3	Based on Am	Ng82a
44 Ru	5.0E-3	IAEA94	Co90	90 Th	4.0E-3	Based on Am	Ng82a
45 Rh	1.0E-1	Based on Co	Ng82a	91 Pa	4.0E-3	Based on Am	Ng82a
46 Pd	4.0E-3	KS92	Na88	92 U	1.0E+0	IAEA94	Ng82a
47 Ag	5.0E-1	Based on Cu	Ng82a	93 Np	4.0E-3	Based on Am	Ng82a
48 Cd	1.0E-1	IAEA94	Ng82a	94 Pu	5.0E-4	IAEA94	Ng82a
49 In	1.0E+0	Based on P	Na88	95 Am	4.0E-3	IAEA94	Ng82a
50 Sn	1.0E+0	Based on P	Na88	96 Cm	4.0E-3	Based on Am	Ng82a
51 Sb	7.0E-2	KS92	Na88	98 Cf	4.0E-3	Based on Am	Ng82a

g.m. = geometric mean.

Table D.4. Concentration Ratios for Freshwater Fish (Bq/kg muscle per Bq/L)

Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference
02 He	1.0E+0	IAEA94	IAEA94	51 Sb	1.0E+2	IAEA94	IAEA82
04 Be	1.0E+2	IAEA94	IAEA94	52 Te	4.0E+2	IAEA94	IAEA82
06 C	5.0E+4	IAEA94	IAEA94	53 I	4.0E+1	IAEA94	IAEA82
07 N	2.0E+5	IAEA94	IAEA94	55 Cs	2.0E+3	IAEA94	IAEA82
08 O	1.0E+0	IAEA94	IAEA94	56 Ba	4.0E+0	IAEA94	IAEA82
09 F	1.0E+1	KS92	St86	57 La	3.0E+1	IAEA94	IAEA82
11 Na	2.0E+1	IAEA94	IAEA82	58 Ce	3.0E+1	IAEA94	IAEA82
12 Mg	5.0E+1	NCRP96	NCRP96	59 Pr	3.0E+1	Based on Ce	IAEA82
14 Si	2.0E+1	NCRP96	NCRP96	60 Nd	3.0E+1	Based on Ce	IAEA82
15 P	5.0E+4	IAEA94	IAEA82	61 Pm	3.0E+1	Based on Ce	IAEA82
16 S	8.0E+2	IAEA94	IAEA82	62 Sm	3.0E+1	Based on Ce	IAEA82
17 Cl	5.0E+1	KS92	St86	63 Eu	3.0E+1	Based on Ce	IAEA82
19 K	1.0E+3	KS92	St86	64 Gd	3.0E+1	Based on Ce	IAEA82
20 Ca	4.0E+1	KS92	St86	65 Tb	3.0E+1	Based on Ce	IAEA82
21 Sc	1.0E+2	IAEA94	IAEA94	66 Dy	3.0E+1	Based on Ce	IAEA82
24 Cr	4.0E+0	Sn94	Th94	67 Ho	3.0E+1	Based on Ce	IAEA82
25 Mn	4.0E+2	IAEA94	IAEA82	68 Er	3.0E+1	Based on Ce	IAEA82
26 Fe	2.0E+2	IAEA94	IAEA82	72 Hf	3.0E+2	Based on Zr	IAEA82
27 Co	3.0E+2	IAEA94	IAEA82	73 Ta	3.0E+2	Based on Nb	IAEA94
28 Ni	1.0E+2	IAEA94	IAEA82	74 W	1.0E+1	Based on Mo	IAEA94
29 Cu	2.0E+2	IAEA94	IAEA94	75 Re	1.2E+2	KS92	St86
30 Zn	3.5E+2	Sn94	Th94	76 Os	1.0E+1	KS92	St86
31 Ga	4.0E+2	NCRP96	NCRP96	77 Ir	1.0E+1	KS92	St86
33 As	1.7E+3	Sn94	Th94	79 Au	3.3E+1	KS92	St86
34 Se	1.7E+2	KS92	St86	80 Hg	1.0E+3	KS92	St86
35 Br	4.0E+2	IAEA94	IAEA94	81 Tl	1.0E+4	NCRP96	NCRP96
37 Rb	2.0E+3	IAEA94	IAEA94	82 Pb	3.0E+2	IAEA94	IAEA82
38 Sr	6.0E+1	IAEA94	IAEA82	83 Bi	1.5E+1	KS92	St86
39 Y	3.0E+1	IAEA94	IAEA82	84 Po	5.0E+1	IAEA94	IAEA82
40 Zr	3.0E+2	IAEA94	IAEA82	88 Ra	5.0E+1	IAEA94	IAEA82
41 Nb	3.0E+2	IAEA94	IAEA82	89 Ac	2.5E+1	KS92	St86
42 Mo	1.0E+1	IAEA94	IAEA94	90 Th	1.0E+2	KS92	Na88
43 Tc	2.0E+1	IAEA94	IAEA82	91 Pa	1.0E+1	NCRP96	NCRP96
44 Ru	1.0E+2	KS92	Na88	92 U	1.0E+1	IAEA94	IAEA82
45 Rh	1.0E+1	IAEA94	IAEA94	93 Np	2.1E+1	Sn94	Th94
46 Pd	1.0E+1	KS92	St86	94 Pu	3.0E+1	IAEA94	IAEA82
47 Ag	5.0E+0	IAEA94	IAEA82	95 Am	3.0E+1	IAEA94	IAEA82
48 Cd	2.0E+2	KS92	St86	96 Cm	3.0E+1	IAEA94	IAEA82
49 In	1.0E+4	NCRP96	NCRP96	98 Cf	2.5E+1	KS92	St86
50 Sn	3.0E+3	KS92	St86				

g.m. = geometric mean.

