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MULTIMEDIA ENVIRONMENTAL POLLUTANT ASSESSMENT SYSTEM (MEPAS®): EXPOSURE PATHWAY AND HUMAN HEALTH IMPACT ASSESSMENT MODELS

D. L. Strenge
P. J. Chamberlain

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Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

The Multimedia Environmental Pollutant Assessment System (MEPAS) is a physics-based environmental analysis code that integrates source-term, transport, and exposure models for endpoints such as concentration, dose, or risk. Developed by Pacific Northwest Laboratory[(a)], MEPAS is designed for site-specific assessments using readily available information. Endpoints are computed for chemical and radioactive pollutants. For human health impacts, risks are computed for carcinogens and hazard quotients for noncarcinogens. This system has wide applicability to a range of environmental problems using air, groundwater, surface-water, overland, and exposure models. With this system, a user can simulate release from the source, transport through air, groundwater, surface water, or overland, and transfer through food chains and exposure pathways to the exposed individual or population. Whenever available and appropriate, U.S. Environmental Protection Agency guidance and models were used to facilitate compatibility and acceptance.

Although based on relatively standard transport and exposure computation approaches, the unique feature of MEPAS is that these approaches are integrated into a single system. The use of a single system provides a consistent basis for evaluating health impacts for a large number of problems and sites. Implemented on a desktop computer, a user-friendly shell allows the user to define the problem, input the required data, and execute the appropriate models. This document describes mathematical formulations used in the MEPAS exposure assessment and human health impact component.

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<u>SUMMARY</u>

The Multimedia Environmental Pollutant Assessment System (MEPAS) provides physics-based models for human health risk assessment for radioactive and hazardous pollutants. MEPAS analyzes pollutant behavior in various media (air, soil, groundwater and surface water) and estimates transport through and between media and exposure and impacts to the environment, to the maximum individual, and to populations. MEPAS includes 25 exposure pathway models, a database with information on more than 650 contaminants, and a sensitivity module that allows for uncertainty analysis.

Four major transport pathways are considered in MEPAS: groundwater, overland, surface water, and atmospheric. Descriptions of the mathematical basis of each of these components will be published in companion reports. Guidelines for determining input parameter values are provided in Buck et al. (1995).

This report describes the exposure pathway and health impact assessment component of MEPAS, which provides an estimate of health impacts to selected individuals and populations from exposure to pollutants. The exposure pathway analysis starts with pollutant concentration in a transport medium and estimates the average daily dose to exposed individuals from contact with the transport medium or a secondary medium contaminated by the transport medium.
The average daily dose is then used to estimate a measure of health impact appropriate to the type of pollutant considered.

Discussions of the exposure pathway models include the assumptions and equations used to convert the transport medium concentrations to exposure medium concentrations. The discussion for a given exposure pathway defines the transport pathways leading to the exposure, the special processes considered in determining the pollutant concentration in the exposure medium, and the exposure model used to estimate the average daily dose.

Models for the exposure pathway and health impact assessments require definition of several parameters. A summary of the notation used for these parameters is provided. The default values used in MEPAS for these parameters are presented and discussed.

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1.0 INTRODUCTION

The exposure pathway and health impact assessment component of the Multimedia Environmental Pollutant Assessment System (MEPAS) provides an estimate of health impacts to selected individuals and populations from exposure to pollutants. The exposure pathway analysis starts with pollutant concentration in a transport medium and estimates the average daily dose[a] to exposed individuals from contact with the transport medium or a secondary medium contaminated by the transport medium. The average daily dose is then used to estimate a measure of health impact appropriate to the type of pollutant considered.

Each exposure pathway analysis in MEPAS involves definition of a transport medium (or medium of measurement), an exposure route for transfer of pollutant from the transport medium to man, exposure conditions for the individual receiving the pollutant, and conversion of the average daily dose to a measure of health impact. These steps are illustrated in Figure 1.1 for all transport and exposure pathways except exposure to measured direct radiation fields. The direct radiation exposure pathway does not involve a specific pollutant, but rather is used to estimate health impacts from exposure to a measured radiation field. With this exception, the steps for the measured direct radiation pathway parallel those indicated in Figure 1.1

The pollutant concentration in the transport medium is the starting point for the exposure and health impact analysis. This concentration is generally represented within MEPAS as a 70-year averaged value. When the exposure duration is less than 70 years, the concentration represents the average for the exposure duration considered for a given exposure scenario.

(a) In the remainder of this section on exposure pathway and human health impact assessment models, the term average daily dose will be used to represent the average daily intake rate of chemicals (mg/kg/d), the average radiation dose rate from intake of radionuclides (rem/d), and the average external radiation dose rate (rem/d).

Such an average value can be provided by the user for the measured soil concentration and measured food concentration transport pathways. For other transport pathways, the calculated 70-year average value is used as an approximation for individual and population exposures.

The transport medium may or may not be the medium of exposure. For example, the groundwater transport pathway generates estimates of pollutant concentration at the well. In this case, the well water is also the medium of exposure, although some modifications to the concentration are possible during transfer through the treatment plant and distribution system to the individuals exposed during domestic water uses. When the well water is used for irrigation of agriculture crops, the exposure medium is not the well water, but the foods produced. For agricultural pathways, models are use to estimate the transfer of pollutants from the irrigation water to the food consumed by humans. For each transport and exposure pathway, the processes affecting the concentration and transfer to the exposure medium are defined in the following sections.

The average daily dose of a pollutant for an exposure pathway involves consideration of the rate of intake (ingestion, dermal absorption, inhalation, or external radiation dose), the frequency of exposure, the exposure duration, the averaging time, and the body weight of the exposed individual or an average member of the population. The general method for converting the medium concentration to average daily dose is described in Section 2.0. Detailed applications to specific pathways are described in subsections of Section 2.0.

Health impact models are used to estimate the health impacts from exposure to the pollutant of concern. Models are defined for noncarcinogenic chemicals, carcinogenic chemicals, and radionuclides and radiation dose in Section 3.0. When populations are exposed to carcinogenic pollutants, including radiation, estimates of health impacts to an exposed population may also be made by multiplication of the effect to an average member of the population by the number of people in the exposed population.

The models for the exposure pathway and health impact assessments require definition of several parameters. A summary of the notation used for the parameters in the exposure pathway and health impact models is given in Section 4.0. The default values used in MEPAS for these parameters are presented and discussed in Section 5.0.

Appendix A provides auxiliary equations used to calculate intermediate summary intake factors. Appendix B describes the algorithms used to evaluate radioactive chain decay.

2.0 EXPOSURE PATHWAY MODELS

This section describes details of the exposure pathway models used in MEPAS. The pathway descriptions are organized by intake route (ingestion, dermal contact, inhalation, and external radiation exposure) and by purpose of transport medium usage (domestic water, aquatic foods, etc.).

Ingestion pathways include ingestion of drinking water, ingestion of water while showering, ingestion of agricultural products (leafy vegetables, other vegetables, meat, and milk), ingestion of aquatic foods (fin fish and shellfish), ingestion of water or sediment while participating in aquatic recreational activities (swimming, boating, or shoreline use), ingestion of soil, and ingestion of special foods (for which measured pollutant concentrations are available). Dermal exposure pathways include contact with soil, shoreline sediments, and water (while swimming or showering). Inhalation exposure pathways include inhalation of air transported from the release site to the exposure location, inhalation of resuspended particulate material from soil, and inhalation of volatile pollutants released from shower water or other domestic water uses. External exposure may occur from proximity of individuals to radionuclides on ground (deposited from air, deposited onto shoreline sediment, or for measured soil concentrations), in water (swimming and boating), or in air (submersion in a passing plume). The direct radiation dose rate measurement pathway is also an external exposure route.

Six major transport pathways are considered in MEPAS including special pathways for handling exposure to measured pollutant levels in soils and foods, and measurement of direct radiation fields. These transport pathways and their associated exposure pathways are listed in Table 2.1. This table also indicates the transport medium, the exposure medium, and the intake or exposure route for each exposure pathway.

The subsections that follow describe the models used for each of the exposure pathways. The discussion for a given exposure pathway defines the

TABLE 2.1. Transport and Exposure Pathway Summary

Transport Pathway	Contaminated Medium	Exposure Route	Exposure Pathways
Groundwater	Water at well location	Ingestion	Drinking water
		Ingestion	Water while showering
		Dermal	Shower water contact
		Inhalation	Air while showering
	Water at intake for agricultural production	Ingestion	Leafy vegetable
		Ingestion	Other vegetables
		Ingestion	Meat
		Ingestion	Milk
Surface Water	Water at domestic intake location	Ingestion	Drinking water
		Ingestion	Water while showering
		Dermal	Shower water contact
		Inhalation	Air while showering
	Water at recreational use location	Ingestion	Water while swimming
		Ingestion	Sediment from shoreline
		Dermal	Swimming water contact
		Dermal	Shoreline sediment contact
		External	Water while swimming
		External	Water while boating
		External	Shoreline sediment
	Water at intake for agricultural production	Ingestion	Leafy vegetable
		Ingestion	Other vegetables
		Ingestion	Meat
		Ingestion	Milk
	Water at aquatic food production location	Ingestion	Fin fish
		Ingestion	Shellfish
Atmospheric	Air at location of people	Inhalation	Air
		External	Submersion in air
	Soil at location of people	Ingestion	Soil
		Dermal	Soil contact
		Inhalation	Soil resuspension
		External	Soil

TABLE 2.1. (cont'd)

Transport Pathway	Contaminated Medium	Exposure Route	Exposure Pathways
Groundwater	Water at well location	Ingestion	Drinking water
		Ingestion	Water while showering
		Dermal	Shower water contact
		Inhalation	Air while showering
	Air at location of agricultural production	Ingestion	Leafy vegetables
		Ingestion	Other vegetables
		Ingestion	Meat
		Ingestion	Milk
	Soil at location of agricultural production	Ingestion	Leafy vegetables
		Ingestion	Other vegetables
		Ingestion	Meat
		Ingestion	Milk
Measured Soil	Soil at location of people	Ingestion	Soil
		Dermal	Soil contact
		Inhalation	Soil suspension
		External	Soil
	Soil at location of agricultural production	Ingestion	Leafy vegetables
		Ingestion	Other vegetables
		Ingestion	Meat
		Ingestion	Milk
Measured Foods	Food eaten by people	Ingestion	Food
Direct Radiation	Radiation dose rate at location of people	External	Radiation exposure

transport pathways leading to the exposure pathway, the special transfers and processes considered in determining the pollutant concentration in the exposure medium, and the exposure model used to estimate the average daily dose or lifetime radiation dose. The estimation of health impacts from the average daily dose is described in Section 3.0.

2.1 DRINKING WATER INGESTION

Use of contaminated water as a source of domestic drinking water is evaluated for groundwater and surface water transport pathways. For each of these transport pathways, consideration is given to reductions of pollutant concentration during processing in the water supply treatment plant (if present) and in transport through the water distribution system to the exposed individuals. The surface water pathway also includes estimation of losses of volatile chemicals in transport between the point of entry to the surface water and the water intake plant.

Transport Medium: water concentration at water treatment plant, C_{dwi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: removal of pollutants during water treatment

loss of pollutants (environmental degradation or radioactive decay) during transport from the treatment plant to the exposure location (households)

loss of pollutants during transport in the surface water body by volatilization.

Exposure Factors: water ingestion rate, exposure duration, and averaging time

The average daily dose for the drinking water pathway for groundwater transport is evaluated as follows for chemical pollutants:

$$D_{dwi} = C_{dwi} \, TF_i \, e^{(-\lambda_{gi} TH_{dw})} \frac{F_{dw} U_{dw} ED_{dw}}{(BW_{dw} AT_{dwi})} \quad (1)$$

where

D_{dwi} = average daily ingestion dose for the drinking water pathway for chemical pollutant i (mg/kg/d)

C_{dwi} = concentration of pollutant i at the pumping station or well for domestic water supply (mg/L or pCi/L)

TF_i = water treatment purification factor giving the fraction of pollutant, i, remaining after treatment (dimensionless)

λ_{gi} = loss rate constant for pollutant i in confined water systems (d^{-1})

TH_{dw} = holdup time in transfer of water from the pumping station or well to the consumer (d)

F_{dw} = fraction of days per year that water is consumed (dimensionless)

U_{dw} = drinking water ingestion rate (L/d)

ED_{dw} = exposure duration for the drinking water pathway (yr)

BW_{dw} = body weight of individuals exposed via the drinking water pathway (kg).

AT_{dwi} = averaging time for drinking water exposure to pollutant i (yr).

The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radionuclide pollutants, the total dose is evaluated, as follows, using the dose conversion factor to convert from intake to dose (rem):

$$D_{dwi} = C_{dwi} \; TF_i \; e^{(-\lambda_{gi} \; TH_{dw})} \; U_{dw} \; DF_{gi} \; F_{dw} \; E \tag{2}$$

where

D_{dwi} = total lifetime dose for the drinking water pathway for radionuclide i (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

365.25 = units conversion factor (d/yr)

and other terms are as previously defined. Note that body weight (BW_{dw}) is not included in the equation for radionuclides and that the averaging time (AD_{dwi}) is fixed at 70 years. A value of 70 kg is always used for radionuclides because the radiation dose conversion factors are based on the standard man parameters (70 kg).

For the surface water transport pathway, the average daily intake is evaluated as for Equation (1) with the water concentration being corrected for loss during transport between the entry point to the surface water body and the pumping station. The water concentration at the pumping station is defined as follows:

$$C_{dwi} = C_{swi}(0)\ e^{(-\lambda_{si} T_{sw})} \qquad (3)$$

where

C_{dwi} = concentration of pollutant i at the pumping for domestic water supply (mg/L)

$C_{swi}(0)$ = concentration of pollutant at the pumping station for domestic water, uncorrected for loss during transit in the surface water system (mg/L or pCi/L)

λ_{si} = loss rate constant for pollutant i in surface waters (d^{-1})

T_{sw} = transit time in the surface water system between the point of entry and the pumping station (d).

The domestic water supply may come from either groundwater (C_{gwi}) or surface water (C_{swi}) transport pathways.

2.2 SHOWER WATER DERMAL CONTACT

Use of domestic water for showering will expose individuals to pollutants from dermal contact with water. Pollutants will be taken into the body through the skin and provide a potential for health impacts. This exposure pathway is applicable to the groundwater and surface water transport pathways. As for the drinking water pathway, consideration is given to reductions of pollutant concentrations during processing in the water supply treatment plant (if present) and in transport through the water distribution system to the exposed individuals. The surface water pathway also includes estimation of losses of volatile chemicals in transport between the point of entry to the surface water and the water intake plant.

Transport Medium: water concentration at the domestic water treatment plant, C_{dwi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: removal of pollutants during water treatment

loss of pollutants (environmental degradation or radioactive decay) during transport from the treatment plant to the exposure location (households)

loss of pollutants during transport in the surface water body by volatilization

absorption through the skin during showering event

Exposure Factors: area of skin exposed, frequency of exposure, and exposure duration.

Dermal exposures to chemicals are treated as ingestion intakes with correction for the fraction of the chemical absorbed in passing through the GI tract. The correction is not needed for dermal exposures to radionuclides because dose factors are available in MEPAS for radionuclide intake through the skin. The intake from dermal contact with water is evaluated using a model that first estimates the dermal intake per event (shower). This value is then used with shower frequency data and exposure parameters to determine the average daily dose.

The intake per shower is evaluated using methods suggested by USEPA (USEPA 1992), as described in the following discussion.

For inorganic chemicals and radionuclides, the intake per shower per unit area of skin contacted is evaluated as follows:

$$I_{shi} = 10^{-3}\, C_{dwi}\, TF_i\, e^{(-\lambda_{gi}\, TH_{dw})}\, K_{pi}\, TE_s \qquad (4)$$

where

I_{shi} = amount of pollutant i absorbed through the skin during one shower event per unit area of skin contacted (mg/cm^2/shower or pCi/cm^2/shower)

10^{-3} = units conversion factor (L/cm^3)

C_{dwi} = concentration of pollutant i in domestic water used for showering (mg/L or pCi/L)

TF_i = water treatment purification factor giving the fraction of pollutant, i, remaining after treatment (dimensionless)

λ_{gi} = loss rate constant for pollutant i in confined water systems (d^{-1})

TH_{dw} = Holdup time in transfer of water from the pumping station or well to the consumer (d)

K_{pi} = skin absorption permeability constant for pollutant i (cm/h)

TE_s = duration of one shower (h).

For organic chemicals, the USEPA model uses the permeability constant for the pollutant of interest, the skin thickness, and the duration of one shower event to estimate the total amount of pollutant transferred through the skin. These parameters are used in a six-step procedure (as defined in USEPA 1992a) to estimate the absorbed dose per unit area per event, as follows:

Step 1 - Evaluate the permeability constant. This value is supplied in MEPAS from the chemical database or estimated from the octanol-water partition coefficient, K_{owi}.

Step 2 - Calculate B (dimensionless), given by

$$B = \frac{K_{owi}}{10^4} \tag{5}$$

Step 3 - Determine the diffusion coefficient for skin, DS_i (cm^2/h), given by

$$DS_i = 0.001906\ l_{sc}\ 10^{-0.0061\ MW_i} \tag{6}$$

where

MW_i = molecular weight of the organic compound i and the skin (stratum corneum) thickness, l_{sc}, set to 10^{-3} cm.

Step 4 - Calculate the delay time, τ (h) from the following equation:

$$\tau = \frac{l_{sc}^2}{6\ DS_i} \tag{7}$$

where terms are as previously defined.

Step 5 - Calculate the time to reach steady state, t^* (h) from the following procedure dependent on the value calculated for B.

For $B \le 0.1$, then $t^* = 2.4\ \tau$

For $0.1 \le B \le 1.17$, then $t^* = (8.4 + 6 \log B)\ \tau$

For $B \le 1.17$, then

$$t^* = 6\ \tau\ [b - \sqrt{b^2 - c^2}] \tag{8}$$

where the constants b and c are given, as follows:

$$b = \frac{2}{\pi}\ [1 + B]^2 - c \tag{9}$$

and

$$c = \frac{1 + 3\ B}{3} \tag{10}$$

where terms are as previously defined.

Step 6 - Calculate the amount absorbed per event per unit area, I_{shi}, using the following equations depending on the value calculated for t^* relative to the event duration, TE_s.

For $TE_s < t^*$,

$$I_{shi} = 2\ 10^{-3}\ K_{pi}\ C_{dwi}\ TF_i\ e^{-\lambda_{gi} TH_{dw}} \sqrt{\frac{6\ \tau\ T}{\pi}} \qquad (11)$$

and for $TE_s > t^*$,

$$I_{shi} = 10^{-3}\ K_{pi}\ C_{dwi}\ TF_i\ e^{(-\lambda_{gi} TH_{dw})} \left[\frac{TE_s}{1 + B}\right. \qquad (12)$$

where 10^{-3} is a unit conversion factor (L/cm^3) and other terms are as previously defined.

The average daily dose, corrected by the gastrointestinal tract absorption fraction, is given as follows:

$$D_{sdi} = I_{shi}\ A_{sd}\ FE_{sh}\ F_{sd} \frac{ED_{sd}}{(BW_{sd}\ AT_{sdi}\ f_{1i})} \qquad (13)$$

where

D_{sdi} = average daily dose from chemical pollutant i via dermal absorption from water contact while showering, equivalent to oral intake (mg/kg/d)

I_{shi} = dose absorbed per unit area per shower for pollutant i (mg/cm^2-shower)

A_{sd} = area of skin exposed to contaminated water while showering (cm^2)

FE_{sh} = frequency of showers (showers/day)

F_{sd} = fraction of days per year that showering occurs (dimensionless)

ED_{sd} = exposure duration for dermal absorption while showering pathway (yr)

BW_{sd} = body weight of exposed individual for dermal absorption while showering pathway (kg)

AT_{sdi} = averaging time for dermal absorption while showering pathway for pollutant i (yr)

f_{1i} = fraction of pollutant i absorbed in passing through the GI tract following ingestion (dimensionless).

The average daily dose as computed by Equation (13) is equivalent to oral exposure because the GI absorption correction has been applied. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years. The equation is used for all pollutants except radionuclides.

For radionuclides, the GI absorption fraction and body weight are not applied because radionuclide specific dose conversion factors for dermal intake are provided in the chemical database for the 70-kg reference man. The dermal dose factors were calculated using the CINDY software package (Strenge et al. 1992; Kennedy and Strenge 1992). The equation for radionuclides is as follows:

$$D_{sdi} = I_{shi}\ A_{sd}\ FE_{sh}\ F_{sd}\ DF_{di}\ ED_{sd}\ 365.25 \tag{14}$$

where

D_{sdi} = total lifetime dose via dermal absorption for radionuclide i (rem)

DF_{di} = dose conversion factor for dermal absorption of radionuclide i (rem/pCi)

and other terms are as previously defined.

2.3 SHOWER WATER INGESTION

While showering with domestic water, individuals may ingest water inadvertently resulting in a potential for health impacts. This exposure pathway is applicable to the groundwater and surface water transport pathways. As for the drinking water pathway, consideration is given to reductions of pollutant concentration during processing in the water supply treatment plant (if present) and in transport through the water distribution system to the exposed individuals. The surface water pathway also includes estimation of losses of volatile chemicals in transport between the point of entry to the surface water and the water intake plant.

Transport Medium:	water concentration at water treatment plant, C_{dwi}, pCi/L or mg/L, expressed as a 70-year average value
Special Process:	removal of pollutants during water treatment
	loss of pollutants (environmental degradation or radioactive decay) during transport from the treatment plant to the exposure location (households)
	loss of pollutants during transport in the surface water body by volatilization
Exposure Factors:	rate of inadvertent ingestion, frequency of exposure, and exposure duration.

The average daily dose for the inadvertent water ingestion while showering pathway for groundwater transport is evaluated as follows for chemical pollutants:

$$D_{swi} = C_{dwi}\ TF_i\ e^{(-\lambda_{gi}\ TH_{dw})}\ \frac{U_{sw}\ TE_s\ FE_{sh}\ F_{s}}{(BW_{sw}\ AT_{sw}} \qquad (15)$$

where

D_{swi} = average daily ingestion dose for the shower ingestion pathway for pollutant i (mg/kg/d)

C_{dwi} = concentration of pollutant i in domestic supply water (well or pumping station) used for showering (mg/L or pCi/L)

TF_i = water treatment purification factor giving the fraction of pollutant, i, remaining after treatment (dimensionless)

λ_{gi} = loss rate constant for pollutant i in confined water systems (d^{-1})

TH_{dw} = holdup time in transfer of water from the pumping station or well to the consumer (d)

U_{sw} = inadvertent water ingestion rate while showering (L/h)

TE_s = length of time period for each shower (h/shower)

FE_{sh} = frequency of showering by the exposed individual (showers/day)

F_{sh} = fraction of days per year that showering occurs for the inadvertent shower ingestion pathway (dimensionless)

ED_{sw} = exposure duration for the shower water ingestion pathway (yr)

BW_{sw} = body weight of individuals exposed to shower water ingestion pathway (kg)

AT_{swi} = averaging time for the shower water ingestion pathway for exposure to pollutant i (yr).