Table D.5. Transfer Factors for Fruit (Bq/kg fruit per Bq/kg soil)

Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference
04 Be	1.5E-3	KS92	Ba84	52 Te	4.0E-3	KS92	Ba84
06 C	7.0E-1	Na88	Na88	53 I	4.0E-2	Sn94	Sn94
07 N	3.0E-2	g.m.	g.m.	55 Cs	2.2E-1	IAEA94	Fr89
09 F	6.0E-3	KS92	Ba84	56 Ba	1.5E-2	KS92	Ba84
11 Na	3.0E-1	IAEA94	Ng82b	57 La	4.0E-3	KS92	Ba84
12 Mg	5.5E-1	KS92	Ba84	58 Ce	2.0E-2	Ng82b	Ng82b
14 Si	7.0E-2	KS92	Ba84	59 Pr	2.0E-2	Based on Ce	Ng82b
15 P	3.5E+0	KS92	Ba84	60 Nd	2.0E-2	Based on Ce	Ng82b
16 S	1.5E+0	KS92	Ba84	61 Pm	2.0E-2	Based on Ce	Ng82b
17 Cl	7.0E+1	KS92	Ba84	62 Sm	2.0E-2	Based on Ce	Ng82b
19 K	5.5E-1	KS92	Ba84	63 Eu	2.0E-2	Based on Ce	Ng82b
20 Ca	3.5E-1	KS92	Ba84	64 Gd	2.0E-2	Based on Ce	Ng82b
21 Sc	1.0E-3	KS92	Ba84	65 Tb	2.0E-2	Based on Ce	Ng82b
24 Cr	4.5E-3	KS92	Ba84	66 Dy	2.0E-2	Based on Ce	Ng82b
25 Mn	5.0E-2	KS92	Ba84	67 Ho	2.0E-2	Based on Ce	Ng82b
26 Fe	5.0E-2	CT83	CT83	68 Er	2.0E-2	Based on Ce	Ng82b
27 Co	7.0E-3	KS92	Ba84	72 Hf	1.0E-3	Based on Zr	Ng82b
28 Ni	6.0E-2	KS92	Ba84	73 Ta	2.5E-2	Based on Nb	CT83
29 Cu	2.5E-1	KS92	Ba84	74 W	3.0E+0	NCRP96	NCRP96
30 Zn	9.0E-1	KS92	Ba84	75 Re	3.5E-1	KS92	Ba84
31 Ga	4.0E-4	Based on In	Ba84	76 Os	4.5E-2	g.m.	g.m.
33 As	6.0E-3	KS92	Ba84	77 Ir	1.5E-2	KS92	Ba84
34 Se	5.0E-2	CT83	CT83	79 Au	1.4E-2	g.m.	g.m.
35 Br	1.5E+0	KS92	Fu78	80 Hg	3.7E-1	g.m.	g.m.
37 Rb	9.0E-1	IAEA94	Ng82b	81 Tl	4.0E-4	KS92	Ba84
38 Sr	2.0E-1	IAEA94	Fr82	82 Pb	1.0E-2	IAEA94	Fr89
39 Y	1.0E-2	IAEA94	Ng82b	83 Bi	5.0E-1	IAEA94	IAEA82
40 Zr	1.0E-3	IAEA94	Ng82b	84 Po	1.2E-3	IAEA94	Ho91
41 Nb	2.5E-2	CT83	CT83	88 Ra	6.1E-3	IAEA94	Fr89
42 Mo	5.0E-2	CT83	CT83	89 Ac	2.5E-4	Based on Am	Ba84
43 Tc	1.5E+0	KS92	Ba84	90 Th	2.5E-4	Based on Am	Ba84
44 Ru	4.0E-2	IAEA94	Ng82b	91 Pa	2.5E-4	Based on Am	Ba84
45 Rh	4.0E-2	KS92	Ba84	92 U	4.0E-3	KS92	Ba84
46 Pd	4.0E-2	KS92	Ba84	93 Np	1.0E-2	KS92	Ba84
47 Ag	8.0E-4	IAEA94	Fr89	94 Pu	4.5E-5	KS92	Ba84
48 Cd	1.5E-1	KS92	Ba84	95 Am	2.5E-4	KS92	Ba84
49 In	4.0E-4	KS92	Fu78	96 Cm	1.5E-5	KS92	Ba84
50 Sn	6.0E-3	KS92	Fu78	98 Cf	2.5E-4	Based on Am	Ba84
51 Sb	8.0E-5	KS92	IUR89				

g.m. = geometric mean.

Table D.6. Transfer Factors for Grain (Bq/kg grain per Bq/kg soil)

Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference
04 Be	2.0E-3	g.m.	g.m.	52 Te	4.0E-3	KS92	Ba84
06 C	7.0E-1	Na88	Na88	53 I	4.0E-2	Sn94	Sn94
07 N	1.3E-1	g.m.	g.m.	55 Cs	2.6E-2	IAEA94	Fr82
09 F	6.0E-3	KS92	Ba84	56 Ba	1.5E-2	KS92	Ba84
11 Na	3.0E-1	IAEA94	Ng82b	57 La	4.0E-3	KS92	Ba84
12 Mg	5.5E-1	KS92	Ba84	58 Ce	2.0E-2	Ng82b	Ng82b
14 Si	7.0E-2	KS92	Ba84	59 Pr	2.0E-2	Based on Ce	Ng82b
15 P	3.5E+0	KS92	Ba84	60 Nd	2.0E-2	Based on Ce	Ng82b
16 S	1.5E+0	KS92	Ba84	61 Pm	2.0E-2	Based on Ce	Ng82b
17 Cl	7.0E+1	KS92	Ba84	62 Sm	2.0E-2	Based on Ce	Ng82b
19 K	5.5E-1	KS92	Ba84	63 Eu	2.0E-2	Based on Ce	Ng82b
20 Ca	3.5E-1	KS92	Ba84	64 Gd	2.0E-2	Based on Ce	Ng82b
21 Sc	1.0E-3	KS92	Ba84	65 Tb	2.0E-2	Based on Ce	Ng82b
24 Cr	4.5E-3	KS92	Ba84	66 Dy	2.0E-2	Based on Ce	Ng82b
25 Mn	3.0E-1	IAEA94	IAEA94	67 Ho	2.0E-2	Based on Ce	Ng82b
26 Fe	5.0E-2	CT83	CT83	68 Er	2.0E-2	Based on Ce	Ng82b
27 Co	3.7E-3	IAEA94	Fr89	72 Hf	1.0E-3	Based on Zr	Ng82b
28 Ni	3.0E-2	IAEA94	Fr89	73 Ta	2.5E-2	Based on Nb	CT83
29 Cu	2.5E-1	KS92	Ba84	74 W	3.0E+0	NCRP96	NCRP96
30 Zn	1.6E+0	IAEA94	Fr89	75 Re	3.5E-1	KS92	Ba84
31 Ga	4.0E-4	Based on In	Ba84	76 Os	3.5E-3	KS92	Ba84
33 As	6.0E-3	KS92	Ba84	77 Ir	1.5E-2	KS92	Ba84
34 Se	2.5E-1	CT83	CT83	79 Au	2.5E-1	Based on Cu	Ba84
35 Br	1.5E+0	KS92	Fu78	80 Hg	4.9E-1	g.m.	g.m.
37 Rb	9.0E-1	IAEA94	Ng82b	81 Tl	4.0E-4	KS92	Ba84
38 Sr	2.1E-1	IAEA94	Fr82	82 Pb	4.7E-3	IAEA94	Fr89
39 Y	1.0E-2	IAEA94	Ng82b	83 Bi	5.0E-1	IAEA94	IAEA82
40 Zr	1.0E-3	IAEA94	Ng82b	84 Po	2.3E-3	IAEA94	HW91
41 Nb	2.5E-2	CT83	CT83	88 Ra	1.2E-3	IAEA94	Fr89
42 Mo	8.0E-1	IAEA94	Ng82b	89 Ac	2.2E-5	Based on Am	Fr82
43 Tc	7.3E-1	IAEA94	Fr89	90 Th	3.4E-5	KS92	IUR89
44 Ru	5.0E-3	IAEA94	Fr89	91 Pa	2.2E-5	Based on Am	Fr82
45 Rh	4.0E-2	KS92	Ba84	92 U	1.3E-3	IAEA94	Bi91
46 Pd	4.0E-2	KS92	Ba84	93 Np	2.7E-3	IAEA94	Fr82
47 Ag	2.5E-1	Based on Cu	Ba84	94 Pu	8.6E-6	IAEA94	Fr82
48 Cd	1.5E-1	KS92	Ba84	95 Am	2.2E-5	IAEA94	Fr82
49 In	4.0E-4	KS92	Fu78	96 Cm	2.1E-5	IAEA94	Fr82
50 Sn	6.0E-3	KS92	Fu78	98 Cf	2.2E-5	Based on Am	Fr82
51 Sb	3.0E-2	KS92	Fu78				

g.m. = geometric mean.

Table D.7. Transfer Factors for Leafy Vegetation (Bq/kg leafy vegetation per Bq/kg soil)

Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference
04 Be	1.0E-2	KS92	Ba84	52 Te	2.5E-2	KS92	Ba84
06 C	7.0E-1	KS92		53 I	4.0E-2	Sn94	Sn94
07 N	5.5E-2	KS92	Ba84	55 Cs	4.6E-1	IAEA94	Fr82
09 F	6.0E-2	KS92	Ba84	56 Ba	1.5E-1	KS92	Ba84
11 Na	3.0E-1	IAEA94	Ng82b	57 La	5.2E-3	IAEA94	Fr89
12 Mg	1.0E+0	KS92	Ba84	58 Ce	2.0E-2	Ng82b	Ng82b
14 Si	3.5E-1	KS92	Ba84	59 Pr	2.0E-2	Based on Ce	Ng82b
15 P	3.5E+0	KS92	Ba84	60 Nd	2.0E-2	Based on Ce	Ng82b
16 S	1.5E+0	KS92	Ba84	61 Pm	2.0E-2	Based on Ce	Ng82b
17 Cl	7.0E+1	KS92	Ba84	62 Sm	2.0E-2	Based on Ce	Ng82b
19 K	1.0E+0	KS92	Ba84	63 Eu	2.0E-2	Based on Ce	Ng82b
20 Ca	3.5E+0	KS92	Ba84	64 Gd	2.0E-2	Based on Ce	Ng82b
21 Sc	6.0E-3	KS92	Ba84	65 Tb	2.0E-2	Based on Ce	Ng82b
24 Cr	7.5E-3	KS92	Ba84	66 Dy	2.0E-2	Based on Ce	Ng82b
25 Mn	7.0E-1	IAEA94	Fr89	67 Ho	2.0E-2	Based on Ce	Ng82b
26 Fe	5.0E-2	CT83	CT83	68 Er	2.0E-2	Based on Ce	Ng82b
27 Co	2.3E-1	IAEA94	Fr89	72 Hf	1.0E-3	Based on Zr	Ng82b
28 Ni	2.8E-1	KS92	IUR89	73 Ta	2.5E-2	Based on Nb	CT83
29 Cu	4.0E-1	KS92	Ba84	74 W	3.0E+0	Na88	NCRP86
30 Zn	1.3E+0	IAEA94	Fr89	75 Re	1.5E+0	KS92	Ba84
31 Ga	4.0E-3	Based on In	Ba84	76 Os	1.5E-2	KS92	Ba84
33 As	4.0E-2	KS92	Ba84	77 Ir	5.5E-2	KS92	Ba84
34 Se	2.5E-1	CT83	CT83	79 Au	1.0E-2	g.m.	g.m.
35 Br	1.5E+0	KS92	Fu78	80 Hg	8.5E-1	g.m.	g.m.
37 Rb	9.0E-1	IAEA94	Ng82b	81 Tl	4.0E-3	Based on In	Fu78
38 Sr	3.0E+0	IAEA94	Fr82	82 Pb	1.0E-2	IAEA94	Fr89
39 Y	1.0E-2	IAEA94	Ng82b	83 Bi	5.0E-1	IAEA94	IAEA82
40 Zr	1.0E-3	IAEA94	Ng82b	84 Po	1.2E-3	IAEA94	Ho91
41 Nb	2.5E-2	CT83	CT83	88 Ra	4.9E-2	IAEA94	Fr89
42 Mo	8.0E-1	IAEA94	Ng82b	89 Ac	4.7E-4	Based on Am	Fr82
43 Tc	2.1E+2	IAEA94	Fr89	90 Th	1.8E-3	IAEA94	Fr89
44 Ru	4.0E-2	IAEA94	Ng82b	91 Pa	4.7E-4	Based on Am	Fr82
45 Rh	1.5E-1	KS92	Ba84	92 U	8.3E-3	IAEA94	Fr89
46 Pd	1.5E-1	KS92	Ba84	93 Np	3.2E-2	IAEA94	Fr82
47 Ag	2.7E-4	IAEA94	Fr89	94 Pu	6.0E-5	IAEA94	Fr82
48 Cd	5.5E-1	KS92	Ba84	95 Am	4.7E-4	IAEA94	Fr82
49 In	4.0E-3	KS92	Fu78	96 Cm	7.7E-4	IAEA94	Fr82
50 Sn	3.0E-2	KS92	Fu78	98 Cf	4.7E-4	Based on Am	Fr82
51 Sb	1.3E-4	KS92	IUR89				

g.m. = geometric mean.