The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radionuclide pollutants the total lifetime dose is evaluated, as follows, using the dose conversion factor to convert from intake (pCi) to dose (rem):

$$= C_{dwi}\ TF_i\ e^{(-\lambda_{gi}\ TH_{dw})}\ U_{sw}\ TE_s\ FE_{sh}\ F_{sw}\ DF_{gi}\ ED_{dw} 36 \qquad (16)$$

where

D_{dwi} = total lifetime ingestion dose for the shower water ingestion pathway for radionuclide i (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

For the surface water transport pathway, the average daily dose is evaluated as for Equation (15), with the water concentration being corrected for loss during transport between the entry point to the surface water body and the pumping station as in Equation (3), as follows:

$$C_{dwi} = C_{swi}(0)\ e^{(-\lambda_{si}\ T_{sw})} \qquad (17)$$

where

$C_{swi}(0)$ = concentration of pollutant at the pumping station uncorrected for loss during transit in the surface water system (mg/L or pCi/L)

λ_{si} = loss rate constant for pollutant i in surface waters (d^{-1})

T_{sw} = transit time in the surface water system between the point of entry and the pumping station (d).

2.4 LEAFY VEGETABLE INGESTION

Agricultural crops may be contaminated when water (groundwater or surface water) is used as a source of irrigation water, airborne pollutants are deposited on agricultural crops or cropland (soil), or measured soil concentrations are available. The paths by which pollutants in transport media may reach the crops are shown in Figure 2.1.

For waterborne transport pathways, the exposure evaluation is performed with the following considerations.

Transport Medium: water concentration at water treatment plant, C_{swi} or C_{gwi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: loss of pollutants (environmental degradation or radioactive decay) during transport from the pumping station to the irrigation location

loss of pollutants during transport in the surface water body by volatilization

application to crops and cropland soils

accumulation in soil over the exposure duration (multiple years)

uptake by roots from soil to edible portions of plants
direct deposition onto plant surfaces and transfer to edible portions of plants

loss of pollutants following harvest before consumption by individuals

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FIGURE 2.1. Pollutant Transfer to Edible Crops

Exposure Factors: rate of crop ingestion and exposure duration.

The application of irrigation water to croplands results in deposition of pollutants to soils and plants at a constant average rate over the period of irrigation. The deposition rate is given as follows:

$$DP_{wi} = \frac{C_{iri}\ IR}{30} \tag{18}$$

where

DP_{wi} = rate of deposition of pollutant i in irrigation water to cropland soil and plants (mg/m^2/d or pCi/m^2/d)

C_{iri} = pollutant i concentration in irrigation water (mg/L or pCi/L)

IR = irrigation water application rate during irrigation periods (L/m^2/mo)

30 = units conversion factor (d/mo).

Note that the irrigation water concentration is taken from the groundwater (C_{gwi}) or surface water (C_{swi}) transport analysis. When surface water is the source of irrigation water, the correction for loss of pollutant during surface water transport is made as indicated by Equation (3).

The accumulation of pollutants in soil over a multiple-year period (multiple growing periods) is accounted for by a soil accumulation factor (SAF). This factor accounts for previous years' deposition and accumulation to evaluate an average soil concentration over the exposure duration defined for the current usage location and exposed population (or individual). The factor is evaluated as a time integral of soil concentration over the exposure period. The soil accumulation factor is evaluated as the time integral of the solution to the deposition and decay differential equation, normalized to unit deposition and averaged over the deposition period. This process is represented by the following two equations:

$$\frac{dC_{awi}}{dt} = UD_{wi} - C_{awi}\,\lambda_{di} \tag{19}$$

and

$$SAF_i = \frac{\int_0^{ED_{kk}\,365.25} C_{awi}\ dt}{UD_{wi}\ ED_{kk}\ 365.25} \tag{20}$$

where

C_{awi} = soil concentration from irrigation water deposition as a function of time (mg/m^2 or pCi/m^2)

UD_{wi} = unit deposition rate to soil (mg/m^2/d or pCi/m^2/d)

λ_{di} = environmental degradation and decay constant for pollutant i in surface soil (d^{-1})

SAF_i = soil accumulation factor for an exposure duration of ED_{kk} years for pollutant i (d)

ED_{kk} = exposure duration for pathway kk (yr)

and other terms are as previously defined.

The division by UD_{wi} normalizes the SAF values to unit deposition rate. The above equations are used for the agricultural exposure pathways from waterborne (irrigation) deposition and for atmospheric deposition. When radionuclide decay chains are evaluated, the above equations apply to the parent radionuclide. The contributions from progeny radionuclides are evaluated similarly using the radionuclide chain decay algorithms defined in Appendix B with their dose contribution added to the parent dose. Progeny radionuclides are assumed to have no activity in the source water or air, and their contribution is limited to ingrowth during the deposition and accumulation period. When the progeny are included as explicit radionuclides in the inventory list, they are treated as a parent radionuclide, and their contribution is reported separately from their ingrowth contributions as progeny of other parent radionuclides in the inventory.

The plant contamination from irrigation deposition onto edible parts of plants will result in a contamination level at harvest that is estimated as follows:

$$CWD_{lvi} = DP_{wi}\ TV_{lv}\ r_{lv}\ \frac{[1 - e^{-\lambda_{ei} TC_{lv}}]}{\lambda_{ei}\ Y_{lv}} \tag{21}$$

where

CWD_{lvi} = pollutant i concentration in leafy vegetables at time of harvest from water deposition onto plants (mg/kg or pCi/kg)

TV_{lv} = translocation factor from plant surfaces to edible parts of the plant for leafy vegetables (dimensionless)

r_{lv} = fraction of deposition retained on plant surfaces (dimensionless)

λe_i = effective weathering and decay constant for pollutant i (d^{-1})

TC_{lv} = duration of the growing period for leafy vegetables (d)

$\lambda_{ei} = \lambda_{di} + \lambda_w$

λ_w = weathering decay constant for losses from plant surfaces (d^{-1})

Y_{lv} = yield of leafy vegetables (kg/m^2)

and other terms are as previously defined.

The plant concentration at the time of harvest for uptake from soil via roots is estimated as follows:

Equation (22) CWR_{lvi}

$$CWR_{lvi} = \frac{FI_{lv}\ SAF_i\ B_{vi}\ DP_{wi}}{P} \qquad (22)$$

where

CWR_{lvi} = pollutant i concentration in edible parts of leafy vegetables at harvest from root uptake (mg/kg or pCi/kg)

FI_{lv} = fraction of year that irrigation occurs for leafy vegetable crops (dimensionless)

B_{vi} = soil-to-plant transfer factor for pollutant i (kg dry soil/kg wet weight plant)

P = area soil density of farmland (kg dry soil/m^2 farmland)

and other terms are as previously defined.

The total concentration in leafy vegetables is evaluated as the sum of concentrations from the two contamination routes: deposition onto plants and root uptake from soil.

$$C_{lvi} = (CWD_{lvi} + CWR_{lvi})\ e^{-\lambda_{gi}\ TH_{lv}} \qquad (23)$$

where

C_{lvi} = leafy vegetable plant concentration at time of consumption (mg/kg)

λ_{gi} = loss and decay rate constant for pollutant i in closed water systems (d^{-1})

TH_{lv} = holdup time between harvest of leafy vegetables and consumption by humans (d) and other terms are as previously defined. The loss rate constant for closed water systems is used to simulate loss from food products between harvest and consumption as a conservative representation for food handling and packaging. This representation is considered appropriate for frozen and canned foods and conservative for fresh foods.

The average daily dose from ingestion of chemical pollutants in leafy vegetables following irrigation water contamination is evaluated as follows:

$$D_{lvi} = U_{lv} \, C_{lvi} \, \frac{F_{lv} \, ED_{lv}}{AT_{lvi} \, BW_{lv}} \qquad (24)$$

where

D_{lvi} = average daily dose from ingestion of leafy vegetables (mg/kg/d)

U_{lv} = ingestion rate of leafy vegetables by the exposed individual (kg/d)

F_{lv} = fraction of days per year that leafy vegetables are consumed (dimensionless)

ED_{lv} = exposure duration for the leafy vegetable ingestion pathway (yr)

AT_{lvi} = averaging time for leafy vegetable ingestion pathway for exposure to pollutant i (yr)

BW_{lv} = body weight of individuals exposed by leafy vegetable ingestion pathway (kg).

and C_{lvi} is as previously defined. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years. For radioactive pollutants, the total lifetime ingestion dose is evaluated as follows:

$$D_{lvi} = U_{lv} \, DF_{gi} \, C_{lvi} \, F_{lv} \, ED_{lv} \, 365.25 \qquad (25)$$

where

D_{lvi} = total lifetime dose from ingestion of leafy vegetables (rem)

DF_{gi} = ingestion dose conversion factor for radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

For the atmospheric transport pathway, the exposure evaluation is performed with the following considerations.

Transport Medium: air at agricultural production location, C_{ari}, pCi/m^3, or mg/m^3, expressed as a 70-year average value

Special Process: deposition to crops and cropland soils

uptake by roots from soil to edible portions of plants

direct deposition onto plant surfaces and transfer to edible portions of plants

loss of pollutants following harvest, prior to consumption by individuals

Exposure Factors: rate of crop ingestion and exposure duration.

The deposition rate from air to plants is given as follows:

$$DP_{ai} = 86,400\ C_{ari}\ Vd_i \tag{26}$$

where

DP_{ai} = rate of deposition of pollutant i from air to plants (mg/m^2/d or pCi/m^2/d)

86,400 = unit conversion factor (s/d).

C_{ari} = average concentration of pollutant i in air at the location of crop production (mg/m^3 or pCi/m^3)

Vd_i = deposition velocity for pollutant i (m/s).

The soil accumulation factor for air deposition is the same as for irrigation water deposition, as defined by Equations (19) and (20).

The concentration in edible parts of plants from airborne deposition is estimated by Equation (21), with parameters for the air pathway substituted for the irrigation pathway as follows:

$$CAD_{lvi} = DP_{ai}\ TV_{lv}\ r_{lv}\ \frac{\left[1 - e^{-\lambda e_i TC_{lv}}\right]}{\lambda_{ei}\ Y_{lv}} \tag{27}$$

where

CAD_{lvi} = pollutant i concentration in leafy vegetables at time of harvest from atmospheric deposition onto plants (mg/kg or pCi/kg)

and other terms are as previously defined.

The plant concentration at the time of harvest for uptake from soil via roots is estimated as follows:

$$CAR_{lvi} = SAF_i\ B_{vi}\ \frac{DP_{si}}{P} \tag{28}$$

where

CAR_{lvi} = pollutant i concentration in edible parts of leafy vegetables at harvest from root uptake (mg/kg or pCi/kg)

DP_{si} = annual average deposition rate of pollutant i to soil from atmospheric transport and deposition (mg/m^2/d or pCi/m^2/d)

and other terms are as previously defined. The annual average deposition rate to soil (DP_{si}) is an output parameter from the atmospheric transport analysis of MEPAS.

The total concentration in leafy vegetables is evaluated as the sum of contributions for the two contamination routes: deposition onto plants and root uptake from soil, as follows:

$$C_{lvi} = \left(CAD_{lvi} + CAR_{lvi} \right) e^{-\lambda_{gi} TH_{lv}} \tag{29}$$

where

C_{lvi} = total concentration in leafy vegetables (mg/kg or pCi/kg)

and other terms are as previously defined. The average daily dose from ingestion of chemical pollutants in leafy vegetables following atmospheric contamination is evaluated as follows:

$$D_{lvi} = U_{lv} \; C_{lvi} \; F_{lv} \; \frac{ED_{lv}}{AT_{lvi} \; BW_{lv}} \tag{30}$$

where

D_{lvi} = average daily dose from ingestion of leafy vegetables for chemical pollutant i (mg/kg/d)

ED_{lv} = exposure duration for the leafy vegetable ingestion pathway (yr)

AT_{lvi} = averaging time for the leafy vegetable ingestion pathway for exposure to pollutant i (yr)

BW_{lv} = body weight of individuals exposed by the leafy vegetable ingestion pathway (kg).

and other terms are as previously defined. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years. For radioactive pollutants, the total lifetime dose is evaluated as follows:

$$D_{lvi} = U_{lv} \; DF_{gi} \; C_{lvi} \; F_{lv} \; ED_{lv} \; 365.25 \tag{31}$$

where

D_{lvi} = total lifetime dose from ingestion of leafy vegetables for radionuclide i (rem)

and other terms are as previously defined.

For the measured soil concentration pathway, the exposure evaluation is performed for an initial soil concentration (measured) with loss and decay during the exposure period. The following considerations are included.

Transport Medium: measured soil at the production location, C_{msi}, pCi/kg or mg/kg, expressed as the concentration at the start of the exposure period

Special Process: uptake by roots from soil to edible portions of plants

loss of pollutants from soil by volatilization or decay

loss of pollutants following harvest, prior to consumption by individuals

Exposure Factors: rate of crop ingestion and exposure duration.

The change in soil concentration over the exposure period affects the total amount of pollutant ingested by the exposed individuals. The average concentration is evaluated as the time integral of the activity in the soil divided by the exposure duration, as follows:

$$SMF_i = \frac{\int_0^{ED_{1v}365.25} C_{msi}\, dt}{ED_{1v}\ 365.25} \qquad (32)$$

where

SMF_i = average soil concentration for pollutant i over the exposure duration (mg/kg dry soil or pCi/kg dry soil)

C_{msi} = measured concentration of pollutant i in soil (mg/kg dry soil or pCi/kg dry soil)

and other terms are as previously defined. The average soil concentration factor is evaluated using Equation (32) for chemicals and parent radionuclides. For progeny radionuclides the average concentration from ingrowth during the exposure period is evaluated using the chain decay algorithms presented in Appendix B.

The concentration in edible parts of plants from root uptake from soil is evaluated as follows:

$$C_{1vi} = SMF_i\ B_{vi} \qquad (33)$$

where terms are as previously defined.

The average daily intake from ingestion of chemicals in leafy vegetables is evaluated using the plant concentration from Equation (33) and intake Equation (30). For radionuclides, the ingestion dose is evaluated using the plant concentration from Equation (33) and dose Equation (31)

2.5 OTHER VEGETABLE INGESTION

This exposure pathway uses the same model as the leafy vegetable pathway except that parameters may be assigned different numerical values representative of food crops that are not characterized as leafy vegetables. This includes grains, root crops, and crops for which the consumed food is generally not exposed directly to the depositing material. The equations for the other vegetable pathway are the same as those for the leafy vegetable pathway. The equations are repeated here for completeness, with subscripts appropriate to the other vegetable pathway.

The pollutant deposition rates to croplands from atmospheric transport and irrigation water application are evaluated using the same equations as for the leafy vegetable pathway [Equation (18) for irrigation deposition and Equation (25) for atmospheric deposition]. The soil accumulation factor is also applied to the other vegetables pathway, as defined by Equations (19) and (20).

When surface water is the source of irrigation water, the correction for loss of pollutant during surface water transport is made as indicated by Equation (3).

The plant contamination from irrigation deposition onto edible parts of plants will result in a contamination level at harvest that is estimated as follows:

$$CWD_{ovi} = DP_{wi}\ TV_{ov}\ r_{ov}\ \frac{\left[1 - e^{-\lambda_{ei}\,TC_{ov}}\right]}{\lambda_{ei}\ Y_{ov}} \tag{34}$$

where

CWD_{ovi} = pollutant i concentration in other vegetables at time of harvest from water deposition onto plants (mg/kg or pCi/kg)

DP_{wi} = deposition rate of pollutant i in irrigation water to crops ($mg/m^2/d$ or $pCi/m^2/d$)

TV_{ov} = translocation factor from plant surfaces to edible parts of the plant for other vegetables (dimensionless)

r_{ov} = fraction of deposition retained on edible parts of the other vegetable plant (dimensionless)

λ_{ei} = $\lambda_{di} + \lambda_w$

λ_{di} = environmental degradation and decay constant for pollutant i in soil (d^{-1})

λ_w = weathering decay constant for losses from plant surfaces (d^{-1})

TC_{ov} = duration of the growing period for other vegetables (d)

Y_{ov} = yield of other vegetables (kg/m^2).

The plant concentration at the time of harvest for uptake from soil via roots, following irrigation deposition, is estimated as follows:

$$CWR_{ovi} = \frac{FI_{ov}\ SAF_i\ B_{vi}\ DP_{wi}}{P} \tag{35}$$

where

CWR_{ovi} = pollutant i concentration in edible parts of other vegetables at harvest from root uptake (mg/kg or pCi/kg)

FI_{ov} = fraction of year that irrigation occurs for other vegetable crops (dimensionless)

SAF_i = soil accumulation factor for the other vegetables exposure duration for pollutant i (d).

and other terms are as previously defined.

The concentration in other vegetables is evaluated as the sum of contributions for the two contamination routes: deposition onto plants and root uptake from soil, as follows.

$$C_{ovi} = \left(CWD_{ovi} + CWR_{ovi}\right) e^{-\lambda_{gi}\ TH_{ov}} \tag{36}$$

where

C_{ovi} = concentration of pollutant i in other vegetables (mg/kg)

λ_{gi} = loss and decay rate constant for pollutant i in closed water systems (d^{-1})

TH_{ov} = holdup time between harvest of other vegetables and consumption by humans (d)

and other terms are as previously defined.

The average daily dose from ingestion of chemical pollutants (for irrigation water contamination) in other vegetables is evaluated as follows:

$$D_{ovi} = U_{ov} \, C_{ovi} \, F_{ov} \, \frac{ED_{ov}}{AT_{ovi} \, BW_{ov}} \tag{37}$$

where

D_{ovi} = average daily dose from ingestion of other vegetables (mg/kg/d)

U_{ov} = ingestion rate of other vegetables by the exposed individual (kg/d)

F_{ov} = fraction of days per year that ingestion of other vegetables occurs (dimensionless)

ED_{ov} = exposure duration for the other vegetable ingestion pathway (yr)

AT_{ovi} = averaging time for other vegetable ingestion pathway for exposure to pollutant i (yr)

BW_{ov} = body weight of individuals exposed by other vegetable ingestion pathway (kg).

and C_{ovi} is as previously defined. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radioactive pollutants, the total lifetime dose is evaluated as follows:

$$D_{ovi} = U_{ov} \, DF_{gi} \, C_{ovi} \, F_{ov} \, ED_{ov} \, 365.25 \tag{38}$$

where

D_{ovi} = total lifetime dose from ingestion of other vegetables (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi)

and other terms are as previously defined.

For the atmospheric deposition pathway, the direct deposition of pollutants from air onto edible parts of plants is estimated by Equation (27), with parameters for the air pathway substituted for the irrigation pathway as follows:

$$CAD_{ovi} = DP_{ai} \, TV_{ov} \, r_{ov} \, \frac{\left[1 - e^{-\lambda e_i TC_{ov}}\right]}{\lambda_{ei} \, Y_{ov}} \tag{39}$$

where

CAD_{ovi} = pollutant i concentration in other vegetables at time of harvest from atmospheric deposition onto plants (mg/kg or pCi/kg)

DP_{ai} = deposition rate from air to plants for pollutant i (mg/m^2/d or pCi/m^2/d)

and other terms are as previously defined.

The soil accumulation factor is also applied to the atmospheric deposition to soil route, as defined by Equations (19) and (20). The plant concentration at the time of harvest for uptake from soil via roots following atmospheric deposition is estimated, as follows:

$$CAR_{ovi} = SAF_i \; B_{vi} \; \frac{DP_{si}}{P} \tag{40}$$

where

CAR_{ovi} = pollutant i concentration in edible parts of other vegetables at harvest from root uptake (mg/kg or pCi/kg)

DP_{si} = annual average deposition rate of pollutant i to soil from atmospheric transport and deposition (mg/m^2/d or pCi/m^2/d)

and other terms are as previously defined.

The concentration of pollutants in other vegetables at the time of consumption is evaluated as the sum of contributions from the two contamination routes: deposition onto plants and root uptake from soil, as follows:

$$C_{ovi} = \left(CAD_{ovi} + CAR_{ovi}\right) e^{-\lambda_{gi} \, TH_{ov}} \tag{41}$$

where

C_{ovi} = concentration of pollutant i in other vegetable crops at the time of consumption (mg/kg or pCi/kg)

and other terms are as previously defined.

The average daily dose from ingestion of chemical pollutants (for the atmospheric transport pathway) in other vegetables is evaluated as follows:

$$D_{ovi} = U_{ov} \; C_{ovi} \; \frac{F_{ov} \; ED_{ov}}{AT_{ovi} \; BW_{ov}} \tag{42}$$

where

D_{ovi} = average daily dose from ingestion of other vegetables (mg/kg/d)

ED_{ov} = exposure duration for the other vegetable ingestion pathway (yr) and other terms are as previously defined. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radioactive pollutants, the total lifetime dose is evaluated as follows:

$$D_{ovi} = U_{ov}\, DF_{gi}\, C_{ovi}\, F_{ov}\, ED_{ov} 365.25 \tag{43}$$

where

D_{ovi} = total lifetime dose from ingestion of other vegetables (rem)

and other terms are as previously defined.

For the measured soil concentration pathway, the exposure evaluation is performed for an initial soil concentration (measured) with loss and decay during the exposure period. The following considerations are included.

Transport Medium:	measured soil at the production location, C_{msi}, pCi/kg or mg/kg, expressed as the concentration at the start of the exposure period
Special Process:	uptake by roots from soil to edible portions of plants
	loss of pollutants from soil by volatilization or decay
	loss of pollutants following harvest, prior to consumption by individuals
Exposure Factors:	rate of crop ingestion and exposure duration.

The average concentration is evaluated as the time integral of the activity in the soil divided by the exposure duration, as given by Equation (32).

The concentration in edible parts of plants from root uptake from soil is evaluated as follows:

$$C_{ovi} = SMF_i\, B_{vi} \tag{44}$$

where terms are as previously defined.