Table D.8. Transfer Factors for Milk (Bq/L milk per Bq/d intake)

Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference
01 H	1.5E-2	IAEA94	Va83	52 Te	4.5E-4	IAEA94	Jo88
04 Be	9.0E-7	KS92	Ng77	53 I	9.0E-3	Sn94	Sn94
07 N	2.5E-2	KS92	Ng77	55 Cs	7.9E-3	IAEA94	Co90
09 F	1.0E-3	KS92	Ng77	56 Ba	4.8E-4	IAEA94	Jo88
11 Na	1.6E-2	IAEA94	IAEA94	57 La	2.0E-5	KS92	Ng77
12 Mg	3.9E-3	IAEA94	Ng82a	58 Ce	3.0E-5	IAEA94	CEC87
14 Si	2.0E-5	KS92	Ng77	59 Pr	3.0E-5	Based on Ce	CEC87
15 P	1.6E-2	IAEA94	Ng82a	60 Nd	3.0E-5	Based on Ce	CEC87
16 S	1.6E-2	IAEA94	Ng82a	61 Pm	3.0E-5	Based on Ce	CEC87
17 Cl	1.7E-2	IAEA94	Bi89	62 Sm	3.0E-5	Based on Ce	CEC87
19 K	7.2E-3	IAEA94	Ng82a	63 Eu	3.0E-5	Based on Ce	CEC87
20 Ca	3.0E-3	IAEA94	CT83	64 Gd	3.0E-5	Based on Ce	CEC87
21 Sc	5.0E-6	KS92	Ng77	65 Tb	3.0E-5	Based on Ce	CEC87
24 Cr	1.0E-5	IAEA94	Va84	66 Dy	3.0E-5	Based on Ce	CEC87
25 Mn	3.0E-5	IAEA94	Va84	67 Ho	3.0E-5	Based on Ce	CEC87
26 Fe	3.0E-5	IAEA94	Va84	68 Er	3.0E-5	Based on Ce	CEC87
27 Co	3.0E-4	IAEA94	Ba84	72 Hf	5.5E-7	Based on Zr	Jo88
28 Ni	1.6E-2	IAEA94	Cr90	73 Ta	4.1E-7	Based on Nb	Jo88
29 Cu	2.0E-3	Na88	IAEA87	74 W	3.0E-4	KS92	Ng77
30 Zn	1.0E-2	KS92	Ng77	75 Re	1.5E-3	KS92	Ng77
31 Ga	5.0E-5	KS92	Ng77	76 Os	5.0E-3	KS92	Ng77
33 As	6.0E-5	KS92	Ng77	77 Ir	2.0E-6	KS92	Ng77
34 Se	4.0E-3	KS92	Ng77	79 Au	5.5E-6	KS92	Ng77
35 Br	2.0E-2	KS92	Ng77	80 Hg	4.7E-4	IAEA94	Ng82a
37 Rb	1.2E-2	IAEA94	Ng82a	81 Tl	2.0E-3	Na88	Na88
38 Sr	2.8E-3	IAEA94	Co90	82 Pb	2.6E-4	KS92	Ng77
39 Y	2.0E-5	KS92	Ng77	83 Bi	5.0E-4	KS92	Ng77
40 Zr	5.5E-7	IAEA94	Jo88	84 Po	3.4E-4	IAEA94	Ng82a
41 Nb	4.1E-7	IAEA94	Jo88	88 Ra	1.3E-3	IAEA94	MB90
42 Mo	1.7E-3	IAEA94	Jo88	89 Ac	2.0E-5	KS92	Ng77
43 Tc	1.4E-4	IAEA94	Jo88	90 Th	5.0E-6	KS92	Ng77
44 Ru	3.3E-6	IAEA94	Co90	91 Pa	5.0E-6	KS92	Ng77
45 Rh	1.0E-2	KS92	Ng77	92 U	4.0E-4	IAEA94	MB90
46 Pd	1.0E-2	KS92	Ng77	93 Np	5.0E-6	IAEA94	Ng82a
47 Ag	5.0E-5	IAEA94	CEC87	94 Pu	1.1E-6	IAEA94	Co90
48 Cd	1.0E-3	KS92	Ng77	95 Am	1.5E-6	IAEA94	Co90
49 In	2.0E-4	Na88	NCRP86	96 Cm	2.0E-5	KS92	Ng77
50 Sn	1.0E-3	Na88	NCRP86	98 Cf	1.5E-6	Based on Am	Co90
51 Sb	2.5E-5	IAEA94	Va82				

g.m. = geometric mean.

Table D.9. Transfer Factors for Poultry (Bq/kg poultry muscle per Bq/d intake)

Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference
04 Be	4.0E-1	KS92	Na88	52 Te	6.0E-1	IAEA94	En88a
07 N	9.8E-2	g.m.	g.m.	53 I	5.0E-2	Sn94	Sn94
09 F	1.4E-2	g.m.	g.m.	55 Cs	3.0E+0	Vo93	Vo93
11 Na	1.0E-2	KS92	Na88	56 Ba	9.0E-3	IAEA94	En88a
12 Mg	3.0E-2	KS92	KS92	57 La	1.0E-1	IAEA94	Ng82a
14 Si	8.0E-1	Based on As	Na88	58 Ce	2.0E-3	IAEA94	Ng82a
15 P	1.9E-1	KS92	Na88	59 Pr	2.0E-3	Based on Ce	Ng82a
16 S	2.3E+0	g.m.	g.m.	60 Nd	2.0E-3	Based on Ce	Ng82a
17 Cl	3.0E-2	KS92	Na88	61 Pm	2.0E-3	Based on Ce	Ng82a
19 K	4.0E-1	KS92	KS92	62 Sm	2.0E-3	Based on Ce	Ng82a
20 Ca	4.0E-2	IAEA94	Ng82a	63 Eu	2.0E-3	Based on Ce	Ng82a
21 Sc	4.0E-3	KS92	Na88	64 Gd	2.0E-3	Based on Ce	Ng82a
24 Cr	2.0E-1	KS92	KS92	65 Tb	2.0E-3	Based on Ce	Ng82a
25 Mn	5.0E-2	IAEA94	Ng82a	66 Dy	2.0E-3	Based on Ce	Ng82a
26 Fe	1.0E+0	IAEA94	Ng82a	67 Ho	2.0E-3	Based on Ce	Ng82a
27 Co	2.0E+0	IAEA94	Ng82a	68 Er	2.0E-3	Based on Ce	Ng82a
28 Ni	1.0E-3	KS92	Na88	72 Hf	6.0E-5	based on Zr	En88a
29 Cu	5.0E-1	IAEA94	Ng82a	73 Ta	3.0E-4	Based on Nb	En88a
30 Zn	7.0E+0	IAEA94	Ng82a	74 W	2.0E-1	Based on Mo	IAEA94
31 Ga	8.0E-1	Based on As	Na88	75 Re	4.0E-2	KS92	Ba84
33 As	8.3E-1	KS92	Na88	76 Os	8.4E-2	g.m.	g.m.
34 Se	9.0E+0	IAEA94	Ng82a	77 Ir	2.0E+0	Based on Co	Ng82a
35 Br	4.0E-3	KS92	Na88	79 Au	1.0E+0	g.m.	g.m.
37 Rb	2.0E+0	KS92	Na88	80 Hg	3.0E-2	IAEA94	Ng82a
38 Sr	8.0E-2	IAEA94	Co90	81 Tl	8.0E-1	Based on In	Na88
39 Y	1.0E-2	IAEA94	Ng82a	82 Pb	8.0E-1	Based on As	Na88
40 Zr	6.0E-5	IAEA94	En88a	83 Bi	9.8E-2	g.m.	g.m.
41 Nb	3.0E-4	IAEA94	En88a	84 Po	2.3E+0	g.m.	g.m.
42 Mo	1.8E-1	En88a	En88a	88 Ra	3.0E-2	KS92	KS92
43 Tc	3.0E-2	IAEA94	En88b	89 Ac	6.0E-3	Based on Am	Co90
44 Ru	7.0E-3	Na88	Ng82a	90 Th	6.0E-3	Based on Am	Co90
45 Rh	2.0E+0	Based on Co	Ng82a	91 Pa	6.0E-3	Based on Am	Co90
46 Pd	3.0E-4	KS92	Na88	92 U	1.0E+0	IAEA94	Ng82a
47 Ag	2.0E+0	IAEA94	CEC87	93 Np	6.0E-3	Based on Am	Co90
48 Cd	8.0E-1	IAEA94	Ng82a	94 Pu	3.0E-3	IAEA94	Co90
49 In	8.0E-1	Based on As	Na88	95 Am	6.0E-3	IAEA94	Co90
50 Sn	8.0E-1	Based on As	Na88	96 Cm	6.0E-3	Based on Am	Co90
51 Sb	6.0E-3	Na88	Na88	98 Cf	6.0E-3	Based on Am	Co90

g.m. = geometric mean.

Table D.10. Transfer Factors for Root Vegetables (Bq/kg root vegetable per Bq/kg soil)

Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Dry Weight)	Compiled in	Primary Reference
04 Be	1.5E-3	KS92	Ba84	52 Te	4.0E-3	KS92	Ba84
06 C	7.0E-1	Na88	Na88	53 I	4.0E-2	Sn94	Sn94
07 N	4.9E-2	KS92	Ba84	55 Cs	1.3E-1	IAEA94	Fr82
09 F	6.0E-3	KS92	Ba84	56 Ba	1.5E-2	KS92	Ba84
11 Na	3.0E-1	IAEA94	Ng82b	57 La	3.5E-4	IAEA94	Fr89
12 Mg	5.5E-1	KS92	Ba84	58 Ce	2.0E-2	Ng82b	Ng82b
14 Si	7.0E-2	KS92	Ba84	59 Pr	2.0E-2	Based on Ce	Ng82b
15 P	3.5E+0	KS92	Ba84	60 Nd	2.0E-2	Based on Ce	Ng82b
16 S	1.5E+0	KS92	Ba84	61 Pm	2.0E-2	Based on Ce	Ng82b
17 Cl	7.0E+1	KS92	Ba84	62 Sm	2.0E-2	Based on Ce	Ng82b
19 K	5.5E-1	KS92	Ba84	63 Eu	2.0E-2	Based on Ce	Ng82b
20 Ca	3.5E-1	KS92	Ba84	64 Gd	2.0E-2	Based on Ce	Ng82b
21 Sc	1.0E-3	KS92	Ba84	65 Tb	2.0E-2	Based on Ce	Ng82b
24 Cr	4.5E-3	KS92	Ba84	66 Dy	2.0E-2	Based on Ce	Ng82b
25 Mn	2.0E-1	IAEA94	Fr89	67 Ho	2.0E-2	Based on Ce	Ng82b
26 Fe	5.0E-2	CT83	CT83	68 Er	2.0E-2	Based on Ce	Ng82b
27 Co	6.7E-2	IAEA94	Fr89	72 Hf	1.0E-3	Based on Zr	Ng82b
28 Ni	6.0E-2	KS92	Ba84	73 Ta	2.5E-2	Based on Nb	CT83
29 Cu	2.5E-1	KS92	Ba84	74 W	3.0E+0	Na88	NCRP86
30 Zn	3.5E-1	IAEA94	Fr89	75 Re	3.5E-1	KS92	Ba84
31 Ga	4.0E-4	Based on In	Ba84	76 Os	3.5E-3	KS92	Ba84
33 As	6.0E-3	KS92	Ba84	77 Ir	1.5E-2	KS92	Ba84
34 SE	5.0E-2	CT83	CT83	79 Au	1.8E-2	g.m.	g.m.
35 Br	1.5E+0	KS92	Fu78	80 Hg	2.0E-1	KS92	Ba84
37 Rb	9.0E-1	IAEA94	Ng82b	81 Tl	4.0E-4	Based on In	Fu78
38 Sr	5.0E-1	IAEA94	Fr82	82 Pb	6.0E-3	IAEA94	Fr89
39 Y	1.0E-2	IAEA94	Ng82b	83 Bi	5.0E-1	IAEA94	IAEA82
40 Zr	1.0E-3	IAEA94	Ng82b	84 Po	7.0E-3	IAEA94	HW91
41 Nb	2.5E-2	CT83	CT83	88 Ra	2.0E-3	IAEA94	Fr89
42 Mo	8.0E-1	IAEA94	Ng82b	89 Ac	3.5E-4	Based on Am	Fr82
43 Tc	2.4E-1	IAEA94	Fr89	90 Th	3.3E-4	IAEA94	Fr89
44 Ru	4.0E-2	IAEA94	Ng82b	91 Pa	3.5E-4	Based on Am	Fr82
45 Rh	4.0E-2	KS92	Ba84	92 U	1.2E-2	IAEA94	Fr89
46 Pd	4.0E-2	KS92	Ba84	93 Np	1.3E-2	IAEA94	Fr82
47 Ag	1.3E-3	IAEA94	Fr89	94 Pu	1.1E-3	IAEA94	Fr82
48 Cd	1.5E-1	KS92	Ba84	95 Am	3.5E-4	IAEA94	Fr82
49 In	4.0E-4	KS92	Fu78	96 Cm	4.3E-4	IAEA94	Fr82
50 Sn	6.0E-3	KS92	Fu78	98 Cf	3.5E-4	Based on Am	Fr82
51 Sb	5.6E-4	IAEA94	Fr89				