The average daily intake from ingestion of chemicals in leafy vegetables is evaluated using the plant concentration from Equation (44) and intake Equation (42). For radionuclides, the ingestion dose is evaluated using the plant concentration from Equation (44) and dose Equation (43).

2.6 MEAT INGESTION

Animals fed contaminated crops or water can be expected to produce contaminated meat. The concentration of pollutants in contaminated feed crops can be generated from the same transport and uptake routes as for the leafy vegetable and other vegetable exposure pathways. In addition, for water-borne transport routes, the animals may be fed contaminated water (groundwater or surface water) from the same source of water as used for irrigation. For soil contamination animal products may also be contaminated by animal ingestion of soil. The paths by which pollutants in transport media may reach animals are shown in Figure 2.2.

For waterborne transport pathways, the exposure evaluation is performed with the following considerations:

Transport Medium: water concentration at water treatment plant, C_{swi} or C_{gwi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: loss of pollutants (environmental degradation or radioactive decay) during transport from the pumping station to the irrigation location

loss of pollutants during transport in the surface water body by volatilization

application of irrigation water to animal feed crops and cropland soils

accumulation of pollutants in soil over the exposure duration

uptake by roots from soil to edible portions of feed crop plants

direct deposition onto feed crop plant surfaces and transfer to edible portions of plants

feeding of crops to animals

ingestion of soil by animals

ingestion of irrigation water by animals loss of pollutants from animal meat following harvest, prior to consumption by humans.

Exposure Factors: rate of animal meat ingestion and exposure duration.

The application of irrigation water to croplands results in deposition of pollutants to soils and feed crop plants at a constant average rate over the period of irrigation. The deposition rate is given by Equation (18). The soil accumulation factor is also applied to the analysis, as given by Equations (19) and (20). The concentration of pollutants in feed-crop plants at the time of feeding to animals is evaluated as follows for irrigation deposition onto plants:

FIGURE 2.2. Pollutant Transfer to Animal Products

$$CWD_{fti} = DP_{wi} \, TV_{ft} \, r_{ft} \, \frac{\left[1 - e^{-\lambda_{ei} TC_{ft}}\right]}{\lambda_{ei} \, Y_{ft}} \qquad (45)$$

where

CWD_{fti} = pollutant i concentration in meat animal feed crops at time of feeding from water deposition onto plants (mg/kg or pCi/kg)

DP_{wi} = deposition rate of pollutant i in irrigation water to crops ($mg/m^2/d$ or $pCi/m^2/d$)

TV_{ft} = translocation factor from plant surfaces to edible parts of the plant for meat animal feed crops (dimensionless)

r_{ft} = fraction of deposition retained on edible parts of meat animal feed crops (dimensionless)

λ_{ei} = $\lambda_{di} + \lambda_w$

λ_{di} = environmental degradation and decay constant for pollutant i in soil (d^{-1})

λ_w = weathering decay constant for losses from plant surfaces (d^{-1})

TC_{ft} = duration of the growing period for meat animal feed crops (d)

Y_{ft} = yield of meat animal feed crops (kg/m^2).

The plant concentration at the time of harvest for uptake from soil via roots, following irrigation deposition, is estimated as follows:

$$CWR_{fti} = \frac{FI_{mt}\,SAF_i\,B_{vi}\,DP_{wi}}{P} \qquad (46)$$

where

CWR_{fti} = pollutant i concentration in edible parts of meat animal feed crops at time of feeding to animals from root uptake (mg/kg or pCi/kg)

FI_{mt} = fraction of year meat animal feed crops are irrigated (dimensionless)

SAF_i = soil accumulation factor for the meat ingestion exposure duration for pollutant i (d)

B_{vi} = soil-to-plant transfer factor for pollutant i (kg dry soil/kg net weight plant)

P = area soil density of farmland (kg dry soil/m^2 farmland)

and other terms are as previously defined.

The animals may ingest soil along with the forage or feed. The soil concentration is evaluated as an average value over the exposure duration using the same soil accumulation factor as for the plant root uptake pathway. This factor is evaluated using Equations (19) and (20). The soil concentration is evaluated as follows:

$$CWS_{fti} = \frac{FI_{mt}\ SAF_i\ DP_{wi}}{P} \tag{47}$$

where

CWS_{fti} = average soil concentration for pollutant i eaten by meat animals along with feed (mg/kg dry soil or pCi/kg dry soil)

and other terms are as previously defined.

The concentration of pollutants in meat products at the time of consumption by humans includes animal intake of feed, water, and soil, as follows:

$$C_{mti} = FM_{mti} \{ FC_{ft} \left[\left(CWD_{fti} + CWR_{fti} \right) Q_f + C_{iri}\ FC_{wt}\ Q_{wt} \} e^{-\lambda_{gi} TH_{mt}} \tag{48}$$

where

C_{mti} = concentration of pollutant i in meat at time of consumption by humans (mg/kg or pCi/kg)

FM_{mti} = transfer factor for uptake of pollutant i by animals to meat (d/kg)

FC_{ft} = fraction of meat animal feed that is contaminated (dimensionless)

Q_{ft} = meat animal ingestion rate of feed (kg/d)

Q_{st} = meat animal intake rate of soil (kg/d)

C_{iri} = average concentration of pollutant i in irrigation water (mg/L or pCi/L)

FC_{wt} = fraction of meat animal drinking water that is contaminated (dimensionless)

Q_{wt} = meat animal ingestion rate of water (L/d)

λ_{gi} = rate constant for decay and loss in confined water system, used to simulate loss during storage and distribution of meat (d^{-1})

TH_{mt} = holdup time between harvest (slaughter) and consumption of animal meat by humans (d)

and other terms are as previously defined.

The average daily dose received by individuals consuming the contaminated animal meat (for the waterborne transport pathways) is evaluated as follows for chemical pollutants.

$$D_{mti} = U_{mt} \, C_{mti} \, \frac{F_{mt} \, ED_{mt}}{AT_{mti} \, BW_{mt}} \tag{49}$$

where

D_{mti} = average daily dose from ingestion of meat (mg/kg/d)

U_{mt} = ingestion rate of meat by the exposed individual (kg/d)

F_{mt} = fraction of days per year that meat is eaten (dimensionless)

ED_{mt} = exposure duration for the meat ingestion pathway (yr)

AT_{mti} = averaging time for the meat ingestion pathway for exposure to pollutant i (yr)

BW_{mt} = body weight of individuals exposed by the meat ingestion pathway (kg)

and C_{mti} is as previously defined. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radioactive pollutants, the total lifetime dose is evaluated as follows:

$$D_{mti} = U_{mt} \, DF_{gi} \, C_{mti} \, F_{mt} \, ED_{mt} \, 365.25 \tag{50}$$

where

D_{mti} = total lifetime dose from ingestion of meat (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi)

and other terms are as previously defined.

For airborne transport pathways, the exposure evaluation is performed with the following considerations.

Transport Medium: air at agricultural production location, C_{ari}, pCi/m^3 or mg/m^3, expressed as a 70-year average value

Special Process: deposition to crops and cropland soils

uptake by roots from soil to edible portions of plants direct deposition onto plant surfaces and transfer to edible portions of plants accumulation in soil over the exposure duration

feeding of crops to animals

loss of pollutants from animal meat following harvest, prior to consumption by humans

Exposure factors: rate of animal meat ingestion and exposure duration.

The deposition rate from air to plants is given by Equation (26). The soil accumulation factor, as defined by Equations (19) and (20), is also applied to this pathway.

The concentration of pollutants in edible parts of plants from atmospheric deposition is estimated by Equation (45) with parameters for the air pathway substituted for the irrigation pathway, as follows:

$$CAD_{fti} = DP_{ai} \; TV_{ft} \; r_{ft} \; \frac{\left[1 - e^{-\lambda_{ei} TC_{ft}}\right]}{\lambda_{ei} \; Y_{ft}} \qquad (51)$$

where

CAD_{fti} = pollutant i concentration in feed plants for meat animals at feeding to animal from atmospheric deposition onto plants (mg/kg or pCi/kg)

DP_{ai} = deposition rate from air to plants for pollutant i (mg/m^2/d or pCi/m^2/d)

and other terms are as previously defined.

The meat animal feed plant concentration at the time of harvest for uptake from soil via roots is estimated as follows:

$$CAR_{fti} = SAF_i \; B_{vi} \; \frac{DP_{si}}{P} \qquad (52)$$

where

CAR_{fti} = pollutant i concentration in edible parts of meat animal feed plants at feeding to animal from root uptake (mg/kg or pCi/kg)

B_{vi} = soil-to-plant transfer factor for pollutant i (kg dry soil/kg wet weight plant)

DP_{si} = annual average deposition rate of pollutant i to soil from atmospheric transport and deposition (mg/m^2/d or pCi/m^2/d)

P = area soil density of farmland (kg dry soil/m^2 farmland)

and other terms are as previously defined.

The concentration of pollutants in meat products at the time of consumption by humans includes animal intake of feed, as follows:

$$C_{mti} = FM_{mti} \left(CAD_{fti} + CAR_{fti} \right) FC_{mt} \, Q_{ft} \, e \qquad (53)$$

where

C_{mti} = concentration of pollutant i in meat at time of consumption by humans (mg/kg or pCi/kg)

FC_{mt} = fraction of meat animal that is contaminated (dimensionless)

and other terms are as previously defined.

The average daily dose received by individuals consuming the contaminated animal meat (for the atmospheric transport pathway) is evaluated using Equation (45) for chemical pollutants and by Equation (46) for radionuclides.

For the measured soil concentration pathway, the exposure evaluation is performed for an initial soil concentration (measured) with loss and decay during the exposure period. The following considerations are included.

Transport Medium: measured soil at the production location, C_{msi}, pCi/kg or mg/kg, expressed as the concentration at the start of the exposure period

Special Process: uptake by roots from soil to edible portions of animal feed plants

loss of pollutants from soil by volatilization or decay

feeding of crops to animals

ingestion of soil by animals

loss of pollutants following harvest, prior to consumption of animal products by individuals

Exposure Factors: rate of animal meat ingestion and exposure duration.

The evaluation of feed plant concentration eaten by meat animals is performed similarly to the evaluation of vegetable plant concentrations described in the previous sections. The soil average concentration is evaluated using Equation (32), and the plant concentration is evaluated using Equation (33). The animal may also ingest soil. The soil concentration ingested by the meat animal is equal to the average soil concentration given by Equation (32). The concentration in the animal product is evaluated as follows:

$$C_{mti} = FM_{mti}\, FC_{ft} \left[C_{fti}\, Q_{ft} + SMF_i\, Q_{st} \right] \qquad (54)$$

where

C_{fti} = concentration in meat animal feed for pollutant i (mg/kg wet weight feed or pCi/wet weight feed)

and other terms are as previously defined.

The average daily intake of chemical pollutants is evaluated using Equation (49) and the lifetime radiation dose for radionuclides is evaluated using Equation (50).

2.7 MILK INGESTION

The models for exposure from ingestion of milk are the same as those used for the meat ingestion exposure pathway. The equations are the same as those presented in Subsection 2.6, except that several of the parameters have subscripts changed to indicate the milk pathway is being considered. The following is a summary of the equations for the milk pathway. Only those equations with differences from the meat exposure pathway are presented; unchanged equations are referenced.

For waterborne transport pathways, the transport media, special processes, and exposure factors are as described for the meat ingestion pathway in Subsection 2.6, except that milk instead of meat is ingested by humans.

The application of irrigation water to croplands results in deposition of pollutants to soils and feed crop plants at a constant average rate over the period of irrigation. The deposition rate is given by Equation (18). The soil accumulation factor is also applied to the analysis as given by Equations (19) and (20). The concentration of pollutants in feed-crop plants at the time of feeding to milk animals is evaluated as follows for irrigation deposition onto plants:

$$CWD_{fki} = DP_{wi}\ TV_{fk}\ r_{fk}\ \frac{\left[1 - e^{-\lambda_{ei} TC_{fk}}\right]}{\lambda_{ei}\ Y_{fk}} \qquad (55)$$

where

CWD_{fki} = pollutant i concentration in milk animal feed crops at time of feeding from water deposition onto plants (mg/kg or pCi/kg)

TV_{fk} = translocation factor from plant surfaces to edible parts of the plant for milk animal feed crops (dimensionless)

r_{fk} = fraction of deposition retained on edible parts of milk animal feed crops (dimensionless)

TC_{fk} = duration of the growing period for milk animal feed crops (d)

Y_{fk} = yield of milk animal feed crops (kg/m^2)

and other terms are as previously defined for the leafy vegetable ingestion pathway.

The milk-animal, feed-plant concentration at the time of harvest for uptake from soil via roots, following irrigation deposition is estimated as follows:

$$CWR_{fki} = \frac{FI_{mk}\ SAF_i\ B_{vi}\ DP_{wi}}{P} \qquad (56)$$

where

CWR_{fki} = pollutant i concentration in edible parts of milk-animal feed crops at time of feeding to animals from root uptake (mg/kg or pCi/kg)

FI_{mk} = fraction of year that milk animal feed crops are irrigated (dimensionless)

and other terms are as previously defined.

The concentration of pollutants in milk at the time of consumption by humans includes animal intake of feed and water, as follows:

$$C_{mki} = FM_{mki}\left\{FC_{fk}\left[\left(CWD_{fki} + CWR_{fki}\right)Q_{fk} + CWS_{fki}\ Q \right.\right. \qquad (57)$$

where

C_{mki} = concentration of pollutant i in milk at time of consumption by humans (mg/l or pCi/l)

FM_{mki} = transfer factor for uptake of pollutant i by animals to milk (d/l)

FC_{fk} = fraction of milk-animal feed that is contaminated (dimensionless)

Q_{fk} = milk-animal ingestion rate of feed (kg/d)

FC_{wk} = fraction of milk-animal drinking water that is contaminated (dimensionless)

Q_{wk} = milk-animal ingestion rate of water (L/d)

Q_{sk} = milk animal ingestion rate of soil (kg/d)

λ_{gi} = rate constant for decay and loss in confined water system, used to simulate loss during storage and distribution of meat (d^{-1})

TH_{mk} = holdup time between harvest (milking) and consumption of animal milk by humans (d)

and other terms are as previously defined.

The average daily dose received by individuals consuming the contaminated milk (for the waterborne transport pathways) is evaluated as follows for chemical pollutants.

$$D_{mki} = U_{mk}\ C_{mki}\ \frac{F_{mk}\ ED_{mk}}{AT_{mki}\ BW_{mk}} \tag{58}$$

where

D_{mki} = average daily dose from ingestion of milk (mg/kg/d)

U_{mk} = ingestion rate of milk by the exposed individual (L/d)

F_{mk} = fraction of days per year that milk is ingested (dimensionless)

ED_{mk} = exposure duration for the milk ingestion pathway (yr)

AT_{mki} = averaging time for the milk ingestion pathway for exposure to pollutant i (yr)

BW_{mk} = body weight of individuals exposed by the milk ingestion pathway (kg).

and other terms are as previously defined. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radioactive pollutants, the total lifetime dose is evaluated, as follows:

$$D_{mki} = U_{mk}\, DF_{gi}\, C_{mki}\, F_{mk}\, ED_{mk}\, 365.25 \quad (59)$$

where

D_{mki} = total lifetime dose from ingestion of milk (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

For airborne transport pathways, the milk ingestion exposure evaluation is performed with the same considerations as defined for the meat ingestion pathway of Subsection 2.6.

The deposition rate from air to plants is given by Equation (26). The soil accumulation factor, as defined by Equations (19) and (20), is also applied to this pathway.

The concentration of pollutants in feed crop plants is estimated by Equation (55) with parameters for the air pathway substituted for the irrigation pathway, as follows:

$$CAD_{fki} = DP_{ai}\, TV_{fk}\, r_{fk}\, \frac{\left[1 - e^{-\lambda_{ei} TC_{fk}}\right]}{\lambda_{ei}\, Y_{fk}} \quad (60)$$

where

CAD_{fki} = pollutant i concentration in feed plants for milk animals at feeding to animal from atmospheric deposition onto plants (mg/kg or pCi/kg)

DP_{ai} = deposition rate from air to plants for pollutant i (mg/m^2/d or pCi/m^2/d)

and other terms are as previously defined.

The milk-animal, feed-plant concentration at the time of harvest for uptake from soil via roots is estimated as follows:

$$CAR_{fki} = SAF_i\, B_{vi}\, \frac{DP_{si}}{P} \quad (61)$$

where

CAR_{fki} = pollutant i concentration in edible parts of milk-animal feed plants at time of feeding to animal from root uptake (mg/kg or pCi/kg)

B_{vi} = soil-to-plant transfer factor for pollutant i (kg dry soil/kg wet weight plant)

DP_{si} = annual average deposition rate of pollutant i to soil from atmospheric transport and deposition (mg/m^2/d or pCi/m^2/d)

P = area soil density of farmland (kg dry soil/m^2 farmland)

and other terms are as previously defined.

The concentration of pollutants in milk at the time of consumption by humans includes animal intake of feed, as follows:

$$C_{mki} = FM_{mki} \left(CAD_{fki} + CAR_{fki} \right) FC_{mk} \; Q_{fk} e^{-} \tag{62}$$

where

C_{mki} = concentration of pollutant i in milk at time of consumption by humans (mg/kg or pCi/kg)

and other terms are as previously defined.

The average daily dose received by individuals consuming the contaminated milk (for the atmospheric transport pathway) is evaluated using Equation (58) for chemical pollutants. The total lifetime dose is evaluated using Equation (59) for radionuclides.

For the measured soil concentration pathway, the exposure evaluation is performed for an initial soil concentration (measured) with loss and decay during the exposure period. The following considerations are included for the milk ingestion exposure pathway.

Transport Medium:	measured soil at the production location, C_{msi}, pCi/kg or mg/kg, expressed as the concentration at the start of the exposure period
Special Process:	uptake by roots from soil to edible portions of animal feed plants
	loss of pollutants from soil by volatilization or decay
	feeding of crops to animals
	ingestion of soil by animals
	loss of pollutants following harvest, prior to consumption of animal products by individuals
Exposure Factors:	rate of animal meat ingestion and exposure duration.

The evaluation of feed plant concentration eaten by milk animals is performed similarly to the evaluation of vegetable plant concentrations described in the previous sections. The soil average concentration is evaluated using Equation (32), and the plant concentration is evaluated using Equation (33). The animal may also ingest soil. The soil concentration ingested by the milk animal is equal to the average soil concentration given by Equation (32). The concentration in the animal product is evaluated as follows:

$$C_{mki} = FM_{mki} \, FC_{fk} \left[C_{fki} \, Q_{fk} + SMF_i \, Q_{sk} \right] \qquad (63)$$

where

C_{fki} = concentration in milk animal feed for pollutant i (mg/kg wet weight feed or pCi/wet weight feed)

and other terms are as previously defined.

The average daily intake of chemical pollutants is evaluated using Equation (58), and the lifetime radiation dose for radionuclides is evaluated using Equation (59).

2.8 FIN FISH INGESTION

Fish raised and caught in contaminated surface waters provide a potential for human health impacts to those individuals who eat the fish. The fish are assumed to be caught (either commercially or recreationally) and transported to the consumer for consumption. This pathway is one of two aquatic food pathways considered in MEPAS: fin fish and shellfish ingestion. The shellfish ingestion pathway is described in the Subsection 2.9. The following considerations are given to estimating the ingestion exposure to fin fish.

Transport Medium: surface water concentration in the water body producing the fin fish, C_{swi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: loss of pollutants during transport in the surface water body by volatilization

bioaccumulation of pollutant in edible fish tissue from the water

loss of pollutants following catching, prior to consumption by individuals

Exposure Factors: rate of fin fish ingestion and duration of ingestion.

The loss of pollutants during transport in the surface water body is evaluated using Equation (3). The concentration in edible fish parts is estimated using bioaccumulation factors for the pollutant of interest. At the time of consumption by humans, the concentration in fish is given as follows:

$$C_{ffi} = C_{swi}\, B_{fi}\, e^{-\lambda_{gi}\, TH_{ff}} \tag{64}$$

where

C_{ffi} = concentration of pollutant i in fin fish at time of consumption by humans (mg/kg or pCi/kg)

C_{swi} = concentration of pollutant i in surface water in which fin fish are grown, corrected for losses in transit through the surface water system (mg/L or pCi/L)

B_{fi} = bioaccumulation factor for pollutant i in fin fish (mg/kg edible fish per mg/L water, or pCi/kg edible fish per pCi/L water)

λ_{gi} = rate constant for loss and decay within confined water systems used here to represent losses inside fish meat (d^{-1})

TH_{ff} = holdup time between catching and consumption of fin fish (d).

The average daily dose from ingestion of fin fish is estimated as follows for chemical pollutants:

$$D_{ffi} = U_{ff}\, C_{ffi}\, \frac{F_{ff}\, ED_{ff}}{AT_{ffi}\, BW_{ff}} \tag{65}$$

where

D_{ffi} = average daily dose from ingestion of fin fish for chemical pollutant i (mg/kg/d)

U_{ff} = ingestion rate of fin fish by the exposed individual (kg/d)

F_{ff} = fraction of days per year that fish are eaten (dimensionless)

ED_{ff} = exposure duration for the fin fish ingestion pathway (yr)

AT_{ffi} = averaging time for the fin fish ingestion pathway for exposure to pollutant i (yr)

BW_{ff} = body weight of individuals exposed by the fin fish ingestion pathway (kg).

For radionuclides, the total lifetime dose for fin fish ingestion is estimated as follows:

$$D_{ffi} = U_{ff}\, DF_{gi}\, C_{ffi}\, F_{ff}\, ED_{ff}\, 365.25 \tag{66}$$

where

D_{ffi} = total lifetime dose from ingestion of fin fish for radionuclide i (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

2.9 SHELLFISH INGESTION

Shellfish raised and caught in contaminated surface waters provide a potential for human health impacts to those individuals who eat the fish. This aquatic food pathway is treated similarly to the fin fish pathway described in the previous section. This pathway is one of two aquatic food pathways considered in MEPAS: fin fish and shellfish ingestion.

The transport medium, special processes, and exposure considerations are the same as those for the fin fish ingestion pathway as defined in Subsection 2.9, except that the exposure medium is contaminated shellfish.

The loss of pollutants during transport in the surface water body is evaluated using Equation (3). The concentration in edible shellfish parts is estimated using bioaccumulation factors for the pollutant of interest. At the time of consumption by humans, the concentration in shellfish is given as follows:

$$C_{sfi} = C_{swi} \, B_{si} \, e^{-\lambda_{gi} \, TH_{sf}} \tag{67}$$

where

C_{sfi} = concentration of pollutant i in shellfish at time of consumption by humans (mg/kg or pCi/kg)

C_{swi} = concentration of pollutant i in surface water in which shellfish are grown, corrected for losses in transit through the surface water system (mg/L or pCi/L)

B_{si} = bioaccumulation factor for pollutant i in shellfish (mg/kg edible shellfish per mg/L water, or pCi/kg edible shellfish per pCi/L water)

λ_{gi} = rate constant for loss and decay within confined water systems used here to represent losses inside shellfish meat (d^{-1})

TH_{sf} = holdup time between catching and consumption of shellfish (d).

The average daily dose from ingestion of shellfish is estimated as follows, for chemical pollutants:

$$D_{sfi} = U_{sf} \, C_{sfi} \, \frac{F_{sf} \, ED_{sf}}{AT_{sfi} \, BW_{sf}} \tag{68}$$

where

D_{sfi} = average daily dose from ingestion of shellfish for chemical pollutant i (mg/kg/d)

U_{sf} = ingestion rate of shellfish by the exposed individual (kg/d)

F_{sf} = fraction of days per year that shellfish is eaten (dimensionless)

ED_{sf} = exposure duration for the shellfish ingestion pathway (yr)

AT_{sfi} = averaging time for the shellfish ingestion pathway for exposure to pollutant i (yr)

BW_{sf} = body weight of individuals exposed by the shellfish ingestion pathway (kg).

For radionuclides, the total lifetime dose for shellfish ingestion is estimated as follows:

$$D_{sfi} = U_{sf}\ DF_{gi}\ C_{sfi}\ F_{sf}\ ED_{sf}\ 365.25 \qquad (69)$$

where

D_{sfi} = total lifetime dose from ingestion of shellfish for radionuclide i (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

2.10 SWIMMING WATER INGESTION

Individuals may inadvertently ingest small amounts of water while swimming. The following considerations are given to estimating the inadvertent water ingestion exposure to surface water while swimming.

Transport Medium: surface water concentration in the water body used for swimming, C_{swi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: loss of pollutants during transport in the surface water body by volatilization

Exposure Factors: swimming frequency, time, and inadvertent ingestion rate.

The loss of pollutants during transport in the surface water body is evaluated using Equation (3). The swimming frequency and time period of each swimming event determine the average time spent swimming per day. The average daily dose for chemical pollutants from the swimming water ingestion exposure pathway is evaluated as follows:

$$D_{wwi} = C_{swi}\ TE_w\ FE_{sw}\ U_{ww}\ \frac{F_{ww}\ ED_{ww}}{AT_{wwi}\ BW_{ww}} \qquad (70)$$

2.41

where

D_{wwi} = average daily dose from pollutant i from inadvertent ingestion of water while swimming (mg/kg/d)

C_{swi} = surface water concentration of pollutant i at the location of swimming (mg/L)

TE_w = duration of an average swimming event (hours/event)

FE_{sw} = average frequency of swimming events (events/d)

U_{ww} = rate of inadvertent ingestion of water while swimming (L/h).

F_{ww} = fraction of days per year that swimming occurs (dimensionless)

ED_{ww} = exposure duration for the swimming water ingestion pathway (yr)

AT_{wwi} = averaging time for the swimming water ingestion pathway for exposure to pollutant i (yr)

BW_{ww} = body weight of individuals exposed by the swimming water ingestion pathway (kg).

The fraction of days per year that swimming occurs (F_{ww}) will normally be set to a value of 1.0, with the average frequency of swimming events (FE_{sw}) set to represent the times a person swims per year. For example, if swimming occurs 7 times per year, the average frequency of swimming events is 7/365, and the fraction of days per year that swimming activities could occur is 1.0 (all year). If the scenario is to represent just the summer months (such as for a transient recreational population), then the fraction of days per year could be set to 0.25 (one quarter of a year). Use of the two parameters must be coordinated. Because both parameters are used as multiplicative factors, either parameter can be used to represent the exposure situation. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years. The total lifetime dose for radionuclide pollutants from the swimming water ingestion exposure pathway is evaluated as follows:

$$D_{wwi} = C_{swi}\ DF_{gi}\ TE_w\ FE_{sw}\ U_{ww}\ F_{ww}\ ED_{ww}\ 36 \qquad (71)$$

where

D_{wwi} = total lifetime dose from radionuclide pollutant i from inadvertent ingestion of water while swimming (rem)

C_{swi} = surface water concentration of pollutant i at the location

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

2.11 SWIMMING DERMAL CONTACT

Individuals swimming will be exposed to contaminated water via the dermal absorption pathway from contact with water. The following considerations are given to estimate the dermal contact exposure to surface water while swimming.

Transport Medium: surface water concentration in the water body used for swimming, C_{swi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: loss of pollutants during transport in the surface water body by volatilization or decay

absorption through the skin during a swimming event

Exposure Factors: area of skin exposed, swimming frequency, swimming event time, and exposure duration.

The loss of pollutants during transport in the surface water body is evaluated using Equation (3). The swimming frequency and time period of each swimming event determine the average time spent swimming per day. The swimming event time and absorption parameters for each pollutant are used to estimate the amount of a pollutant absorbed through the skin during each swimming event. This calculation is performed using the same dermal absorption model described for the shower dermal absorption exposure pathway in Subsection 2.2.

For inorganic chemicals and radionuclides, the intake per swimming event per unit area of skin contacted is evaluated as follows:

$$I_{swi} = 10^{-3} C_{swi} K_{pi} TE_w \qquad (72)$$

where

I_{swi} = amount of pollutant absorbed through the skin during one swimming event per unit area of skin contacted (mg/cm^2/event or pCi/cm^2/event)

10^{-3} = units conversion factor (L/cm^3)

C_{swi} = concentration of pollutant i in surface water at the swimming location (mg/L or pCi/L)

K_{pi} = skin absorption permeability constant for pollutant i (cm/h)

TE_w = duration of one swimming event (h).

For organic pollutants, the absorption per event is evaluated using the six-step process described in Subsection 2.2 by Equations (5) through (12). These equations give the amount of a pollutant absorbed per unit area of skin contacted during one swimming event of duration TE_w. In performing the evaluation for swimming exposures, the swimming event time is used in place of the showering event time, TE_s.

The average daily dose from chemical pollutants for the swimming dermal contact exposure pathway is evaluated as follows, with correction for the gastrointestinal tract absorption fraction:

$$D_{wdi} = I_{wdi} \, A_{wd} \, FE_{sw} \frac{F_{wd} \, ED_{wd}}{\left(AT_{wdi} \, BW_{wd} \, f_{1i}\right)} \tag{73}$$

where

D_{wdi} = average daily dose from chemical pollutants via dermal absorption from water contact while swimming, equivalent to oral intake (mg/kg/d)

I_{wdi} = dose absorbed per unit area of skin contacted per swimming event (mg/cm^2/event)

A_{wd} = area of skin exposed to contaminated water while swimming (cm^2)

FE_{sw} = frequency of swimming events (events/day)

F_{wd} = fraction of days per year that swimming occurs (dimensionless)

ED_{wd} = exposure duration for the swimming dermal contact exposure pathway (yr)

AT_{wdi} = averaging time for swimming dermal contact for pollutant i (yr)

BW_{wd} = body weight of exposed individual for the swimming dermal contact pathway (kg)

f_{1i} = fraction of pollutant i absorbed in passing through the GI tract following ingestion (dimensionless).

The average daily dose as computed by Equation (73) is equivalent to oral exposure because the GI absorption correction has been applied. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years. The equation is used for all pollutants except radionuclides. For radionuclides, the GI absorption fraction and body weight are not applied because radionuclide specific dose conversion factors for dermal intake are provided in the chemical database for the 70-kg reference man. The equation for radionuclides is as follows:

$$D_{wdi} = I_{wdi}\ A_{wd}\ FE_{sw}\ DF_{di}\ F_{wd}\ ED_{wd}\ 365.25 \qquad (74)$$

where

D_{wdi} = total lifetime dose from radionuclide pollutants via dermal absorption from water contact while swimming (rem)

I_{wdi} = dose absorbed per unit area of skin contacted per swimming event (pCi/cm^2/event)

DF_{di} = dose conversion factor for dermal absorption of radionuclide i (rem/pCi)

and other terms are as previously defined.

2.12 SHORELINE DERMAL CONTACT

This pathway involves contact with contaminated sediments during shoreline recreational activities. Contaminants in surface water are transferred to shoreline sediments over a period of time. The pollutants in sediment may result in exposure by dermal contact with sediments, inadvertent ingestion of sediments (discussed in Subsection 2.13), and external exposure to radionuclides in sediments (discussed in Subsection 2.22). The analysis for these exposure pathways begins with the pollutant concentration in surface water at the location of the shoreline being used for recreational activities. For the dermal contact with sediment exposure pathway, the following considerations are given to the exposure evaluation.

Transport Medium: surface water concentration in the water at the shoreline location, C_{swi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: loss of pollutants during transport in the surface water body by volatilization or decay

transfer of pollutant from water to shoreline sediment

accumulation of pollutant in sediment over time

contact of individuals with shoreline sediment

absorption through the skin

Exposure Factors: area of skin exposed, shoreline event frequency, and exposure duration.

The loss of pollutants during transport in the surface water body is evaluated using Equation (3). The transfer and accumulation of pollutants in sediments is estimated from the model developed by (Soldat et al. 1974) relating water concentration to shoreline sediment concentration following a long period of deposition. The pollutant concentration in sediment is given by the expression below. The equation provides an effective surface contamination (pCi/m^2) for use in calculating gamma exposure rates from radionuclides to persons standing on sediment. This surface contamination rate can be converted to a sediment concentration for use in calculating dermal exposure and ingestion exposure for chemical and radionuclide pollutants. The sediment surface contamination level is estimated as follows:

$$CS_i = 100 \ln(2)\, C_{swi} \frac{1 - e^{-\lambda_{si} \frac{TE_l\, 369.25}{2}}}{\lambda_{si}} \tag{75}$$

where

- CS_i = surface concentration of pollutant i in shoreline sediment (mg/m^2 or pCi/m^2)
- 100 = empirical constant for transfer of pollutants from water to sediment (L/m^2/d).
- C_{swi} = concentration of pollutant i in surface water at the location of the shoreline (mg/L or pCi/L)
- λ_{si} = loss or decay rate constant for pollutant i in surface waters (d^{-1})
- TE_l = period over which shoreline sediment has accumulated (yr).

The value of the transfer constant was derived for several radionuclides by using data obtained from an analysis of water and sediment samples taken from the Columbia River at Richland, Washington, and at Tillamook Bay, Oregon, 75 km south of the river mouth (Nelson 1965; Toombs and Cutler 1968).

The surface sediment concentration can be converted to a sediment mass concentration using the sediment density and an assumed sediment thickness, as follows:

$$C_{ssi} = \frac{CS_i\, 10^{-6}\, 10^3}{t_{ss}\, \rho_{ss}} \tag{76}$$

where

- C_{ssi} = shoreline sediment concentration for pollutant i at the location of recreational shoreline use (mg/kg or pCi/kg)

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

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

t_{ss} = thickness of shoreline sediments (m)

ρ_{ss} = density of shoreline sediments (g/cm^3)

and CS_i is as previously defined.

The intake of pollutants from dermal contact with sediments is estimated using a soil adherence factor (mg/cm^2) and a total absorption fraction per contact event. The average daily dose of chemical pollutants is estimated, as follows:

$$D_{hdi} = 10^{-6} \, C_{ssi} \, FE_{sl} \, AD \, A_{hd} \, AB_{di} \, \frac{F_{hd}}{AT_{hdi}} \quad (77)$$

where

D_{hdi} = average daily dose for chemical pollutant i from dermal contact with shoreline sediment (mg/kg/d)

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

FE_{sl} = shoreline contact event frequency (events/d)

AD = adhesion factor for contact with soil or sediment (mg/cm^2 skin)

A_{hd} = area of skin contacted by sediment (cm^2/event)

AB_{di} = fraction of pollutant i on skin that is absorbed into the body during one soil or sediment contact event (dimensionless)

F_{hd} = fraction of days per year that shoreline exposure occurs (dimensionless)

ED_{hd} = exposure duration for the shoreline sediment dermal contact pathway (yr)

AT_{hdi} = averaging time for pollutant i for the shoreline sediment dermal contact pathway (yr)

BW_{hd} = body weight of exposed individual for the shoreline sediment dermal contact pathway (kg)

f_{1i} = fraction of ingested pollutant absorbed by the gut from ingestion intake (dimensionless).

The total lifetime dose from radionuclide pollutants is estimated as follows:

$$D_{hdi} = 10^{-6}\ C_{ssi}\ FE_{sl}\ AD\ A_{hd}\ AB_{di}\ DF_{di}\ F_{l} \qquad (78)$$

where

D_{hdi} = total lifetime dose for radionuclide pollutant i from dermal contact with shoreline sediment (rem)

DF_{di} = dose conversion factor for radionuclide i for the dermal absorption intake route (rem/pCi intake)

and other terms are as previously defined.

2.13 SHORELINE SEDIMENT INGESTION

Individuals may inadvertently ingest sediments while involved in shoreline recreational activities. This pathway is based on the shoreline sediment concentration, as defined in Subsection 2.12, and is similar to the soil ingestion pathway (described in Subsection 2.14). For the shoreline sediment ingestion pathway, the following considerations are given to the exposure evaluation.

Transport Medium: surface water concentration in the water at the shoreline location, C_{swi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: loss of pollutants during transport in the surface water body by volatilization

transfer of pollutant from water to shoreline sediment

accumulation of pollutant in sediment over time

contact of individuals with shoreline sediment

Exposure Factors: ingestion rate of sediments, shoreline event frequency, and exposure duration.

The loss of pollutants during transport in the surface water body is evaluated using Equation (3). The transfer and accumulation of pollutants in sediments is estimated using the same model described in Subsection 2.12. The concentration to which individuals are exposed is evaluated using Equations (68) and (69). This concentration is used to estimate the average daily dose to chemical pollutants as follows:

$$D_{hsi} = 10^{-3}\ C_{ssi}\ FE_{sl}\ TE_{l}\ U_{hs}\ \frac{F_{hs}\ ED_{hs}}{AT_{hsi}\ BW_{hs}} \qquad (79)$$

where

D_{hsi} = average daily dose for chemical pollutant i from ingestion of shoreline sediment (mg/kg/d)

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

C_{ssi} = shoreline sediment concentration for pollutant i at the location of recreational shoreline use (mg/kg or pCi/kg)

FE_{sl} = shoreline use event frequency (events/d)

TE_l = length of each shoreline exposure event (h/event)

U_{hs} = ingestion rate for shoreline sediment (g/h)

F_{hs} = fraction of days per year that shoreline sediment ingestion occurs (dimensionless)

ED_{hs} = exposure duration for the shoreline sediment ingestion pathway (yr)

AT_{hsi} = averaging time for pollutant i for the shoreline sediment ingestion pathway (yr)

BW_{hs} = body weight of exposed individual for the shoreline sediment ingestion pathway (kg).

The total lifetime dose to radionuclide pollutants from inadvertent ingestion of shoreline sediments is estimated as follows:

$$D_{hsi} = 10^{-3} C_{ssi} FE_{sl} TE_l F_{hs} U_{hs} DF_{gi} E[\qquad (80)$$

where

D_{hsi} = total lifetime dose for radionuclide pollutant i from ingestion of shoreline sediment (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

2.14 SOIL INGESTION

During normal daily activities, individuals ingest small amounts of soil from such sources as outdoor soil and indoor house dust (derived from outdoor soil). In MEPAS, there are two situations in which soil ingestion is evaluated: deposition following atmospheric transport and cases for which measured soil concentrations are available. The shoreline sediment ingestion pathway is treated separately from the soil ingestion pathway.

The considerations given to estimation of the soil ingestion dose from atmospheric transport and deposition are as follows.

Transport Medium: soil concentration at the location of the exposed individual, C_{asi}, pCi/m^2 or mg/m^2, expressed as an annual deposition accumulation value

Special Process: accumulation of pollutants in soil over the exposure duration for the soil ingestion pathway

Exposure Factors: ingestion rate of soil, event frequency, and exposure duration.

The soil concentration is provided from the transport analysis as an average annual deposition amount, averaged over a 70-year exposure period. The accumulation of pollutants in soil over a multiple-year exposure duration is estimated using the deposition and accumulation Equations (19) and (20) given in Subsection 2.4. The average daily dose for chemical pollutants from soil ingestion is evaluated as follows for the atmospheric transport and deposition pathway:

$$D_{dsi} = 10^{-6}\ SAF_i\ U_{ds}\ F_{ds} \left[\frac{DP_{si}}{t_{dd}\ \rho_{dd}}\right]\left[\frac{ED}{AT_{dsi}}\right] \qquad (81)$$

where

D_{dsi} = average daily dose for chemical pollutant i from ingestion of soil (mg/kg/d)

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

SAF_i = soil deposition and accumulation factor for the soil ingestion pathway exposure duration (d)

U_{ds} = ingestion rate for soil (g/d)

F_{ds} = fraction of days per year that soil ingestion occurs (dimensionless)

DP_{si} = annual average deposition rate to soil for pollutant i (mg/m^2/d)

t_{dd} = thickness of soil layer that deposited pollutant is uniformly distributed within (m)

ρ_{dd} = density of soil deposited pollutant is distributed within (g/cm^3)

ED_{ds} = exposure duration for the soil ingestion pathway (yr)

AT_{dsi} = averaging time for pollutant i for the soil ingestion pathway (yr)

BW_{ds} = body weight of exposed individual for the soil ingestion pathway (kg).

For radionuclide pollutants, the total lifetime dose is evaluated as follows:

$$D_{dsi} = 10^{-6}\ SAF_i\ U_{ds}\ DF_{gi}\ F_{ds} \left[\frac{DP_{si}}{t_{dd}\ \rho_{dd}} \right] E \tag{82}$$

where

D_{dsi} = total lifetime dose for radionuclide pollutant i from ingestion of soil (rem)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

DP_{si} = annual average deposition rate of pollutant i to soil from atmospheric transport and deposition (pCi/m^2/d)

and other terms are as previously defined.

When measured soil concentrations are defined by the user, the exposed individuals are assumed to ingest the soil directly without special processes being applied to the concentrations provided, except for losses according to the environmental half time for soil and radioactive decay. The average soil concentration during the exposure period is evaluated using Equation (32). The average daily dose from inadvertent soil ingestion for the measured soil pathway is evaluated as follows for chemical pollutants:

$$D_{dsi} = 10^{-3}\ U_{ds}\ SMF_i\ F_{ds} \left[\frac{1 - e^{-\lambda_{di}\ ED_{ds}}}{\lambda_{di}\ AT_{dsi}\ BW_{ds}} \right. \tag{83}$$

where

D_{dsi} = average daily dose for chemical pollutant i from ingestion of soil (mg/kg/d)

U_{ds} = ingestion rate for soil (g/d)

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

SMF_i = average soil concentration for pollutant i (mg/kg)

F_{ds} = fraction of days per year that soil ingestion occurs (dimensionless)

λ_{di} = environmental loss rate constant for surface soil for pollutant i (d^{-1})

ED_{ds} = exposure duration for the soil ingestion pathway (yr)

AT_{dsi} = averaging time for pollutant i for the soil ingestion pathway (yr)

BW_{ds} = body weight of exposed individual for the soil ingestion pathway (kg).

For radionuclide pollutants, the total lifetime dose is evaluated as follows:

$$D_{dsi} = 10^{-3} \; U_{ds} \; SMF_i \; DF_{gi} \; F_{ds} \; \frac{1 - e^{-\lambda_{di} \, ED}}{\lambda_{di}} \tag{84}$$

where

D_{dsi} = total lifetime dose for radionuclide pollutant i from ingestion of soil (rem)

SMF_i = average soil concentration for pollutant i (pCi/kg)

and other terms are as previously defined.

2.15 SOIL DERMAL CONTACT

Normal daily activities generally involve contact with small amounts of soil from which dermal contact and absorption may occur. This pathway is considered for the atmospheric deposition to soil transport pathway and the user- defined measured soil concentration pathway.

The considerations given to estimation of the exposure from contact with soil from atmospheric transport and deposition are as follows.

Transport Medium: soil concentration at the location of the exposed individual, C_{asi}, pCi/m^2 or mg/m^2, expressed as an annual deposition accumulation value

Special Process: accumulation of pollutants in soil over the exposure duration for the soil dermal contact pathway

transfer of contaminated soil particles onto skin of the exposed individual

transfer of contaminant through skin

Exposure Factors: soil contact event frequency and exposure duration.

The soil concentration is provided from the transport analysis as an average annual deposition amount averaged over a 70-year exposure period. The accumulation of pollutants in soil over a multi-year exposure duration is estimated using the deposition and accumulation Equations (19) and (20) given in Subsection 1.2.4. The amount transferred to skin is estimated using a soil adherence factor (as for the shoreline sediment dermal contact pathway) and the area of skin contaminated. This transfer through skin is estimated using a pollutant specific total absorption fraction applicable to each soil contact event.

The average daily dose for chemical pollutants from soil dermal contact is evaluated as follows for the atmospheric transport and deposition pathway:

$$D_{ddi} = 10^{-6}\ 10^{-3}\ SAF_i \left[\frac{F_{dd}\ FE_{dd}\ AD\ A_{dd}\ AB_{di}}{f_{1i}}\right]\left[\frac{DP}{t_{dd}}\right] \qquad (85)$$

where

D_{ddi} = average daily dose for chemical pollutant i from dermal contact with soil, equivalent to ingestion intake (mg/kg/d)

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

10^{-3} = units conversion factor (g/mg)

SAF_i = soil deposition and accumulation factor for the soil ingestion pathway exposure duration (d)

F_{dd} = fraction of days per year that soil dermal contact occurs (dimensionless)

FE_{dd} = soil contact event frequency (events/d)

AD = adherence factor for contact with soil or sediment (mg/cm^2 skin)

A_{dd} = area of skin contacted by soil (cm^2)

AB_{di} = fraction of pollutant i on skin that is absorbed into the body during one soil or sediment contact event (fraction/event)

f_{1i} = fraction of pollutant i absorbed in passing through the GI tract following ingestion (mg absorbed/mg ingested)

DP_{si} = average annual deposition rate to soil for pollutant i ($mg/m^2/d$)

t_{dd} = thickness of soil layer that atmospherically deposited pollutant is uniformly distributed within (m)

ρ_{dd} = density of soil that atmospherically deposited pollutant is distributed within (g/cm^3)

ED_{dd} = exposure duration for the soil dermal contact pathway (yr)

AT_{ddi} = averaging time for pollutant i for the soil dermal contact pathway (yr)

BW_{dd} = body weight of exposed individual for the soil dermal contact pathway (kg).