g.m. = geometric mean.

Table D.11. Concentration Ratios for Salt Water Fish (Bq/kg muscle per Bq/L)

Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference	Z and Element	Recommended Value (Wet Weight)	Compiled in	Primary Reference
02 He	1.0E+0	Na88		51 Sb	1.0E+3	Na88	
04 Be	1.0E+3	Na88		52 Te	1.0E+3	Na88	
06 C	2.0E+4	Na88		53 I	1.0E+1	Na88	
07 N	1.0E+0	Na88		55 Cs	1.0E+2	Na88	
08 O	--			56 Ba	1.0E+1	Na88	
09 F	4.0E+0	Na88		57 La	3.0E+1	Na88	
11 Na	1.0E+0	Na88		58 Ce	1.0E+2	Na88	
12 Mg	--			59 Pr	1.0E+2	Na88	
14 Si	5.0E+4	Na88		60 Nd	1.0E+2	Na88	
15 P	2.8E+4	Na88		61 Pm	5.0E+2	Na88	
16 S	2.0E+0	Na88		62 Sm	5.0E+2	Na88	
17 Cl	1.0E+0	Na88		63 Eu	3.0E+2	Na88	
19 K	--			64 Gd	5.0E+2	Na88	
20 Ca	2.0E+0	Na88		65 Tb	6.0E+1	Na88	
21 Sc	7.5E+2	Na88		66 Dy	5.0E+2	Na88	
24 Cr	6.0E+2	Na88		67 Ho	3.0E+2	Na88	
25 Mn	4.0E+2	Na88		68 Er	1.0E+2	Na88	
26 Fe	3.0E+3	Na88		72 Hf	4.0E+1	Na88	
27 Co	1.0E+2	Na88		73 Ta	6.0E+1	Na88	
28 Ni	1.0E+2	Na88		74 W	1.0E+1	Na88	
29 Cu	1.0E+3	Na88		75 Re	--		
30 Zn	1.0E+3	Na88		76 Os	--		
31 Ga	1.0E+3	Na88		77 Ir	2.0E+1	Na88	
33 As	3.0E+2	Na88		79 Au	--		
34 Se	6.0E+3	Na88		80 Hg	2.0E+4	Na88	
35 Br	1.0E+1	Na88		81 Tl	5.0E+3	Na88	
37 Rb	5.0E+2	Na88		82 Pb	2.0E+2	Na88	
38 Sr	4.0E+0	Na88		83 Bi	1.5E+1	Na88	
39 Y	2.0E+1	Na88		84 Po	2.0E+3	Na88	
40 Zr	5.0E+1	Na88		88 Ra	9.5E+2	Na88	
41 Nb	1.0E+2	Na88		89 Ac	3.0E+1	Na88	
42 Mo	4.0E+1	Na88		90 Th	6.0E+2	Na88	
43 Tc	3.0E+1	Na88		91 Pa	3.0E+2	Na88	
44 Ru	1.0E+1	Na88		92 U	5.0E+1	Na88	
45 Rh	1.0E+1	Na88		93 Np	2.5E+3	Na88	
46 Pd	5.0E+1	Na88		94 Pu	1.0E+3	Na88	
47 Ag	3.0E+2	Na88		95 Am	2.5E+3	Na88	
48 Cd	2.0E+3	Na88		96 Cm	2.5E+3	Na88	
49 In	1.0E+3	Na88		98 Cf	5.0E+1	Na88	
50 Sn	5.0E+4	Na88					

Table D.12. Concentration Ratios for Crustaceans (Bq/kg muscle per Bq/L [wet])