For radionuclide pollutants, the total lifetime dose from soil contact following atmospheric deposition is evaluated as follows:

$$D_{ddi} = 10^{-6}\ 10^{-3}\ SAF_i\ F_{dd}\ FE_{dd}\ AD\ A_{dd}\ AB_{di}\ DF_{di} \Big[\qquad (86)$$

where

D_{ddi} = total lifetime dose for radionuclide pollutant i from soil dermal contact (rem)

DF_{di} = dose conversion factor for dermal absorption of radionuclide i (rem/pCi absorbed)

DP_{si} = annual average deposition rate to soil for radionuclide pollutant i (pCi/m^2/d).

and other terms are as previously defined.

When measured soil concentrations are defined by the user, the exposed individuals are assumed to be exposed directly to the soil with the average soil concentrations evaluated using Equation (32). The average daily dose from dermal contact with soil for the measured soil pathway is evaluated as follows for chemical pollutants:

$$D_{ddi} = 10^{-6}\ SMF_i \left[\frac{F_{dd}\ FE_{dd}\ AD\ A_{dd}\ AB_{di}}{f_{1i}} \right] \left[\frac{1 - e^{-}}{\lambda_{di}\ AT_{ddi}} \right] \qquad (87)$$

where

D_{ddi} = average daily dose for chemical pollutant i from dermal contact with soil (mg/kg/d)

SMF_i = average soil concentration for pollutant i (mg/kg).

and other terms are as previously defined. The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radionuclide pollutants, the total lifetime dose from dermal contact with measured soil is evaluated as follows:

$$D_{ddi} = 10^{-6}\ SMF_i\ F_{dd}\ FE_{dd}\ AD\ A_{dd}\ AB_{di}\ DF_{gi}\ \frac{1 - e^{-\lambda}}{} \qquad (88)$$

2.54

where

D_{ddi} = total lifetime dose for radionuclide pollutant i from ingestion of soil (rem)

SMF_i = average soil concentration for radionuclide pollutant i (pCi/kg)

and other terms are as previously defined. The average soil concentration is evaluated using Equation (32).

2.16 SPECIAL FOOD INTAKE

When measurements of contaminated food concentrations are available, the dose and health impacts to individuals consuming the foods may be estimated. This pathway involves direct ingestion of foods at the concentration specified. Considerations given to this exposure pathway are as follows.

Transport Medium: measured food concentration at the time of ingestion by the exposed individual, C_{msi}, mg/kg or pCi/kg

Special Process: none (food is ingested directly)

Exposure Factors: food ingestion rate and exposure duration.

There are no special processes applied to modify the given food concentration.

For chemical pollutants, the average daily dose from ingestion of a special food is calculated, as follows:

$$D_{fdi} = C_{mfi}\, U_{fd}\, F_{fd} \left[\frac{ED_{fd}}{AT_{fdi}\, BW_{fd}} \right] \qquad (89)$$

where

D_{fdi} = average daily dose from chemical pollutant i from ingestion of special foods (mg/kg/d)

C_{mfi} = concentration of chemical pollutant i in special food (mg/kg)

U_{fd} = ingestion rate of special food (kg/d)

F_{fd} = fraction of days per year that special food ingestion occurs (dimensionless)

ED_{fd} = exposure duration for the special food ingestion pathway (yr)

AT_{fdi} = averaging time for pollutant i for the special food ingestion pathway (yr)

BW_{fd} = body weight of exposed individual for the special food ingestion pathway (kg).

The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radionuclides, the total lifetime dose from ingestion of special foods is estimated as follows:

$$D_{fdi} = C_{mfi} \, U_{fd} \, DF_{gi} \, F_{fd} \, ED_{fd} \, 365.25 \tag{90}$$

where

D_{fdi} = total lifetime dose from radionuclide i from ingestion of special foods (rem)

C_{mfi} = concentration of radionuclide i in special food (pCi/kg)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

2.17 INDOOR INHALATION OF VOLATILE POLLUTANTS

Indoor uses of domestic water will allow volatile pollutants to escape and cause inhalation exposure. Two models are available in MEPAS for estimating the risk from indoor inhalation of volatile pollutants: the MEPAS shower inhalation model and the USEPA Andelman indoor inhalation model. The MEPAS shower inhalation model is described first, followed by the USEPA Andelman model.

During showering with domestic water, individuals may be exposed to airborne volatile pollutants released from the hot shower water. This exposure pathway is applicable to the groundwater and surface water transport pathways. As for the drinking water pathway, consideration is given to reductions of pollutant concentration during processing in the water supply treatment plant (if present) and in transport through the water distribution system to the exposed individuals. The surface water pathway also includes estimation of losses of volatile chemicals in transport between the point of entry to the surface water and the water-intake plant. The considerations for this exposure pathway are as follows.

Transport Medium: water concentration at water treatment plant, C_{swi} or C_{gwi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: removal of pollutants during water treatment

loss of pollutants (environmental degradation or radioactive decay) during transport from the treatment plant to the exposure location (households)

loss of pollutants during transport in the surface water body by volatilization

volatilization of pollutants from the hot shower water to the air inside the shower

Exposure Factors: inhalation rate, shower duration, shower frequency, and exposure duration.

The pollutant concentration reaching the home in domestic water for shower use is calculated as for the drinking water pathway described in Subsection 1.2.1. The water concentration is used to estimate the shower air concentration. Because showering represents a system that promotes release of volatile chemicals from the water (i.e., high turbulence, high surface area, and small droplets), the concentration of the contaminant in the shower air is assumed to be in equilibrium with the concentration in the water. The concentration in shower air can be estimated using Henry's law constant (Lyman et al. 1982) as follows:

$$C_{sai} = 10^3 \, C_{dwi} \, TF_i \, e^{-\lambda_{gi} \, TH_{dw}} \left[\frac{H_i}{R \, T} \right] \tag{91}$$

where

C_{sai} = concentration of pollutant i in shower air (mg/m^3 or pCi/m^3)

10^3 = units conversion factor (L/m^3)

C_{dwi} = concentration of pollutant i at the pumping station or well for domestic water supply (mg/L or pCi/L)

TF_i = water treatment purification factor giving the fraction of pollutant, i, remaining after treatment (dimensionless)

λ_{gi} = environmental degradation and decay rate constant for closed water system (d^{-1})

TH_{dw} = holdup time in transfer of water from the pumping station or well to the consumer (d)

H_i = Henry's law constant (m^3 atm/g-mole)

R = gas law constant (m^3 atm/g-mole K°)

T = average absolute water temperature in the shower (degrees Kelvin).

Equation (91) will predict relatively high air concentrations for highly volatile contaminants; therefore, a mass balance must be performed to ensure that the amount of contaminant predicted to be in the shower air is not greater than the total amount in the shower water. The mass balance can be represented as

$$C_{sai} \, V_a \leq C_{dwi} \, V_w \tag{92}$$

where

V_a = volume of air in the shower stall (m^3)

V_w = volume of water used during the shower (L)

and other terms are as previously defined. Nominal volumes of 2 m^3 and 190 L (about 50 gal) are assumed for the air and water volumes, respectively. By using these values in Equation (91), and solving for the Henry's law constant, the maximum allowable Henry's law constant is found to be 2.4 x 10^{-3} m^3-atm/ g-mole. The value of the Henry's law constant is therefore limited to a maximum value of 2.4 x 10^3 in application of Equation (90). The air concentration is used to estimate the average daily dose for the shower inhalation pathway for groundwater transport for chemical pollutants, as follows:

$$D_{sii} = C_{sai} \left[\frac{U_{si}\, F_{si}\, FE_{sh}\, TE_s}{24} \right] \left[\frac{ED_{si}}{BW_{si}\, AT_{si}} \right] \qquad (93)$$

where

D_{sii} = average daily inhalation dose from chemical pollutant i for the shower inhalation pathway (mg/kg/d)

U_{si} = inhalation rate while showering (m^3/d)

F_{si} = fraction of days per year that showering occurs (dimensionless)

FE_{sh} = average frequency of showering events (events/d)

TE_s = average duration of each showering event (h/event)

24 = units conversion factor (h/d)

ED_{si} = exposure duration for the shower inhalation pathway (yr)

BW_{si} = body weight of individuals exposed via the shower inhalation pathway (kg).

AT_{sii} = averaging time for shower inhalation exposure to pollutant i (yr).

The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radionuclide pollutants, the total lifetime dose is evaluated as follows using the dose conversion factor to convert from intake to dose (rem).

$$D_{sii} = C_{sai} \frac{F_{si} U_{si} FE_{sh} TE_s}{24} DF_{hi} ED_{si} 36 \qquad (94)$$

where

D_{sii} = total lifetime ingestion dose from radionuclide i for the shower inhalation pathway (rem)

DF_{hi} = dose conversion factor for inhalation of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

The second model available for estimation of exposure from indoor inhalation of volatile pollutants is the USEPA model (USEPA 1991) based on work by Andelman (1990). This model uses a factor applied to the water concentration to estimate the average indoor air concentration of the volatile pollutant. The considerations for this exposure pathway are as follows.

Transport Medium: water concentration at water treatment plant, C_{swi} or C_{gwi}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: removal of pollutants during water treatment

loss of pollutants (environmental degradation or radioactive decay) during transport from the treatment plant to the exposure location (households)

loss of pollutants during transport in the surface water body by volatilization

volatilization of pollutants from the hot shower water to the indoor air, circulated throughout the house

Exposure Factors: inhalation rate.

The pollutant concentration reaching the home in domestic water for indoor inhalation is calculated as for the drinking water pathway described in Subsection 2.1. The concentration in indoor air is estimated using a volatilization factor applied to the water concentration, as suggested by Andelman (1990). The factor is set to zero for pollutants for which the following conditions are not met:

Henry's Law Constant $>10^{-5}$ atm-m^3/mole

and

molecular weight <200 g/mole

When these conditions are met, the factor is set as described in Subsection 5.19.

$$C_{iai} = C_{dwi} \ TF_i \ e^{(-\lambda_{gi} TH_{dw})} \ K_c \tag{95}$$

The daily intake rate is evaluated from the air concentration in the home following volatilization of a pollutant from domestic water. The concentration of chemical pollutants in the air in the home is evaluated as follows.

where

C_{iai} = concentration of pollutant i in indoor air from volatilization from domestic water uses (mg/m^3)

C_{dwi} = concentration of pollutant i at the pumping station or well for domestic water supply (mg/L or pCi/L)

TF_i = water treatment purification factor giving the fraction of pollutant, i, remaining after treatment (dimensionless)

λ_{gi} = environmental degradation and decay rate constant for closed water systems (d^{-1})

TH_{dw} = holdup time in transfer of water from the pumping station or well to the consumer (d)

K_c = Andelman volatilization factor for chemical pollutants (L/m^3).

The average daily dose for chemical pollutants is calculated from the indoor air concentration as follows:

$$D_{iai} = C_{iai} \ U_{ia} \ \frac{F_{ia} \ ED_{ia}}{BW_{ia} \ AT_{iai}} \tag{96}$$

where

D_{iai} = average daily inhalation dose from chemical pollutant i for the indoor air inhalation pathway (mg/kg/d)

C_{iai} = concentration of pollutant i in indoor (mg/m^3)

U_{ia} = indoor inhalation rate (m^3/d)

F_{ia} = fraction of days per year that exposure to indoor air occurs (dimensionless)

ED_{ia} = exposure duration for the shower inhalation pathway (yr)

BW_{ia} = body weight of individuals exposed via the indoor inhalation pathway (kg)

AT_{iai} = averaging time for shower inhalation exposure to pollutant i (yr).

The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radionuclides, the indoor air concentration is evaluated using Equation (95) with the Andelman factor defined for radionuclides as follows:

$$C_{iai} = C_{dwi}\ TF_i\ e^{(-\lambda_{gi} TH_{dw})}\ K_r \tag{97}$$

where

C_{iai} = concentration of radionuclide i in indoor air from volatilization from domestic water uses (pCi/m^3)

K_r = Andelman volatilization factor for radionuclide pollutants (L/m^3)

and other terms are as previously defined.

The Andelman factor for radionuclides is applied to radionuclides that meet the criteria on molecular weight and Henry's Law constant, and for Rn-222. The total lifetime dose from inhalation of indoor air is evaluated as follows:

$$D_{iai} = C_{iai}\ DF_{hi}\ U_{ia}\ F_{ia}\ ED_{ia}\ 365.25 \tag{98}$$

where

D_{iai} = total lifetime inhalation dose from radionuclide i for the indoor air inhalation pathway (rem)

C_{iai} = concentration of radionuclide i in indoor air (pCi/m^3)

and other terms are as previously defined.

2.18 AIR INHALATION

Pollutants released and transported in the atmosphere are subject to inhalation by people in the site region. The atmospheric transport component provides pollutant air concentrations at selected locations throughout the region within 50 miles of the release site. These air concentrations are used to calculate intake via inhalation by individuals and the population.

Transport Medium: air concentration at selected locations in the region about the release site, C_{ari}, pCi/L or mg/L, expressed as a 70-year average value

Special Process: none (the transport component accounts for special processes during downwind transport)

Exposure Factors: inhalation rate and exposure duration.

The air concentration is used to estimate the average daily dose for the air inhalation pathway for atmospheric transport, as follows, for chemical pollutants:

$$D_{aii} = C_{ari}\ U_{ai}\ F_{ai}\ \frac{ED_{ai}}{BW_{ai}\ AT_{aii}} \tag{99}$$

where

D_{aii} = average daily inhalation dose from chemical pollutant i for the air inhalation pathway (mg/kg/d)

C_{ari} = concentration of pollutant i in air at the point of inhalation (mg/m^3)

U_{ai} = inhalation rate (m^3/d)

F_{ai} = fraction of days per year that inhalation exposure occurs (dimensionless)

ED_{ai} = exposure duration for the air inhalation pathway (yr)

BW_{ai} = body weight of individuals exposed via the air inhalation pathway (kg)

AT_{aii} = averaging time for air inhalation exposure to pollutant i (yr).

The averaging time for noncarcinogenic chemicals is set to the exposure duration, and the averaging time for carcinogenic chemicals is fixed at 70 years.

For radionuclide pollutants, the total lifetime dose is evaluated as follows, using the dose conversion factor to convert from intake to dose (rem):

$$D_{aii} = C_{ari}\ U_{ai}\ DF_{hi}\ F_{ai}\ ED_{ai}\ 365.25 \tag{100}$$

where

D_{aii} = total lifetime inhalation dose from radionuclide i for the air inhalation pathway (rem)

C_{ari} = concentration of radionuclide i in air at the point of inhalation (pCi/m^3)

DF_{hi} = dose conversion factor for inhalation of radionuclide i (rem/pCi inhaled)

and other terms are as previously defined.

2.19 INHALATION OF RESUSPENDED SOIL

The atmospheric transport pathway and the measured soil pathways involve material contained in soil. This material may be suspended and inhaled by nearby individuals resulting in inhalation exposure. The atmospheric transport component provides estimates of soil deposition from which the concentration in soil over the exposure period may be estimated. The soil concentration is used as the starting point in the resuspension model to estimate the air concentration to which individuals are exposed.

Transport Medium: soil concentration at the location of the exposed individual, C_{asi}, pCi/m^2 or mg/m^2, expressed as an annual deposition accumulation value

Special Process: accumulation of pollutants in soil over the exposure duration for the soil ingestion pathway

resuspension of pollutants in soil to air

Exposure Factors: ingestion rate of soil, event frequency, and exposure duration.

The soil concentration is provided from the atmospheric transport analysis as an average annual deposition amount averaged over a 70-year exposure period. The accumulation of pollutants in soil over a multiple-year exposure duration is estimated using the deposition and accumulation Equations (19) and (20). The concentration in the air above the contaminated soil is estimated by using the resuspension factor method. This method relates the air concentration to soil concentration by a single factor to represent the average ratio of air concentration to soil concentration.

The average daily dose for chemical pollutants from inhalation of resuspended pollutants following atmospheric transport and deposition is evaluated as follows:

$$D_{dii} = DP_{si}\ SAF_i\ U_{di}\ RF \left[\frac{F_{di}\ ED_{di}}{AT_{dii}\ BW_{di}} \right] \qquad (101)$$

where

D_{dii} = average daily dose for chemical pollutant i from inhalation of resuspended pollutants (mg/kg/d)

DP_{si} = annual average deposition rate pollutant i to soil from atmospheric transport and deposition (mg/m^2/d)

SAF_i = soil deposition and accumulation factor for the soil pathways evaluated for the current exposure duration (d)

U_{di} = inhalation rate of air for the resuspension pathway (m^3/d)

RF = resuspension factor (m^{-1})

F_{di} = fraction of days per year that resuspension inhalation exposure occurs (dimensionless)

ED_{di} = exposure duration for the pollutant resuspension pathway (yr)

AT_{dii} = averaging time for pollutant i for the pollutant resuspension pathway (yr)

BW_{di} = body weight of exposed individual for the pollutant resuspension pathway (kg).

For radionuclide pollutants, the total lifetime dose is evaluated as follows:

$$D_{dii} = DP_{si}\ SAF_i\ U_{di}\ DF_{hi}\ RF\ F_{di}\ ED_{di}\ 36 \qquad (102)$$

where

D_{dii} = total lifetime dose for radionuclide pollutant i from inhalation of resuspended pollutants (rem)

DP_{si} = annual average deposition rate of radionuclide i to soil from atmospheric transport and deposition (pCi/m^2/d)

DF_{hi} = dose conversion factor for inhalation of radionuclide i (rem/pCi ingested)

and other terms are as previously defined.

When the measured soil pathway is used, the soil concentration is expressed per unit mass of soil (rather than per unit area as for the atmospheric transport pathway). The air concentration is evaluated for the measured soil pathway using a mass loading factor that provides the amount of soil airborne. This airborne soil is assumed to have the same pollutant concentration as the measured soil.

Transport Medium: measured soil concentration at selected locations, C_{msi}, pCi/kg or mg/kg, expressed as the amount present at the start of the first 70-year period

Special Process: loss of pollutant from the soil according to the defined soil retention half time

suspension of soil containing the pollutants

Exposure Factors: inhalation rate and exposure duration.

The soil average concentration is evaluated using Equation (32) and is used to estimate the average daily dose for inhalation of suspended pollutants as follows:

$$D_{dii} = SMF_i \; ML \; U_{di} \; F_{di} \left[\frac{1 - e^{-\lambda_{di} \, ED_{di} 365}}{\lambda_{di} \, AT_{dii} \, BW_{di} \, 36} \right] \tag{103}$$

where

D_{dii} = average daily dose for chemical pollutant i from inhalation of suspended pollutants for the measured soil pathway (mg/kg/d)

SMF_i = average soil concentration of pollutant i (mg/kg)

ML = mass loading factor for airborne particulate material (kg/m^3)

U_{di} = inhalation rate of air for the resuspension pathway (m^3/d)

F_{di} = fraction of days in a year that exposure to suspended material occurs (dimensionless)

ED_{di} = exposure duration for the pollutant resuspension pathway (yr)

AT_{dii} = averaging time for pollutant i for the pollutant resuspension pathway (yr)

BW_{di} = body weight of exposed individual for the pollutant resuspension pathway (kg)

λ_{di} = environmental loss rate constant for pollutant i in soil (d^{-1})

365.25 = units conversion factor (d/yr).

For radionuclide pollutants, the total lifetime dose is evaluated as follows:

$$D_{dii} = SMF_i \; DF_{hi} \; ML \; U_{di} \; F_{di} \left[\frac{1 - e^{-\lambda_{di} \, ED_{di}}}{\lambda_{di}} \right] \tag{104}$$

where

D_{dii} = total lifetime dose for radionuclide i from inhalation of suspended pollutants for the measured soil pathway (rem)

SMF_i = average soil concentration over the exposure period for radionuclide pollutant i (pCi/kg)

and other terms are as previously defined.

2.20 SWIMMING EXTERNAL RADIATION

Individuals swimming in water contaminated with radioactive pollutants may receive external radiation exposure. This exposure pathway is applicable to the surface water transport pathway when aquatic recreational activities are specified. As for the drinking water pathway, consideration is given to losses of volatile chemicals in transport between the point of entry to the surface water and the water intake plant.

Transport Medium:	radionuclide concentration in water at the surface water body location for aquatic recreational activities, C_{swi}, pCi/L, expressed as a 70-year average value
Special Process:	loss of pollutants during transport in the surface water body by volatilization
	immersion of the swimmer in water
Exposure Factors:	frequency of swimming exposure and exposure duration.

The total lifetime dose from external exposures to radionuclides while swimming is evaluated as follows:

$$D_{wei} = C_{swi} \, F_{we} \, FE_{sw} \, TE_{w} \, DE_{wi} \, ED_{we} \, 365.2\text{⁵} \qquad (105)$$

where

D_{wei} = total lifetime dose for radionuclide pollutant i from swimming in contaminated surface water (rem)

C_{swi} = concentration of radionuclide i in surface water at the swimming location (pCi/L)

F_{we} = fraction of days per year that swimming occurs (dimensionless)

FE_{sw} = average frequency of swimming events (events/d)

TE_{w} = duration of an average swimming event (h/event)

DE_{wi} = dose conversion factor for immersion in contaminated water for radionuclide i (rem/h per pCi/L)

ED_{we} = exposure duration for the swimming pathway (yr)

and the final term is as previously defined.

2.21 BOATING EXTERNAL RADIATION

Recreational boating on water contaminated with radioactive pollutants may result in external exposure to the occupants of the boat. This exposure is estimated using the same model as for swimming in contaminated water except that the boat occupants are assumed to receive a fraction of the dose compared to the swimmer who is completely immersed in water.

Transport Medium:	water concentration at the surface water body location for aquatic recreational activities, C_{swi}, pCi/L, expressed as a 70-year average value
Special Process:	loss of pollutants during transport in the surface water body by volatilization
	dose rate exposure reduction due to being in a boat relative to immersion while swimming
Exposure Factors:	frequency of boating exposure and exposure duration.

The total lifetime dose from external exposures to radionuclides while boating is evaluated as follows:

$$D_{bei} = C_{swi}\ SB\ F_{be}\ FE_{be}\ TE_b\ DE_{wi}\ ED_{be}\ 36 \tag{106}$$

where

D_{bei} = total lifetime dose for radionuclide pollutant i from boating in contaminated surface water (rem)

C_{swi} = concentration of pollutant i in surface water at the boating location (pCi/L)

DE_{wi} = dose conversion factor for immersion in contaminated water for radionuclide i (rem/h per pCi/L)

SB = shielding factor for boating exposures (dimensionless)

F_{be} = fraction of days per year that boating occurs (dimensionless)

FE_{bt} = average frequency of boating events (events/d)

TE_b = duration of an average boating event (hours/event)

ED_{be} = exposure duration for the boating pathway (yr).

2.22 SHORELINE EXTERNAL RADIATION

Proximity of individuals to shoreline soils contaminated with radioactive surface water sediments may result in external dose. The dose from this pathway is based on the average radionuclide concentration in sediment over the exposure duration for the shoreline activities. Considerations in evaluating this pathway are as follows.

Transport Medium: radionuclide concentration in surface water at the shoreline location, C_{swi}, pCi/L, expressed as a 70-year average value

Special Process: loss of pollutants during transport in the surface water body by volatilization

transfer of pollutant from water to shoreline sediment

accumulation of pollutant in sediment over time

presence of individuals near shoreline sediment

dose rate reduction because shoreline is narrow

Exposure Factors: shoreline event frequency, time per event, and exposure duration.

The loss of pollutants during transport in the surface water body is evaluated using Equation (3). The transfer and accumulation of pollutants in sediments is estimated using the same model describe for dermal contact with shoreline sediments. The concentration to which individuals are exposed is evaluated using Equation (76). This concentration is used to estimate the total lifetime dose to radionuclide pollutants as follows:

$$D_{hei} = CS_i \, F_{he} \, FE_{sl} \, TE_l \, SW \, DE_{gi} \, ED_{he} \, 36 \qquad (107)$$

where

D_{hei} = total lifetime dose for radionuclide pollutant i from external exposure to shoreline sediment (rem)

CS_i = average concentration of radionuclide i in shoreline sediment over the shoreline exposure duration (pCi/m^2)

F_{he} = fraction of days per year that shoreline exposure occurs (dimensionless)

FE_{sl} = shoreline use event frequency (events/d)

TE_l = length of each shoreline exposure event (h/event)

SW = shoreline width factor for the exposure location (dimensionless)

DE_{gi} = dose conversion factor for external exposure to radionuclides on a ground plane for radionuclide i (rem/h per pCi/m^2)

ED_{he} = exposure duration for the shoreline external exposure pathway (yr)

The dose conversion factors are based on exposure to an infinitely large plane source. Because the typical shoreline is better represented by a long narrow source, the shore width factor is included to account for the source being less than infinite.

2.23 SOIL EXTERNAL RADIATION

Soils contaminated with radioactive material provide a potential for external exposure to nearby individuals. Estimates of soil contamination may be available from atmospheric deposition calculations or measurements of soil contamination levels may be known.

The considerations given to estimation of the external radiation dose from exposure to radionuclides in soil from atmospheric transport and deposition are as follows.

Transport Medium: soil concentration at the location of the exposed individual, C_{asi}, pCi/m^2, expressed as an annual deposition accumulation value

Special Process: accumulation of pollutants in soil over the exposure duration for the soil ingestion pathway

Exposure Factors: exposure time to soil, and exposure duration.

As for the other pathways involving deposition of atmospherically transported pollutants, the soil concentration is provided from the transport analysis as an average annual deposition amount averaged over a 70-year exposure period. The accumulation of pollutants in soil over a multiple-year exposure duration is estimated using the deposition and accumulation Equations (19) and (20). The total lifetime dose for radionuclides is evaluated as follows for the atmospheric transport and deposition pathway:

$$D_{dei} = DP_{si}\ SAF_1\ U_{de}\ DE_{gi} \left[SH_h\ FT_h + SH_o \right. \qquad (108)$$

where

D_{dei} = total lifetime dose for radionuclide pollutant i from external exposure to soil (rem)

DP_{si} = annual average deposition rate to soil for pollutant i (pCi/m^2/d)

SAF_i = soil deposition and accumulation factor for the soil external exposure pathway over the exposure period (d)

U_{de} = exposure time to contaminated ground (h/d)

DE_{gi} = dose conversion factor for external exposure to radionuclides on a ground plane for radionuclide i (rem/h per pCi/m^2)

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

FT_h = fraction of time spent inside a home (dimensionless)

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

FT_o = fraction of time spent outside (dimensionless)

F_{de} = fraction of days per year that soil ingestion occurs (dimensionless)

ED_{de} = exposure duration for the external exposure to soil pathway (yr)

and 365.25 is as previously defined.

The considerations given to estimation of the external radiation dose from exposure to radionuclides in soil when measurements of soil radionuclide contamination levels are available are as follows.

Transport Medium: measured soil concentration at the location of the exposed individual, C_{msi}, pCi/kg

Special Process: decay of pollutants over time following the measurement of contamination levels

Exposure Factors: exposure time to soil and exposure duration.

The total lifetime dose from external exposure to radionuclides in soil for the measured soil pathway is evaluated as follows:

$$D_{dei} = 10^{-3}\ 10^{6}\ SMF_i\ t_{ms}\ \rho_{ms}\ U_{de}\ DE_{gi}\ F_{de} \left[\frac{1 - e^{-\lambda}}{} \right. \qquad (109)$$

where

D_{dei} = total lifetime dose for radionuclide pollutant i from external exposure to measured soil levels (rem)

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

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

SMF_i = average measured soil concentration for radionuclide i (pCi/kg)

ρ_{ms} = density of soil at the location of soil measurement (g/cm^3)

t_{ms} = thickness through which contamination is mixed in soil at the location of soil measurement (m)

and other terms are as previously defined. The exponential term with division by λ_{di} represents the time integral of activity over the exposure duration, accounting for radioactive decay during this period.

2.24 AIR EXTERNAL RADIATION

While radioactive pollutants are being transported past individuals, radiation emitted from the plume may cause radiation exposure. This pathway will normally be overshadowed by the inhalation route except when noble gas radionuclides are involved. The exposure for this pathway is estimated using dose conversion factors for material uniformly distributed in air. The considerations given to this exposure pathway are as follows.

Transport Medium: air concentration at selected locations in the region about the release site, C_{ari}, pCi/L, expressed as a 70-year average value

Special Process: none (the transport component accounts for special processes during downwind transport)

Exposure Factors: exposure rate and exposure duration.

The air concentration is used to estimate the total lifetime dose for the air external exposure pathway for atmospheric transport for radionuclides as follows:

$$D_{aei} = C_{ari} \, U_{ae} \, DE_{ai} \, F_{ae} \, ED_{ae} \, 365.25 \tag{110}$$

where

D_{aei} = total lifetime dose for the air external exposure pathway (rem)

C_{ari} = concentration of pollutant i in air at the point of exposure (pCi/m^3)

U_{ae} = exposure rate (h/d)

DE_{ai} = dose conversion factor for external exposure to airborne radionuclide i (rem/h per pCi/m^3)

F_{ae} = fraction of days per year external exposure to air occurs (dimensionless)

ED_{ae} = exposure duration for the air external exposure pathway (yr).

2.25 MEASURED DIRECT RADIATION

When measurements are available to characterize radiation fields where people are expected to reside, an estimate of the health impacts from direct radiation exposure to the fields may be made.

Transport Medium: direct radiation dose rate for radiation transport from source to the exposed individual, rem/yr, expressed as an instantaneous dose rate

Special Process: reduction of dose rate with time according to a user-defined half-time

Exposure Factors: exposure rate and exposure duration.

The total lifetime dose from external exposure to measured radiation fields is evaluated as follows:

$$D_{dr} = DR\ U_{dr}\ F_{dr}\ \frac{1 - e^{-\lambda_{dr}\ ED_{dr}\ 365.25}}{\lambda_{dr}} \qquad (111)$$

where

D_{dr} = total lifetime dose for exposure to the measured direct radiation field (rem)

DR = measured direct radiation dose rate at the exposure location (rem/h)

U_{dr} = daily exposure time to the direct radiation field (h/d)

F_{dr} = fraction of days per year direct radiation occurs (dimensionless)

λ_{dr} = effective rate constant for reduction of the measured direct radiation rate (d^{-1})

ED_{dr} = exposure duration for exposure to the direct radiation field (yr)

and 365.25 is as previously defined.

The user may supply a value for the dose reduction half-time from which the effective rate constant, λ_{dr}, is evaluated. If no value is given for the half-time, the dose rate is assumed to be constant over time.

3.0 HUMAN HEALTH IMPACT MODELS

Human health impacts are estimated from the average daily dose provided by the exposure pathway models. Models used for conversion of the average daily dose to health impacts are described in the following sections. Models are described for impacts from radiation exposure (radionuclides and measured direct radiation), carcinogenic chemicals, and noncarcinogenic chemicals. The first sections describe models for health impact assessments for exposure of an individual or an average member of the population. The last section describes extension of the individual results to estimation of impacts for the entire exposed population.

3.1 RADIATION HEALTH IMPACTS

Health impacts from exposure to radiation and radionuclides are expressed as the risk of developing cancer. This risk may be reported as the lifetime risk of total cancer incidence or as cancer fatalities. Two methods are available to estimate the risk of cancer fatalities: use of health- effects conversion factors and use of USEPA slope factors. These methods are described in the following section.

3.1.1 Lifetime Cancer Risk: Health Effects Conversion Factors

The radiation dose calculated for each of the radionuclide intake and direct radiation exposure pathways are expressed as lifetime dose (rem) from intake or exposure over the exposure duration for the given exposure pathway. The risk of cancer from exposure at the lifetime dose is estimated using health-effects conversion factors. The lifetime fatal cancer risk is estimated as follows:

$$R_{fkki} = HE_f \, D_{kki} \tag{112}$$

where

R_{fkki} = risk of developing fatal cancer from the lifetime exposure for pathway kk and radionuclide i (risk/lifetime)

HE_f = fatal cancer lifetime risk, health-effects conversion factor (risk per rem).

D_{kki} = total lifetime dose as committed effective dose equivalent for pathway kk and radionuclide i (rem).

The lifetime total cancer incidence risk is estimated as follows:

$$R_{tkki} = HE_t \, D_{kki} \qquad (113)$$

where

R_{tkki} = total risk of developing cancer from lifetime exposure for pathway kk and radionuclide i (risk/lifetime)

HE_t = total cancer lifetime risk health effects conversion factor (risk per rem)

and D_{kki} is as previously defined.

3.1.2 Lifetime Cancer Risk: USEPA Slope Factors

The USEPA has developed slope factors (USEPA 1994) for exposure to radionuclides via inhalation, ingestion, and external direct radiation from contamination on a ground plane. This method may be used only to estimate lifetime risk of cancer incidence because the slope factors are specific to total cancer incidence. The slope factors are intended to be used to convert from radionuclide intake expressed as pCi ingested or inhaled to lifetime cancer incidence risk. Factors are also given for exposure to contaminated ground surfaces expressed as risk/yr per pCi/g soil. Slope factors are not given for dermal absorption or external exposure from air submersion or water immersion.

For ingestion exposures, the USEPA slope factors may be applied as follows to the lifetime ingestion radiation doses generated as described in the exposure pathway section:

$$R_{tkki} = D_{kki} \, \frac{SF_{gi}}{DF_{gi}} \qquad (114)$$

where

R_{tkki} = total risk of developing cancer from the lifetime exposure for ingestion pathway kk and radionuclide i (risk/lifetime)

D_{kki} = lifetime committed effective dose equivalent for pathway kk and radionuclide i (rem)

SF_{gi} = cancer incidence lifetime risk ingestion slope factor for radionuclide i (risk per pCi ingested)

DF_{gi} = dose conversion factor for ingestion of radionuclide i (rem/pCi ingested).

For inhalation exposures, the USEPA slope factors may be applied as follows to the lifetime inhalation radiation doses generated as described in the exposure pathways section:

$$R_{tkki} = D_{kki} \frac{SF_{hi}}{DF_{hi}} \tag{115}$$

where

R_{tkki} = total risk of developing cancer from the lifetime exposure for inhalation pathway kk and radionuclide i (risk/lifetime)

D_{kki} = lifetime committed effective dose equivalent for pathway kk and radionuclide i (rem)

SF_{hi} = cancer incidence lifetime risk inhalation slope factor for radionuclide i (risk per pCi inhaled)

DF_{hi} = dose conversion factor for inhalation of radionuclide i (rem/pCi inhaled).

For external exposures to soil, the USEPA external slope factors may be applied as follows to the

$$R_{tkki} = D_{kki} \frac{SF_{si}}{DE_{gi}\ 5.28 \times 10^{-8}} \tag{116}$$

lifetime external radiation dose generated as described in the exposure pathway section.

where

R_{tkki} = total risk of developing cancer from the lifetime exposure for external soil pathway kk and radionuclide i (risk/lifetime)

D_{kki} = lifetime committed effective dose equivalent for external pathway kk and radionuclide i (rem)

SF_{hi} = cancer incidence external slope factor for exposure to contaminated ground (risk/yr per pCi/g soil)

DE_{gi} = dose conversion factor for external exposure to radionuclides on a ground plane for radionuclide i (rem/h per pCi/m^2)

5.28×10^8 = units conversion factor to convert from concentration per unit area to concentration per unit mass and to convert time units (h/yr m^2/g soil).

The units conversion factor is evaluated for an effective soil depth of 4 cm and a soil density of 1.5 g/cm^3.

3.3

The USEPA radiation slope factors have been developed specifically for estimation of lifetime cancer incidental risks. These factors can not be used to obtain a precise estimate of fatal cancer risk. However, an approximate estimate of these risks can be obtained using the radiation dose health- effects conversion factors described in Subsection 3.1.1. The lifetime total cancer fatality risk is estimated, as follows:

$$R_{fkki} = R_{tkki} \frac{HE_f}{HE_t} \tag{117}$$

where

R_{fkki} = risk of developing fatal cancer from lifetime exposure for pathway kk and radionuclide i (risk/lifetime)

R_{tkki} = total risk of developing cancer from lifetime exposure for pathway kk and radionuclide i, evaluated using the USEPA slope factors (risk/lifetime)

HE_t = total cancer lifetime risk health-effects conversion factor (risk per rem)

HE_f = fatal cancer lifetime risk health-effects conversion factor (risk per rem).

3.2 CARCINOGENIC CHEMICAL HEALTH IMPACTS

The lifetime risk of total cancer incidence is estimate using USEPA slope factors for chemical carcinogens for inhalation and ingestion exposure pathways. Dermal exposures are evaluated as equivalent ingestion intakes as described in the sections on dermal absorption pathways. The USEPA slope factors give the lifetime cancer incidence risk per average daily dose. For ingestion exposures, the lifetime cancer incidence risk is evaluated as follows:

$$R_{tkki} = D_{kki} \; SF_{gi} \tag{118}$$

where

R_{tkki} = risk of developing cancer from the lifetime exposure for ingestion pathway kk and chemical pollutant i (risk/lifetime)

D_{kki} = average daily ingestion intake for exposure pathway kk for chemical pollutant i (mg/kg/d)

SF_{gi} = ingestion slope factor for cancer incidence risk for chemical pollutant i (risk per mg/kg/d ingestion intake).

When the risk value estimated using Equation (118) is greater than 0.01, the value must be revised using the following equation, which mathematically limits the maximum risk value to 1.0:

$$R_{tkki} = 1 - e^{-D_{kki}\,SF_{gi}} \qquad (119)$$

where terms are as previously defined.

Inhalation lifetime cancer incidence risk is evaluated similarly, as follows:

$$R_{tkki} = D_{kki}\,SF_{hi} \qquad (120)$$

where

R_{tkki} = risk of developing cancer from the lifetime exposure for inhalation pathway kk and chemical pollutant i (risk/lifetime)

D_{kki} = average daily inhalation intake for exposure pathway kk for chemical pollutant i (mg/kg/d)

SF_{hi} = inhalation slope factor for cancer incidence risk for chemical pollutant i (risk per mg/kg/d inhalation intake).

When the inhalation risk is greater than 0.01, Equation (120) is used to mathematically limit the risk to a maximum value of 1.0, as follows:

$$R_{tkki} = 1 - e^{-D_{kki}\,SF_{hi}} \qquad (121)$$

where terms are as previously defined.

3.3 NONCARCINOGENIC CHEMICAL HEALTH IMPACTS

The health impacts for exposure to noncarcinogenic chemicals are expressed as a hazard quotient. The hazard quotient is the ratio of the average daily dose to the reference dose. The reference dose is defined by the USEPA for many chemicals for ingestion and inhalation intakes (USEPA 1993). The reference dose represents a level that is believed to be safe for members of the general population. Exposure at this level will result in a hazard quotient of 1.0. The hazard quotient for ingestion pathways is evaluated as follows:

$$HQ_{gkki} = \frac{D_{kki}}{RfD_{gi}} \tag{122}$$

where

HQ_{gkki} = hazard quotient for ingestion pathway kk for noncarcinogenic chemical pollutant i (dimensionless)

D_{kki} = average daily dose for ingestion pathway kk for noncarcinogenic chemical pollutant i (mg/kg/d)

RfD_{gi} = ingestion reference dose for noncarcinogenic chemical pollutant i (mg/kg/d).

The hazard quotient for inhalation pathways can be written similarly, as follows:

$$HQ_{hkki} = \frac{D_{kki}}{RfD_{hi}} \tag{123}$$

where

HQ_{hkki} = hazard quotient for inhalation pathway kk for noncarcinogenic chemical pollutant i (dimensionless)

D_{kki} = average daily dose for inhalation pathway kk for noncarcinogenic chemical pollutant i (mg/kg/d)

RfD_{hi} = inhalation reference dose for noncarcinogenic chemical pollutant i (mg/kg/d).

Dermal exposures are treated as equivalent ingestion exposures as described in Subsections 2.2, 2.11, 2.12, and 2.15.

When hazard quotient values are added across exposure pathways or pollutants, the resulting sum is referred to as a hazard index.

3.4 POPULATION HEALTH IMPACTS

Health impacts from exposure to carcinogenic chemicals and radionuclides can be estimated for the entire exposed population. For these pollutants, the population health impacts are assumed to be proportional to the exposure level. This allows a population health impact to be evaluated as the product of the lifetime risk to the average member of the population times the number of people in the population. This calculation can be expressed by the following equations for the two types of cancer risk considered:

$$RP_{fkki} = R_{fkki}\ PE_{kk} \tag{124}$$

where

RP_{fkki} = total fatal cancer risk to the population exposed via pathway kk to pollutant i (fatal cancers)

R_{fkki} = fatal cancer lifetime risk to an average member of the population exposed via pathway kk to pollutant i (fatal cancer risk/lifetime)

PE_{kk} = number of people exposed via exposure pathway kk (people).

$$RP_{tkki} = R_{tkki}\ PE_{kk} \tag{125}$$

where

RP_{tkki} = total cancer incidence risk to the population exposed via pathway kk to pollutant i (cancers)

R_{tkki} = total cancer incidence lifetime risk to an average member of the population exposed via pathway kk to pollutant i (fatal cancer risk/lifetime)

and PE_{kk} is as previously defined.

There are no meaningful measures of health impact to population from exposure to noncarcinogenic chemicals.

4.0 NOMENCLATURE SUMMARY

This section contains information useful to understanding the mathematical notation used for parameters of the exposure pathway and health impact models. The symbols used are presented alphabetically in Table 2 with a brief definition of the parameter and detailed usage of subscripts (if any). For example, the table entry for "C" indicates that C_{gwi} represents the concentration of pollutant i in groundwater at some defined location. The first subscript has 2 letters ("gw" for groundwater) and the second subscript has one letter ("i" for pollutant).