Z and Element	Salt Water	Fresh Water	Compiled in	Z and Element	Salt Water	Fresh Water	Compiled in
02 He	1.0E+0	1.0E+0	Na88	51 Sb	1.0E+2	1.0E+2	Na88
04 Be	1.0E+4	5.0E+1	Na88	52 Te	1.0E+3	6.1E+3	Na88
06 C	2.0E+4	9.0E+3	Na88	53 I	5.0E+1	1.0E+2	Na88
07 N	1.0E+0	1.0E+0	Na88	55 Cs	3.0E+1	5.0E+2	Na88
08 O	--	--	Na88	56 Ba	1.0E+0	2.0E+2	Na88
09 F	4.0E+0	1.0E+2	Na88	57 La	1.0E+2	1.0E+3	Na88
11 Na	1.0E-0	1.0E+2	Na88	58 Ce	5.0E+2	1.0E+3	Na88
12 Mg	--	--		59 Pr	1.0E+3	1.0E+3	Na88
14 Si	5.0E+4	1.0E+4	Na88	60 Nd	--		Na88
15 P	3.8E+4	1.0E+5	Na88	61 Pm	1.0E+3	3.0E+3	Na88
16 S	1.0E+0	1.0E+2	Na88	62 Sm	1.0E+3	3.0E+3	Na88
17 Cl	1.0E+0	5.0E+1	Na88	63 Eu	1.0E+3	3.0E+3	Na88
19 K	--	--	Na88	64 Gd	2.0E+3	2.0E+3	Na88
20 Ca	5.0E+0	2.0E+3	Na88	65 Tb	1.0E+3	1.0E+3	Na88
21 Sc	3.0E+2	1.0E+3	Na88	66 Dy	1.0E+3	1.0E+3	Na88
24 Cr	5.0E+2	2.0E+3	Na88	67 Ho	1.0E+3	3.0E+3	Na88
25 Mn	8.0E+2	1.0E+5	Na88	68 Er	5.0E+2	1.0E+3	Na88
26 Fe	5.0E+3	1.0E+2	Na88	72 Hf	1.0E+3	1.0E+3	Na88
27 Co	2.0E+3	2.0E+3	Na88	73 Ta	3.0E+3	3.0E+3	Na88
28 Ni	5.0E+2	5.0E+2	Na88	74 W	1.0E+1	1.0E+1	Na88
29 Cu	5.0E+3	4.0E+2	Na88	75 Re	--	--	
30 Zn	5.0E+4	1.0E+4	Na88	76 Os	--	--	
31 Ga	1.0E+4	1.0E+4	Na88	77 Ir	1.0E+2	2.0E+2	Na88
33 As	3.0E+2	3.0E+2	Na88	79 Au	--	--	
34 Se	5.0E+3	2.0E+3	Na88	80 Hg	2.0E+4	2.0E+4	Na88
35 Br	1.0E+1	3.3E+2	Na88	81 Tl	1.0E+3	1.0E+3	Na88
37 Rb	2.0E+2	1.0E+3	Na88	82 Pb	1.0E+3	5.0E+2	Na88
38 Sr	1.0E+0	1.0E+2	Na88	83 Bi	1.0E+3	1.0E+5	Na88
39 Y	1.0E+3	1.0E+3	Na88	84 Po	5.0E+4	2.0E+4	Na88
40 Zr	5.0E+1	5.0E+1	Na88	88 Ra	1.0E+2	1.0E+3	Na88
41 Nb	5.0E+1	5.0E+1	Na88	89 Ac	1.0E+3	1.0E+3	Na88
42 Mo	2.0E+1	1.0E+2	Na88	90 Th	1.0E+3	1.0E+2	Na88
43 Tc	1.0E+1	1.0E+2	Na88	91 Pa	1.0E+1	3.0E+1	Na88
44 Ru	1.0E+2	3.0E+2	Na88	92 U	1.0E+1	1.0E+2	Na88
45 Rh	1.0E+2	3.0E+2	Na88	93 Np	1.0E+1	3.0E+1	Na88
46 Pd	3.0E+2	2.0E+3	Na88	94 Pu	3.0E+2	1.0E+2	Na88
47 Ag	3.5E+2	2.0E+2	Na88	95 Am	3.6E+2	1.0E+2	Na88
48 Cd	5.0E+3	1.0E+4	Na88	96 Cm	4.6E+2	1.0E+3	Na88
49 In	1.0E+4	1.0E+4	Na88	98 Cf	5.0E+2	1.0E+3	Na88
50 Sn	5.0E+4	1.0E+4	Na88				

Table D.13. Concentration Ratios for Molluscs (Bq/kg muscle per Bq/L [wet])

Z and Element	Salt Water	Fresh Water	Compiled in	Z and Element	Salt Water	Fresh Water	Compiled in
02 He	1.0E+0	1.0E+0	Na88	51 Sb	1.2E+3	1.0E+2	Na88
04 Be	1.0E+4	5.0E+1	Na88	52 Te	1.0E+3	6.1E+3	Na88
06 C	2.0E+4	9.0E+3	Na88	53 I	5.0E+1	1.0E+2	Na88
07 N	1.0E+0	1.0E+0	Na88	55 Cs	3.0E+1	5.0E+2	Na88
08 O	--	--	Na88	56 Ba	2.0E+1	2.0E+2	Na88
09 F	4.0E+0	1.0E+2	Na88	57 La	1.0E+2	1.0E+3	Na88
11 Na	3.0E-0	1.0E+2	Na88	58 Ce	5.0E+2	1.0E+3	Na88
12 Mg	--	--		59 Pr	1.0E+3	1.0E+3	Na88
14 Si	5.0E+4	1.0E+4	Na88	60 Nd	--	--	Na88
15 P	4.5E+4	1.0E+5	Na88	61 Pm	5.0E+3	3.0E+3	Na88
16 S	4.0E+0	1.0E+2	Na88	62 Sm	5.0E+3	3.0E+3	Na88
17 Cl	1.0E+0	5.0E+1	Na88	63 Eu	7.0E+3	3.0E+3	Na88
19 K	--	--	Na88	64 Gd	5.0E+3	5.0E+3	Na88
20 Ca	1.0E+0	2.0E+3	Na88	65 Tb	3.0E+3	1.0E+3	Na88
21 Sc	1.0E+2	1.0E+3	Na88	66 Dy	5.0E+3	5.0E+3	Na88
24 Cr	1.1E+3	2.0E+3	Na88	67 Ho	1.0E+3	3.0E+3	Na88
25 Mn	6.0E+3	1.0E+5	Na88	68 Er	5.0E+2	1.0E+3	Na88
26 Fe	3.0E+4	1.0E+2	Na88	72 Hf	3.0E+3	3.0E+3	Na88
27 Co	3.0E+3	2.0E+3	Na88	73 Ta	3.0E+3	3.0E+3	Na88
28 Ni	5.0E+2	5.0E+2	Na88	74 W	1.0E+2	1.0E+1	Na88
29 Cu	5.0E+3	4.0E+2	Na88	75 Re	--	--	
30 Zn	3.0E+4	1.0E+4	Na88	76 Os	--	--	
31 Ga	1.0E+4	1.0E+4	Na88	77 Ir	1.0E+2	2.0E+2	Na88
33 As	3.0E+2	3.0E+2	Na88	79 Au	--	--	
34 Se	6.0E+3	2.0E+3	Na88	80 Hg	1.0E+4	2.0E+4	Na88
35 Br	1.0E+1	3.3E+2	Na88	81 Tl	5.0E+3	5.0E+3	Na88
37 Rb	2.0E+2	1.0E+3	Na88	82 Pb	1.0E+3	5.0E+2	Na88
38 Sr	4.0E+1	1.0E+2	Na88	83 Bi	1.0E+3	1.0E+5	Na88
39 Y	1.0E+3	1.0E+3	Na88	84 Po	1.0E+4	2.0E+4	Na88
40 Zr	5.0E+1	5.0E+1	Na88	88 Ra	1.0E+2	1.0E+3	Na88
41 Nb	5.0E+1	5.0E+1	Na88	89 Ac	1.0E+3	1.0E+3	Na88
42 Mo	2.0E+1	1.0E+2	Na88	90 Th	1.0E+3	1.0E+2	Na88
43 Tc	2.0E+1	1.0E+2	Na88	91 Pa	1.0E+1	3.0E+1	Na88
44 Ru	2.0E+3	3.0E+2	Na88	92 U	3.0E+1	1.0E+2	Na88
45 Rh	1.0E+2	3.0E+2	Na88	93 Np	1.5E+2	3.0E+1	Na88
46 Pd	3.0E+2	2.0E+3	Na88	94 Pu	3.0E+3	1.0E+2	Na88
47 Ag	5.8E+2	2.0E+2	Na88	95 Am	2.9E+2	1.0E+2	Na88
48 Cd	1.0E+4	1.0E+4	Na88	96 Cm	4.6E+2	1.0E+3	Na88
49 In	1.0E+4	1.0E+4	Na88	98 Cf	2.0E+3	1.0E+3	Na88
50 Sn	5.0E+4	1.0E+4	Na88				