TABLE 4.1. Summary of Nomenclature Used in Exposure Assessment Models

Parameter	Number of Subscripts	Order of Subscripts	Description
A	1		area of skin exposed for specific pathways (cm^2)
		1	exposure activity index (2 letters) dd - soil dermal contact hd - sediment dermal contact sd - showering dermal contact wd - swimming dermal contact
AB_{di}	skin absorption fraction for soil or sediment dermal contact exposure for pollutant i		
AD	adhesion factor for contact with soil or sediment with skin (mg/cm^2 skin)		
AT	2		averaging time for exposure to pollutant i for each pathway (yr)
		1	exposure pathway index (2 letters) ae - air submersion external exposure ai - air inhalation be - boating external exposure dd - soil dermal contact de - soil external exposure di - soil resuspension inhalation dr - direct radiation dose (no pollutant subscript is used when the direct radiation dose is considered) ds - soil inadvertent ingestion dw - drinking water ingestion fd - special food ingestion ff - finfish ingestion sf - shellfish ingestion

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
			he - shoreline external exposure
			hs - shoreline soil inadvertent ingestion
			ia - indoor air inhalation
			lv - leafy vegetable ingestion
			kk - general pathway index
			mk - milk ingestion
			mt - meat ingestion
			ov - other vegetable ingestion
			sd - showering dermal contact
			sf - shellfish ingestion
			si - showering inhalation
			sw - shower water inadvertent ingestion
			wd - swimming dermal contact
			we - swimming external exposure
			ww - swimming water inadvertent ingestion
		2	i - pollutant index
b	intermediate parameter in the USEPA dermal absorption model (dimensionless)		
B	intermediate parameter in the USEPA dermal absorption model (dimensionless)		
B	2		bioaccumulation factors (dimensionless)
		1	food index
			f - water-to-fin fish
			s - water-to-shellfish
			v - soil-to-plant uptake via roots
		2	i - pollutant index
BW	1		body weight of individuals exposed to each exposure pathway (kg)
		1	exposure pathway index (see parameter AT for a complete list of subscript usage for exposure pathways)
c	intermediate parameter in the USEPA dermal absorption model (dimensionless)		
C	2		concentration of a pollutant in a medium
		1	medium index (2 letters)
			ar - air (mg/m^3 or pCi/m^3)
			as - surface soil from atmospheric deposition (mg/m^2 or pCi/m^2)
			dw - domestic water (mg/L or pCi/L)

4.2

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
			ff - finfish (mg/kg or pCi/kg)
			gw - ground water (mg/L or pCi/L)
			lv - leafy vegetables (mg/kg or pCi/kg)
			mf - measured food (mg/kg or pCi/kg)
			ms - measured soil (mg/kg or pCi/kg)
			ov - other vegetables (mg/kg or pCi/kg)
			sa - shower air (mg/m^3 or pCi/m^3)
			sf - shellfish (mg/kg or pCi/kg)
			ss - shoreline sediment (mg/kg or pCi/kg)
			sw - surface water (mg/L or pCi/L)
		2	i - pollutant index
CAD	2		plant concentration at time of harvest from airborne deposition onto plants (mg/kg or pCi/kg)
		1	plant type index (2 letters)
			lv - leafy vegetables
			ov - other vegetables
			ft - meat animal feed crops
			fk - milk animal feed crops
		2	i - pollutant index
CAR	2		plant concentration at time of harvest from root uptake from soil (mg/kg or pCi/kg)
		1	plant type index
			lv - leafy vegetables
			ov - other vegetables
			ft - meat animal feed crops
			fk - milk animal feed crops
		2	i - pollutant index
CWD	2		plant concentration at time of harvest from water deposition onto plants (mg/kg or pCi/kg)
		1	plant type index
			lv - leafy vegetables
			ov - other vegetables
			ft - meat animal feed crops
			fk - milk animal feed crops
		2	i - pollutant index
CWR	2		plant concentration at time of harvest from root uptake from soil (mg/kg or pCi/kg)
		1	plant type index

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
			lv - leafy vegetables
			ov - other vegetables
			ft - meat animal feed crops
			fk - milk animal feed crops
		2	i - pollutant index
D	2		average daily dose (mg/kg/d) or lifetime dose (rem)
		1	exposure pathway index (see parameter AT for a complete list of subscript usage for exposure pathways)
		2	i - pollutant index
DE	2		external dose conversion factors for radionuclides
		1	radiation exposure route index
			a - submersion in air (rem/h per pCi/m^3)
			g - ground plane (rem/h per pCi/m^2)
			w - water immersion (rem/h per pCi/L)
		2	i - radionuclide index
DF	2		internal dose conversion factors for radionuclides
		1	intake route index
			d - dermal (rem/pCi absorbed via skin)
			g - ingestion (rem/pCi ingested)
			h - inhalation (rem/pCi inhaled)
		2	i - radionuclide index
DP	2		deposition rate to crops and ground (mg/m^2/d or pCi/m^2/d)
		1	medium
			a - atmospheric
			s - soil
			w - water
		2	i - pollutant index
DR	measured direct radiation dose rate (rem/h)		
DS_i	diffusion coefficient for skin for pollutant i (cm^2/h)		
ED	1		exposure duration for each exposure pathway (yr)
		1	k - general exposure pathway index

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
			(see parameter AT for a complete list of subscript usage for exposure pathways)
f_{1i}	fraction of material absorbed in passing through the GI tract for pollutant i		
F	1		fraction of days per year that each exposure pathway occurs
		1	exposure pathway index (see parameter AT for a complete list of subscript usage for exposure pathways)
FC	2		fraction of animal feed or water that is contaminated
		1	intake media
			f - feed
			w - water
		2	animal type
			k - milk animal
			t - meat animal
FE	1		event frequency (events/day)
		1	bt - boating
			dd - soil contact
			sh - showers (showers/day)
			sl - shoreline use
			sw - swimming
FI	1		irrigation time fraction
		1	agricultural product index (2 letters)
			lv - leafy vegetables
			mk - milk
			mt - meat
			ov - other vegetables
FM	2		feed-to-animal product transfer factors for each pollutant
		1	animal product index (2 letters)
			mk - milk
			mt - meat
		2	i - pollutant index

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
H_i	Henry's Law Constant for each pollutant, i (atm m^3/mole)		
HE	1		radiation health effects conversion factors (risk per rem)
		1	health impact endpoint type
			f - fatal cancer
			h - hereditary effects
			t - total cancer incidence
HQ	2		hazard quotient for exposure to noncarcinogenic chemicals (dimensionless)
		1	intake route index
			g - ingestion
			h - inhalation
		2	i - pollutant index
HT	2		environmental half times for each pollutant (d)
		1	media index
			a - air
			g - groundwater (or confined water systems)
			s - surface water
			d - soil
		2	i - pollutant index
I	2		dose absorbed per unit area per water contact event (mg/cm^2-event)
		1	water contact event type index
			sh - showering using domestic water
			sw - swimming in surface water
		2	i - pollutant index
K_{ai}	Atmospheric deposition class index by pollutant, i (dimensionless)		
K_i	Volatilization factor for indoor inhalation for pollutant i (L/m^3)		
K_{oci}	Carbon matter partition coefficient for each pollutant, i (ml/g)		
K_{owi}	Octanol-water partition coefficient for each pollutant, i (ml/g)		
K_{pi}	Skin permeability constant for aqueous solutions for each pollutant (cm/h)		

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
l_{sc}	Thickness of skin (stratum corneum), (cm)		
MW_i	Molecular weight (g/mole)		
NT	Integer number of years in the exposure duration for an agricultural production usage location (yr)		
Q	2		animal intake rate of feed or water
		1	intake media f - feed w - water
		2	animal type k - milk animal t - meat animal
r	1		fraction of deposition retained on plant surfaces
		1	plant type index lv - leafy vegetables ov - other vegetables ft - meat animal feed crops fk - milk animal feed crops
R	3		lifetime risk
		1	health impact endpoint type f - fatal cancer h - hereditary effects t - total cancer incidence
		2	exposure pathway index (2 letters) usage is as defined for parameter AT
		3	i - pollutant index
RF	Resuspension factor for inhalation of pollutants deposited onto soil from atmospheric transport (m^{-1})		
RfD	2		chemical reference dose by intake route and pollutant (mg/kg/d)
		1	route index g - ingestion h - inhalation
		2	i - chemical pollutant index
S_i	water solubility for each pollutant, i (mg/L)		

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
SAF_i	soil accumulation factor for prior years deposition for pollutant i (dimensionless)		
SB	boating shielding factor relative to water immersion (dimensionless)		
SF	2		carcinogen slope factor by intake route and pollutant: chemicals risk per (mg/kg/d) dose, radionuclides risk per pCi intake, external risk per ....
		1	route index
			g - ingestion
			h - inhalation
			s - external exposure to surface contamination (radionuclides only)
		2	i - pollutant index
SMF_i	measured soil average concentrations over the exposure duration for pollutant i (mg/kg or pCi/kg)		
SW	shore width factor for external exposure to radionuclides in shoreline sediment (dimensionless)		
t	1		thickness of soil or sediment layer (m)
		1	media index (2 letters)
			dd - atmospheric deposition onto soil
			ms - measured soil
			ss - shoreline
			sl - soil
t^*	time to reach steady state in the USEPA dermal absorption model (h)		
T_{sw}	transit time in a surface water system between the point of entry and a pumping station (d)		
TC	1		crop growing period (d)
		1	plant type index
			lv - leafy vegetables
			ov - other vegetables
			ft - meat animal feed crops
			fk - milk animal feed crops
TE	1		event duration, hours
		1	exposure activities
			b - boating

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
			d - soil (dirt) dermal contact l - shoreline s - showering w - swimming
TF_i	water treatment purification factor giving the fraction of pollutant, i, remaining after treatment (dimensionless)		
TH	1		holdup period in an exposure pathway (d)
		1	dw - domestic water holdup between the pumping station and the consumer ff - harvest to consumer holdup period for the fin fish ingestion pathway fs - harvest to consumer holdup period for the shellfish ingestion pathway lv - harvest to consumer holdup period for the leafy vegetable ingestion pathway ov - harvest to consumer holdup period for the other vegetable ingestion pathway mk - harvest to consumer holdup period for the milk ingestion pathway mt - harvest to consumer holdup period for the meat ingestion pathway
TV	1		translocation factor from plant surfaces to edible parts of the plant (dimensionless)
		1	plant type index (2 letters) lv - leafy vegetables ov - other vegetables ft - meat animal feed crops fk - milk animal feed crops
U	1		intake parameters for each inhalation, ingestion, and some external exposure pathways
		1	ai - air inhalation rate (m^3/d) de - soil external exposure (h/d) di - soil resuspension inhalation rate (m^3/d) dr - direct radiation (h/d) ds - soil inadvertent ingestion rate (g/d) dw - drinking water ingestion rate (L/d) fd - special food ingestion rate (kg/d) ff - finfish ingestion rate (kg/d)

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
			fs - shellfish ingestion rate (kg/d)
			hs - shoreline soil inadvertent ingestion rate (kg/d)
			k - general pathway index
			lv - leafy vegetable ingestion rate (kg/d)
			mk - milk ingestion rate (L/d)
			mt - meat ingestion rate (kg/d)
			ov - other vegetable ingestion rate (kg/d)
			si - showering inhalation rate (m^3/d)
			sw - shower water inadvertent ingestion rate (L/shower)
			ww - swimming water inadvertent ingestion rate (L/h)
Vd_i	Deposition velocity (m/sec)		
VP_i	Vapor pressure (mm Hg)		
Y	1		production yield of plants
		1	plant type index
			lv - leafy vegetables
			ov - other vegetables
			ft - meat animal feed crops
			fk - milk animal feed crops
λ	2		loss rate constant for a pollutant from a medium (d^{-1})
		1	medium index
			a - air
			d - soil exposed to air
			e - effective loss from plant surfaces
			g - groundwater or confined water systems
			s - surface water
		2	i - pollutant index
λ_w	weathering rate constant from plant surfaces (d^{-1})		

4.10

TABLE 4.1. (Cont'd)

Parameter	Number of Subscripts	Order of Subscripts	Description
ρ	1		soil or sediment density
		1	media index
			dd - atmospheric deposition onto soil
			ms - measured soil
			ss - shoreline sediment
			sl - soil
τ	delay time parameter in the USEPA dermal absorption model (h)		

5.0 DEFAULT PARAMETER VALUES

As described in the previous section, the exposure pathway and human health impact calculations rely on numerous parameters and data values. These include exposure pathway parameters, physical properties, agricultural practice parameters, radiation dose factors, chemical toxicity parameters, and others. This section explains the selection of data values used in the current version of MEPAS and provides the default parameter values for those parameters that are not specific to pollutants.

5.1 CHEMICAL DATABASE SUMMARY

Pollutant-specific parameters are provided to the MEPAS software package through a chemical database described in detail by Strenge and Peterson (1989). A summary of the parameters given in the database is presented in Table 5.1 to establish the relationship with the parameters described in Sections 2.0 and 3.0.

TABLE 5.1. Parameters Contained in the Chemical Database for Each Pollutant

Symbol	Units	Default Value	Parameter Description
MW_i	g/mole	None	Molecular weight
VP_i	mm Hg	None	Vapor pressure
H_i	atm m^3/mole	None	Henry's Law Constant
S_i	mg/L	None	Water solubility
K_{owi}	ml/g	None	Octanol-water partition coefficient
K_{oci}	ml/g	None	Carbon matter partition coefficient
K_{pi}	cm/h	0.001	Skin permeability constant for aqueous solutions
HT_{ai}	d	3.7E9	Half-time for the constituent in air
HT_{gw}	d	3.7E9	Half-time for the constituent in ground- water or confined water systems
HT_{sw}	d	3.7E9	Half-time for the constituent in surface water
HT_{sl}	d	3.7E9	Half-time for the constituent in soil
DF_{gi}	rem/pCi	None	Radionuclide ingestion dose factor
DF_{hi}	rem/pCi	None	Radionuclide ingestion dose factor
DF_{di}	rem/pCi	None	Radionuclide dermal absorption dose factor

TABLE 5.1. (Cont'd)

Symbol	Units	Default Value	Parameter Description
DE_{ai}	rem/h per pCi/m^3	None	External radiation dose factor for exposure to activity in air
DE_{gi}	rem/h per pCi/m^2	None	External radiation dose factor for exposure to ground activity
DE_{wi}	rem/h per pCi/L	None	External radiation dose factor for exposure by immersion in water
B_{if}	None	None	Bioaccumulation factor for finfish
B_{is}	None	None	Bioaccumulation factor for shellfish
B_{vi}	None	None	Soil-to-edible plant concentration ratio
FM_{mti}	d/kg	None	Feed-to-animal meat transfer factor
FM_{mki}	d/L	None	Feed-to-cow milk transfer factor
TF_i	None	1.0	Water purification factor, fraction remaining after treatment
V_{di}	m/sec	None	Deposition velocity
K_{ai}	None	None	Atmospheric deposition class
SF_{hi}	$(mg/kg/d)^{-1}$	None	Chemical inhalation slope factor
SF_{hi}	risk per pCi	None	Radionuclide inhalation slope factor
SF_{gi}	$(mg/kg/d)^{-1}$	None	Chemical ingestion slope factor
SF_{gi}	risk per pCi	None	Radionuclides ingestion slope factor
RfD_{hi}	mg/kg/d	None	Chemical inhalation reference dose
SF_{si}	risk/yr per pCi/g	None	Radionuclide external dose slope factor for exposure to surface contamination
RfD_{gi}	mg/kg/d	None	Chemical ingestion reference dose
f_{1i}	None	1.0	GI tract absorption fraction
AB_{di}	None	0.001	Skin absorption fraction for soil exposure for inorganic chemicals and radionuclides
		1.0	Skin absorption fraction for soil exposure for organic chemicals

5.2 EXPOSURE PATHWAY PARAMETERS

The parameters for each exposure pathway are described in the following subsections. Default parameter values are provided for those parameters that are not pollutant specific. For pollutant-specific parameters, see the MEPAS chemical database report (Strenge and Peterson 1989).

For each primary medium of usage, parameters must be defined for the exposed population or individuals. These parameters are exposure duration, body weight, and averaging time. The default values for these parameters are set as used in the original MEPAS formulations (Whelan et al. 1987; Droppo et al. 1989). The values are as defined in Table 5.2.

The exposure duration may be set by the user for each of the usage media (locations) defined. The body weight may also be set; however, a value of 70 kg is always used for radionuclides because the radiation dose conversion factors are base on the standard man parameters (70 kg). The averaging time is not set by the user. For carcinogenic chemicals the averaging time is fixed at 70 years. For noncarcinogenic chemicals, the averaging time is set equal to the exposure duration.

TABLE 5.2. General Exposure Parameter Default Values

Parameter	Definition	Default Value Individual	Default Value Population
ED	Exposure Duration (yr)	70	70
BW	Body Weight (kg)	70	70
AT	Averaging Time (yr)	70	70

5.3 DRINKING WATER INGESTION

The drinking water ingestion pathway requires definition of the water ingestion rate and the holdup time for distribution of water from the well or pumping station to the consumer. Default values for these parameters are given in Table 5.3.

5.4 SHOWER WATER DERMAL CONTACT

Exposure pathways related to showering require definition of the holdup time for distribution of water from the well or pumping station to the consumer, as for the drinking water scenario. These pathways also require definition of the length of a shower and the frequency of showering. Shower dermal water contact also requires an estimate of the surface area of the body contacted with the water, and the thickness of the skin while in contact with water. Default values for these parameters are given in Table 5.4.

TABLE 5.3 Drinking Water Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
U_{dw}	water ingestion rate	L/d	2.0	2.0
F_{dw}	time fraction	-[(a)]	1.0	1.0
TH_{dw}	water system holdup time	d	0.5	0.5

(a) Dash indicates not applicable.

TABLE 5.4. Shower Water Dermal Contact Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
Th_{dw}	water system holdup time	d	0.5	0.5
TE_s	shower event time	h/shower	0.167	0.167
FE_{sh}	shower frequency	shower/d	1.0	1.0
A_{sd}	skin area contacted	cm^2	20,000	20,000
F_{sd}	time fraction	-[(a)]	1.0	1.0
l_{sc}	skin thickness	cm	0.001	0.001

(a) Dash indicates not applicable.

5.5 SHOWERING INADVERTENT INGESTION

This pathway requires the general shower exposure parameters, as defined in the above section, for the shower water dermal contact pathway (holdup time, event time, and frequency), plus the rate at which water is inadvertently ingested while showering. Default values for parameters for this pathway are given in Table 5.5.

The water ingestion rates are set to give a total intake of 0.01 L per shower to be consistent with the initial MEPAS model.

TABLE 5.5. Shower Inadvertent Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
Th_{dw}	water system holdup time	d	0.5	0.5
TE_s	shower event time	h/shower	0.167	0.167
F_{sw}	time fraction	-[(a)]	1.0	1.0
FE_{sh}	shower frequency	shower/d	1.0	1.0
U_{sw}	water ingestion rate	L/h	0.06	0.06

(a) Dash indicates not applicable.

5.6 LEAFY VEGETABLES

The leafy vegetable ingestion pathway is considered for groundwater, surface water, and atmospheric transport pathways. The parameters for the leafy vegetable pathway are given in Table 5.6.

5.7 OTHER VEGETABLES

This exposure pathway is similar to the leafy vegetable ingestion exposure pathway and uses similar parameters. The default parameter values for the other vegetable ingestion pathway are given in Table 5.7.

Note that the areal soil density and the weathering constant values are the same as defined for the leafy vegetable ingestion pathway. One value is defined for each of these parameters, and the value is used for all agricultural product routes.

TABLE 5.6. Leafy Vegetable Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value	
			Individual	Population
P	areal soil density	kg/m^2	240	240
r_{lv}	retention fraction	--[a]	0.25	0.25
TC_{lv}	growing period	d	60	60
TH_{lv}	holdup time	d	2	2
TV_{lv}	translocation factor	--	1.0	1.0
F_{lv}	intake time fraction	--	1.0	1.0
U_{lv}	intake leafy vegetable consumption rate	kg/d	0.021	0.021
Y_{lv}	crop yield	kg/m^2	2.0	2.0
λ_w	weathering constant	d^{-1}	0.0495	0.0495
FI_{lv}	irrigation time fraction	---	1.0	1.0

(a) Dash indicates not applicable.

TABLE 5.7. Other Vegetable Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
P	areal soil density	kg/m^2	240	240
r_{ov}	retention fraction	--[(a)]	0.25	0.25
TC_{ov}	growing period	d	60	60
TH_{ov}	holdup time	d	60	60
TV_{ov}	translocation factor	--	0.1	0.1
F_{ov}	intake time fraction	--	1.0	1.0
U_{ft}	intake other vegetables consumption rate	kg/d	0.13	0.13
Y_{ov}	crop yield	kg/m^2	2.0	2.0
λ_w	weathering constant	d^{-1}	0.0495	0.0495
FI_{ov}	irrigation time fractions	--	1.0	1.0

(a) Dash indicates not applicable.

5.8 MEAT

This exposure pathway involves contamination of animal meat by feeding the animal contaminated crops and/or water. Default parameter values for the meat ingestion pathway are given in Table 5.8.

5.9 MILK

This exposure pathway involves contamination of cow milk by feeding the cows contaminated crops and/or water. Default parameter values for the milk ingestion pathway are given in Table 5.9.

TABLE 5.8. Meat Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
P	areal soil density	kg/m^2	240	240
Q_{ft}	animal feed rate	kg/d	68	68
Q_{wt}	animal water rate	L/d	50	50
r_{ft}	retention fraction	--[a]	0.25	0.25
TC_{ft}	growing period	d	60	60
TH_{ft}	holdup time	d	20.	20
TV_{ft}	translocation factor	--	0.1	0.1
F_{mt}	intake time fraction	--	1.0	1.0
U_{mt}	meat consumption rate	kg/d	0.065	0.065
Y_{ft}	crop yield	kg/m^2	0.7	0.7
FI_{mt}	irrigation time fraction	--	1.0	1.0
λ_w	weathering constant	d^{-1}	0.0495	0.0495

(a) Dash indicates not applicable.

TABLE 5.9. Milk Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
P	areal soil density	kg/m^2	240	240
Q_{fk}	animal feed rate	kg/d	55	55
Q_{wk}	animal water rate	L/d	60	60
r_{fk}	retention fraction	--[a]	0.25	0.25
TC_{fk}	growing period	d	30	30
TH_{fk}	holdup time	d	4	4
TV_{fk}	intake translocation factor	--	1.0	1.0
F_{mk}	intake time fraction	--	1.0	1.0
U_{mk}	milk consumption rate	kg/d	0.075	0.075
Y_{fk}	crop yield	kg/m^2	0.7	0.7
λ_w	weathering constant	d^{-1}	0.0495	0.0495
FI_{mk}	irrigation time fraction	--	1.0	1.0

(a) Dash indicates not applicable.

5.10 FIN FISH

The parameters for the fin fish ingestion pathway are the holdup time between catching and consumption of the fish, and the fin fish ingestion rate by humans. Default values for these parameters are given in Table 5.10.

5.11 SHELLFISH

The parameters for the shellfish ingestion pathway are the holdup time between catching and consumption of the shellfish, and the shellfish ingestion rate by humans. Default values for these parameters are given in Table 5.11.

TABLE 5.10. Fin Fish Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
TH_{ff}	holdup time	d	10	10
F_{ff}	time fraction	--[a]	1.0	1.0
U_{ff}	fin fish ingestion rate	kg/d	0.0065	0.0065

(a) Dash indicates not applicable.

TABLE 5.11. Shellfish Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
TH_{sf}	holdup time	d	10	10
F_{sf}	time fraction	--[a]	1.0	1.0
U_{sf}	fin fish ingestion rate	kg/d	0.0027	0.0027

(a) Dash indicates not applicable.

5.12 SWIMMING WATER INGESTION

The exposure pathways involving swimming all require definition of the duration of a swimming event and the frequency of swimming. Other parameters are required for specific swimming pathways. For inadvertent ingestion of water while swimming the default parameter values are given in Table 5.12.

Note that the product of swimming event time and swimming frequency is equal to an average daily swimming time of 0.033 hours, consistent with the initial MEPAS daily swimming time.

5.13 SWIMMING DERMAL CONTACT

The swimming dermal contact exposure pathway is based on the same dermal exposure model used for the shower dermal contact exposure pathway. Default parameter values for the swimming dermal contact exposure pathway are given in Table 5.13.

Note that the product of swimming event time and swimming frequency is equal to an average daily swimming time of 0.033 hours, consistent with the initial MEPAS daily swimming time.

TABLE 5.12. Swimming Water Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value	
			Individual	Population
TE_w	swimming event time	h/event	0.5	0.5
FE_{sw}	swimming frequency	event/d	0.066	0.066
F_{ww}	time fraction	--[a]	1.0	1.0
U_{ww}	water ingestion rate	L/h	0.10	0.10

(a) Dash indicates not applicable.

TABLE 5.13. Swimming Dermal Contact Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
TE_w	swimming event time	h/event	0.5	0.5
FE_{sw}	swimming frequency	event/d	0.066	0.066
F_{wd}	time fraction	--[(a)]	1.0	1.0
A_{wd}	skin area contacted	cm^2	20,000	20,000
l_{sc}	skin thickness	cm	0.001	0.001

(a) Dash indicates not applicable.