Table D.14. Concentration Ratios for Water Plants (Bq/kg per Bq/L [wet])

Z and Element	Salt Water	Fresh Water	Compiled in	Z and Element	Salt Water	Fresh Water	Compiled in
02 He	1.0E+0	1.0E+0	Na88	51 Sb	1.0E+2	1.0E+3	Na88
04 Be	1.0E+4	2.0E+2	Na88	52 Te	4.0E+2	1.0E+2	Na88
06 C	1.8E+3	4.5E+3	Na88	53 I	1.5E+3	3.0E+2	Na88
07 N	1.0E+0	1.0E+0	Na88	55 Cs	7.0E+2	1.0E+3	Na88
08 O	--	--	Na88	56 Ba	1.0E+2	5.0E+2	Na88
09 F	1.0E+0	2.0E+0	Na88	57 La	3.0E+2	5.0E+3	Na88
11 Na	1.0E+0	1.0E+2	Na88	58 Ce	5.0E+3	4.0E+3	Na88
12 Mg	--	--		59 Pr	1.0E+3	5.0E+3	Na88
14 Si	5.0E+4	5.0E+4	Na88	60 Nd	--	--	Na88
15 P	1.0E+5	5.0E+5	Na88	61 Pm	3.0E+3	5.0E+3	Na88
16 S	5.0E+0	1.0E+0	Na88	62 Sm	5.0E+3	5.0E+3	Na88
17 Cl	1.0E+0	5.0E+1	Na88	63 Eu	5.0E+3	5.0E+3	Na88
19 K	--	--	Na88	64 Gd	1.0E+0	1.0E+0	Na88
20 Ca	5.0E+1	1.0E+3	Na88	65 Tb	1.0E+3	5.0E+3	Na88
21 Sc	1.0E+3	1.0E+4	Na88	66 Dy	1.0E+0	1.0E+0	Na88
24 Cr	4.0E+4	4.0E+4	Na88	67 Ho	5.0E+3	5.0E+3	Na88
25 Mn	1.0E+4	1.0E+4	Na88	68 Er	5.0E+3	4.0E+3	Na88
26 Fe	5.0E+4	1.0E+3	Na88	72 Hf	1.0E+0	1.0E+0	Na88
27 Co	4.0E+2	1.0E+3	Na88	73 Ta	1.0E+0	1.0E+0	Na88
28 Ni	3.0E+3	5.0E+2	Na88	74 W	1.0E+2	1.2E+3	Na88
29 Cu	1.0E+3	2.0E+3	Na88	75 Re	--	--	
30 Zn	5.0E+4	2.0E+4	Na88	76 Os	--	--	
31 Ga	1.0E+0	1.0E+0	Na88	77 Ir	1.0E+2	2.0E+2	Na88
33 As	3.0E+2	3.0E+2	Na88	79 Au	--	--	
34 Se	1.0E+3	1.0E+2	Na88	80 Hg	3.4E+4	3.4E+4	Na88
35 Br	1.0E+1	5.0E+1	Na88	81 Tl	1.0E+0	1.0E+0	Na88
37 Rb	1.0E+3	1.0E+3	Na88	82 Pb	5.0E+4	2.0E+3	Na88
38 Sr	3.0E+2	3.0E+3	Na88	83 Bi	1.0E+4	1.5E+3	Na88
39 Y	3.0E+2	5.0E+3	Na88	84 Po	1.0E+3	2.0E+3	Na88
40 Zr	5.0E+3	5.0E+3	Na88	88 Ra	1.0E+3	3.0E+4	Na88
41 Nb	5.0E+2	5.0E+2	Na88	89 Ac	1.0E+3	1.0E+4	Na88
42 Mo	1.0E+2	1.0E+3	Na88	90 Th	2.0E+3	3.0E+3	Na88
43 Tc	5.0E+3	5.0E+3	Na88	91 Pa	5.0E+1	3.0E+2	Na88
44 Ru	1.0E+3	2.0E+3	Na88	92 U	1.0E+3	9.0E+2	Na88
45 Rh	1.0E+2	2.0E+2	Na88	93 Np	6.0E+0	3.0E+2	Na88
46 Pd	2.0E+4	2.0E+3	Na88	94 Pu	3.6E+3	8.9E+2	Na88
47 Ag	1.0E+3	1.0E+3	Na88	95 Am	2.9E+3	3.0E+3	Na88
48 Cd	1.0E+3	5.0E+2	Na88	96 Cm	4.3E+4	1.0E+4	Na88
49 In	1.0E+0	1.0E+0	Na88	98 Cf	5.0E+3	5.0E+3	Na88
50 Sn	5.0E+4	5.0E+4	Na88				

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