5.14 SHORELINE DERMAL CONTACT

Dermal contact with shoreline sediments requires values for the shoreline sediment thickness, the density of shoreline sediments, shoreline contact event frequency, area of skin contacted, and adherence factor for sediment on skin. Default values for these parameters are as defined in Table 5.14.

TABLE 5.14. Shoreline Dermal Contact Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
t_{ss}	sediment thickness	m	0.01	0.01
ρ_{ss}	sediment density	g/cm^3	1.5	1.5
FE_{sl}	contact frequency	event/d	0.066	0.066
F_{wd}	time fraction	--[(a)]	1.0	1.0
A_{wd}	skin area contacted	cm^2	5,800	5,800
A_{hd}	adherence factor	mg/cm^2	1.0	1.0

(a) Dash indicates not applicable.

5.15 SHORELINE SEDIMENT INGESTION

The model for inadvertent ingestion of shoreline sediments requires an estimate of the time spent in shoreline activities and the rate at which shoreline sediments are ingested. Default values for these parameters are given in Table 5.15.

Note that the product of shoreline event time and shoreline frequency is equal to an average daily exposure time of 0.033 hours, consistent with the initial MEPAS daily shoreline exposure time. The hourly sediment ingestion intake values are set equal to the daily USEPA (USEPA 1989) recommended values for soil ingestion intake. This is done because shoreline activities are expected to represent a high-contact situation and inadvertent ingestion rates would be considerably higher than rates for normal daily activities.

5.16 SOIL INGESTION

Soil ingestion is considered for the atmospheric transport pathway and the measured soil concentration pathway. Default parameter values for each of these pathways are given in Table 5.16.

TABLE 5.15. Shoreline Sediment Ingestion Parameter Default Values

			Default Value	
Parameter	Definition	Units	Individual	Population
F_{sl}	contact frequency	event/d	0.066	0.066
TE_l	event time	h/event	0.5	0.5
F_{hs}	time fraction	--[a]	1.0	1.0
U_{hs}	sediment ingestion rate	g/h	0.1	0.1

(a) Dash indicates not applicable.

TABLE 5.16. Soil Ingestion Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
Both routes:				
F_{ds}	time fraction	--	1.0	1.0
U_{ds}	soil ingestion rate	g/d	0.1	0.1
Atmospheric deposition route:				
t_{dd}	soil layer thickness	m	0.04	0.04
ρ_{dd}	soil density	g/cm^3	1.5	1.5

5.17 SOIL DERMAL CONTACT

Soil dermal contact is considered for the atmospheric transport pathway and the measured soil concentration pathway. Default parameter values for each of these pathways are given in Table 5.17.

TABLE 5.17. Soil Dermal Contact Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
Both routes:				
F_{dd}	time fraction	--	1.0	1.0
FE_{dd}	soil contact frequency	event/d	1.0	1.0
AD	adherence factor	mg/cm^2	1.0	1.0
A_{dd}	skin contact area	cm^2	5,800	5,800
Atmospheric deposition route:				
t_{dd}	soil layer thickness	m	0.04	0.04
ρ_{dd}	soil density	g/cm^3	1.5	1.5

5.18 SPECIAL FOODS

The special food ingestion pathway requires definition of the rate at which the food is ingested. Because there are no assumption related to the type of food being consumed, it is not appropriate to provide default values for the special food ingestion pathway. The user must provide a positive value when this pathway is used. Default values for the exposure parameters (exposure duration, body weight, and averaging time) are as described in Section 5.2.

5.19 INDOOR INHALATION FROM VOLATILIZATION

The two indoor inhalation pathways for volatilization from domestic water are shower inhalation and indoor inhalation. Only one of these pathways is used for any exposure scenario. Default values for parameters for these models are given in Table 5.18.

The default inhalation rate is set equal to the average daily inhalation rate.

TABLE 5.18. Indoor Air Inhalation Parameter Default Values

Parameter	Definition	Units	Default Value	
			Individual	Population
Shower Inhalation Model:				
TH_{dw}	water system holdup time	d	0.5	0.5
TE_s	shower event time	h/shower	0.167	0.167
FE_{sh}	shower frequency	shower/d	1.0	1.0
F_{si}	time fraction	--	1.0	1.0
U_{si}	inhalation rate	m^3/d	20	20
Indoor Inhalation from Volatilization				
K_c	volatilization, chemicals	L/m^3	0.5	0.5
K_r	volatilization, Rn222	L/m^3	0.1	0.1
TH_{dw}	water system holdup time	d	0.5	0.5
F_{si}	time fraction	--	1.0	1.0
U_{si}	inhalation rate	d	15	15

5.20 AIR INHALATION

The air inhalation rate is a primary exposure pathway for the atmospheric transport pathway. This pathway requires an estimate of the average daily inhalation rate, as given in Table 5.19.

5.21 SOIL RESUSPENSION INHALATION

Soil inhalation following suspension is considered for the atmospheric transport and measured soil pathways. The pollutant-independent parameters for this pathway are the resuspension rate and the inhalation rate, as given in Table 5.20.

5.22 SWIMMING EXTERNAL

The swimming external exposure pathway is based on the same swimming exposure time parameters as for the other swimming exposure routes. Default parameter values for the swimming external exposure pathway are given in Table 5.21.

TABLE 5.19. Air Inhalation Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
F_{ai}	time fraction	--	1.0	1.0
U_{ai}	inhalation rate	m^3/d	20	20

TABLE 5.20. Soil Resuspension Inhalation Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
RF	resuspension factor	m^{-1}	1.E-8	1.E-8
ML	mass loading factor	kg/m^3	1.E-7	1.E-7
F_{di}	time fraction	--	1.0	1.0
U_{di}	inhalation rate	m^3/d	20	20

TABLE 5.21. Swimming External Exposure Parameter Default Values

Parameter	Definition	Units	Default Value: Individual	Default Value: Population
F_{we}	time fraction	--	1.0	1.0
TE_w	swimming event time	h/event	0.5	0.5
FE_{sw}	swimming frequency	event/d	0.066	0.066

Note that the product of swimming event time and swimming frequency is equal to an average daily swimming time of 0.033 hours, consistent with the initial MEPAS daily swimming time.

5.23 BOATING EXTERNAL

The boating external exposure pathway is the same as the swimming external exposure model, except a shielding correction is applied for less than complete immersion in the water. Default parameter values for the boating external exposure pathway are given in Table 5.22.

Note that the product of boating event time and swimming frequency is equal to an average daily swimming time of 0.033 hours, consistent with the initial MEPAS daily boating exposure time.

TABLE 5.22. Boating External Exposure Parameter Default Values

Parameter	Definition	Units	Default Value: Individual	Default Value: Population
F_{be}	time fraction	--	1.0	1.0
TE_w	boating event time	h/event	0.5	0.5
FE_{sw}	boating frequency	event/d	0.066	0.066
SB	boating shielding factor	--	0.5	0.5

5.24 SHORELINE EXTERNAL

Shoreline exposure occurs when an individual is near contaminated shoreline sediments during periods of shoreline recreational activity. Parameters for this pathway include frequency of shoreline use, length of time in shoreline activities, and a shore width factor to account for the shoreline being less than infinite. Default parameter values for the shoreline external exposure pathway are given in Table 5.23.

Note that the product of shoreline event time and shoreline frequency is equal to an average daily shoreline exposure time of 0.033 hours, consistent with the initial MEPAS daily shoreline exposure time.

5.25 SOIL EXTERNAL

External exposure to contaminated soil is considered for the atmospheric transport pathway and the measured soil pathway. Default parameter values for these exposure pathways are given in Table 5.24.

5.26 AIR EXTERNAL

Exposure to air contaminated with radioactive material may result in external exposure while an individual is near the plume. This exposure pathway requires definition of the daily exposure time, as given in Table 5.25.

The default value for the air external exposure time is set to 24 hours representing continuous exposure.

TABLE 5.23. Shoreline External Exposure Parameter Default Values

Parameter	Definition	Units	Default Value	
			Individual	Population
F_{he}	time fraction	--	1.0	1.0
TE_l	shoreline event time	h/event	0.5	0.5
FE_{sl}	shoreline frequency	event/d	0.066	0.066
SW	shore width factor	--	0.5	0.5

TABLE 5.24. Soil External Exposure Parameter Default Values

Parameter	Definition	Units	Default Value: Individual	Default Value: Population
Atmospheric and measured soil routes:				
F_{de}	time fraction	--	1.0	1.0
U_{de}	soil exposure time	h/d	0.24	24
Atmospheric deposition route:				
t_{ms}	soil layer thickness	m	0.04	0.04
ρ_{ms}	soil density	g/cm^3	1.5	1.5

5.27 DIRECT RADIATION

The direct radiation exposure pathway involves external radiation exposure for a period of time to a measures radiation field. The two parameters for this pathway are the daily exposure time and the effective rate constant for reduction of the measured direct radiation dose rate. The default values for these parameters are given in Table 5.26.

The daily exposure time default values represent continuous exposure. The default reduction rate constant represents a radiation field that is constant with time.

TABLE 5.25. Air External Exposure Parameter Default Values

Parameter	Definition	Units	Default Value: Individual	Default Value: Population
F_{ae}	time fraction	--	1.0	1.0
U_{ae}	air exposure time	h/d	24	24

TABLE 5.26. Direct Radiation Exposure Parameter Default Values

Parameter	Definition	Units	Default Value Individual	Default Value Population
F_{dr}	time fraction	--	1.0	1.0
U_{dr}	daily exposure time	h/d	24	24
λ_{dr}	reduction rate constant	d^{-1}	1.E-8	1.E-8

5.28 HUMAN HEALTH IMPACT PARAMETERS

The parameters for the human health impact models are described here with default numerical values given for those parameters that are not pollutant specific. The parameters are described for each of the three model types; radiation, chemical carcinogens, and chemical noncarcinogens.

5.29 RADIATION HEALTH IMPACT PARAMETERS

Health impacts from exposure to radiation are estimated using health effects conversion factors or USEPA slope factors. Default values for health effects conversion factors are as given in Table 5.27. These values are based on recommendation given in the BEIR V report (NAS 1990) and International Commission on Radiological Protection (ICRP) Publication 60 (ICRP 1990).

There are no pollutant-independent parameters used in the health impacts model for radiation exposure based on the use of USEPA slope factors.

TABLE 5.27. Health Effects Conversion Factor Default Values

Parameter	Definition	Units	Default Value
HE_f	fatal cancer effects factor	risk/rem	6.3×10^{-4}
HE_i	cancer incidence effects factor	risk/rem	7.3×10^{-4}

5.30 CHEMICAL CARCINOGEN HEALTH IMPACT PARAMETERS

There are no pollutant-independent parameters used in the health impacts model for chemical carcinogens.

5.31 CHEMICAL NONCARCINOGEN HEALTH IMPACT PARAMETERS

There are no pollutant-independent parameters used in the health impacts model for chemical noncarcinogens.

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APPENDIX A

EQUATIONS FOR SUMMARY INTAKE FACTORS (SIF)

The exposure pathway equations given in Section 2.0 of this report describe evaluation of daily intake of chemicals and lifetime dose from radionuclides. These equations can be re-written with separation of the pollutant-specific parameters from parameters that are independent of the pollutant. The pollutant-independent parameters can be combined to provide a summary intake factor (SIF). The use of SIF values has been proposed by others (USDOE 1993) and is useful in performing calculation checks by hand. Summary intake factors can be calculated and provided as input for all of the MEPAS exposure pathways. The SIF values for each run are calculated (if not input) and printed in the output listings.

This section describes the equations for calculation of SIF values for the 25 MEPAS exposure pathways. The nomenclature for parameter symbols is the same as provided in Section 4.0 of this report. Equations are provided by exposure pathway for the three pollutant types (as appropriate for the particular exposure pathway): noncarcinogenic chemicals, carcinogenic chemicals, and radionuclides.

The SIFs are combined with pollutant-specific parameters in the exposure pathway assessment component of MEPAS to estimate daily intake rates for chemicals and total doses (effective dose equivalent) for radionuclides. The general equation for this analysis is as follows.

$$D_{kkit} = C_{mi} \, PF_{kkit} \, SIF_{kkt} \tag{A.1}$$

where

D_{kkit} = daily intake or total dose for exposure pathway kk for pollutant i of type t [mg/(kg·d) or rem]

PF_{kkit} = pollutant specific factor for exposure pathway kk for pollutant i of type t (units depend on pathway and pollutant type)

SIF_{kkt} = summary intake factor for exposure pathway kk for pollutants of type t (units depend on pathway and pollutant type).

The calculation of the pollutant-specific factors, PF_{kkit}, is not defined explicitly in this report, but can be deduced by comparison with equations in Section 2.0 of this report and the following equations for SIFs.

Exposure Pathway: Drinking Water Ingestion

Noncarcinogenic Chemicals

$$SIF_{dwn} = U_{dw} F_{dw} / BW_{dw} \quad (A.2)$$

where

SIF_{dwn} = summary intake factor for the drinking water ingestion exposure pathway for noncarcinogenic chemicals [L/(kg·d)].

Carcinogenic Chemicals

$$SIF_{dwc} = U_{dw} F_{dw} ED_{dw} / (BW_{dw} AT_{dwc}) \quad (A.3)$$

where

SIF_{dwc} = summary intake factor for the drinking water ingestion exposure pathway for carcinogenic chemicals [L/(kg·d)].

Radionuclides

$$SIF_{dwr} = U_{dw} F_{dw} E_{dw} 365.25 \quad (A.4)$$

where

SIF_{dwr} = summary intake factor for the drinking water ingestion exposure pathway for radionuclides (L).

Exposure Pathway: Shower Water Dermal Contact

Noncarcinogenic Chemicals

$$SIF_{sdn} = 10^{-3} A_{sd} \ TE_s \ FE_{sh} \ F_{sd} / BW_{sd} \quad (A.5)$$

where

SIF_{sdn} = summary intake factor for the shower water dermal contact exposure pathway for noncarcinogenic chemicals

[L·h/(kg·d·cm)].

Carcinogenic Chemicals

$$SIF_{sdc} = 10^{-3} A_{sd} \ TE_s \ FE_{sh} \ F_{sd} \ ED_{sd} / (BW_{sd} \quad (A.6)$$

A.2

where

SIF_{sdc} = summary intake factor for the shower water dermal contact exposure pathway for carcinogenic chemicals [L·h/(kg·d·cm)].

Radionuclides

$$SIF_{sdr} = 10^{-3}\ A_{sd}\ TE_{s}\ FE_{sh}\ F_{sd}\ ED_{sd}\ 365.2 \tag{A.7}$$

where

SIF_{sdr} = summary intake factor for the shower water dermal contact exposure pathway for radionuclides (L·h/cm).

__**Exposure Pathway: Shower Water Ingestion**__

Noncarcinogenic Chemicals

$$SIF_{swn} = U_{sw}\ TE_{s}\ FE_{sh}\ F_{sw} / BW_{sw} \tag{A.8}$$

where

SIF_{swn} = summary intake factor for the shower water inadvertent ingestion exposure pathway for noncarcinogenic chemicals [L/(kg·d)].

Carcinogenic Chemicals

$$SIF_{swc} = U_{sw}\ TE_{s}\ FE_{sh}\ F_{sw} ED_{sw} / (BW_{sw} AT_{swc} \tag{A.9}$$

where

SIF_{swc} = summary intake factor for the shower water inadvertent ingestion exposure pathway for carcinogenic chemicals

[L/(kg·d)].

Radionuclides

$$SIF_{swr} = U_{sw}\ TE_{s}\ FE_{sh}\ F_{sw}\ ED_{sw}\ 365.25 \tag{A.10}$$

where

SIF_{swr} = summary intake factor for the shower water inadvertent ingestion exposure pathway for radionuclides (L).

Exposure Pathway: Leafy Vegetable Ingestion

Noncarcinogenic Chemicals

$$SIF_{lvn} = U_{lv} F_{lv} / BW_{lv} \qquad (A.11)$$

where

SIF_{lvn} = summary intake factor for the leafy vegetable ingestion exposure pathway for noncarcinogenic chemicals [kg/(kd·d)].

Carcinogenic Chemicals

$$SIF_{lvc} = U_{lv} F_{lv} ED_{lv} / (BW_{lv} AT_{lvc}) \qquad (A.12)$$

where

SIF_{lvc} = summary intake factor for the leafy vegetable ingestion exposure pathway for carcinogenic chemicals [kg/(kd·d)].

Radionuclides

$$SIF_{lvr} = U_{lv} F_{lv} ED_{lv} 365.25 \qquad (A.13)$$

where

SIF_{lvr} = summary intake factor for the leafy vegetable ingestion exposure pathway for radionuclides (kg).

Exposure Pathway: Other Vegetable Ingestion

Noncarcinogenic Chemicals

$$SIF_{ovn} = U_{ov} F_{ov} / BW_{ov} \qquad (A.14)$$

where

SIF_{ovn} = summary intake factor for the other vegetable ingestion exposure pathway for noncarcinogenic chemicals [kg/(kd·d)].

Carcinogenic Chemicals

$$SIF_{ovc} = U_{ov} F_{ov} ED_{ov} / (BW_{ov} AT_{ovc}) \qquad (A.15)$$

where

SIF_{ovc} = summary intake factor for the other vegetable ingestion exposure pathway for carcinogenic chemicals [kg/(kd·d)].

Radionuclides

$$SIF_{ovr} = U_{ov} F_{ov} ED_{ov} 365.25 \quad (A.16)$$

where

SIF_{ovr} = summary intake factor for the other vegetable ingestion exposure pathway for radionuclides (kg).

<u>**Exposure Pathway, Meat Ingestion**</u>

Noncarcinogenic Chemicals

$$SIF_{mtn} = U_{mt} F_{mt} / BW_{mt} \quad (A.17)$$

where

SIF_{mtn} = summary intake factor for the meat ingestion exposure pathway for noncarcinogenic chemicals [kg/(kd·d)].

Carcinogenic Chemicals

$$SIF_{mtc} = U_{mt} F_{mt} ED_{mt} / (BW_{mt} AT_{mtc}) \quad (A.18)$$

where

SIF_{mtc} = summary intake factor for the meat ingestion exposure pathway for carcinogenic chemicals [kg/(kd·d)].

Radionuclides

$$SIF_{mtr} = U_{mt} F_{mt} ED_{mt} 365.25 \quad (A.19)$$

where

SIF_{mtr} = summary intake factor for the meat ingestion exposure pathway for radionuclides chemicals (kg).

Exposure Pathway: Milk Ingestion

Noncarcinogenic Chemicals

$$SIF_{mkn} = U_{mk} F_{mk} / BW_{mk} \qquad (A.20)$$

where

SIF_{mkn} = summary intake factor for the milk ingestion exposure pathway for noncarcinogenic chemicals [L/(kd·d)].

Carcinogenic Chemicals

$$SIF_{mkc} = U_{mk} F_{mk} ED_{mk} / (BW_{mk} AT_{mkc}) \qquad (A.21)$$

where

SIF_{mkc} = summary intake factor for the milk ingestion exposure pathway for carcinogenic chemicals [L/(kd·d)].

Radionuclides

$$SIF_{mkr} = U_{mk} F_{mk} ED_{mk} 365.25 \qquad (A.22)$$

where

SIF_{mkr} = summary intake factor for the milk ingestion exposure pathway for radionuclides (L).

Exposure Pathway: Fin Fish Ingestion

Noncarcinogenic Chemicals

$$SIF_{ffn} = U_{ff} F_{ff} / BW_{ff} \qquad (A.23)$$

where

SIF_{ffn} = summary intake factor for the fin fish ingestion exposure pathway for noncarcinogenic chemicals [kg/(kd·d)].

Carcinogenic Chemicals

$$SIF_{ffc} = U_{ff} F_{ff} ED_{ff} / (BW_{ff} AT_{ffc}) \qquad (A.24)$$

where

SIF_{ffc} = summary intake factor for the fin fish ingestion exposure pathway for carcinogenic chemicals [kg/(kd·d)].

Radionuclides

$$SIF_{ffr} = U_{ff} F_{ff} ED_{ff} 365.25 \tag{A.25}$$

where

SIF_{ffr} = summary intake factor for the fin fish ingestion exposure pathway for radionuclides (kg).

<u>**Exposure Pathway: Shellfish Ingestion**</u>

Noncarcinogenic Chemicals

$$SIF_{sfn} = U_{sf} F_{sf} / BW_{sf} \tag{A.26}$$

where

SIF_{sfn} = summary intake factor for the shellfish ingestion exposure pathway for noncarcinogenic chemicals [kg/(kd·d)].

Carcinogenic Chemicals

$$SIF_{sfc} = U_{sf} F_{sf} ED_{sf} / (BW_{sf} AT_{sfc}) \tag{A.27}$$

where

SIF_{sfc} = summary intake factor for the shellfish ingestion exposure pathway for carcinogenic chemicals [kg/(kd·d)].

Radionuclides

$$SIF_{sfr} = U_{sf} F_{sf} ED_{sf} 365.25 \tag{A.28}$$

where

SIF_{sfr} = summary intake factor for the shellfish ingestion exposure pathway for radionuclides (kg).

Exposure Pathway: Swimming Water Ingestion

Noncarcinogenic Chemicals

$$SIF_{wwn} = U_{ww}\ TE_{w}\ FE_{sw}\ F_{ww} / BW_{ww} \tag{A.29}$$

where

SIF_{wwn} = summary intake factor for the swimming water inadvertent ingestion exposure pathway for noncarcinogenic chemicals [L/(kg·d)].

Carcinogenic Chemicals

$$SIF_{wwc} = U_{ww}\ TE_{w}\ FE_{sw}\ F_{ww}\ ED_{ww} / (BW_{ww} AT_{wwc} \tag{A.30}$$

where

SIF_{wwc} = summary intake factor for the swimming water inadvertent ingestion exposure pathway for carcinogenic chemicals [L/(kg·d)].

Radionuclides

$$SIF_{wwr} = U_{ww}\ TE_{w}\ FE_{sw}\ F_{ww}\ ED_{ww}\ 365.25 \tag{A.31}$$

where

SIF_{wwr} = summary intake factor for the swimming water inadvertent ingestion exposure pathway for radionuclides (L).

Exposure Pathway: Swimming Dermal Contact

Noncarcinogenic Chemicals

$$SIF_{wdn} = 10^{-3}\ A_{wd}\ TE_{w}\ FE_{sw}\ F_{wd} / BW_{wd} \tag{A.32}$$

where

SIF_{wdn} = summary intake factor for the swimming water dermal contact exposure pathway for noncarcinogenic chemicals

[L·h/(kg·d cm)].

Carcinogenic Chemicals

$$SIF_{wdc} = 10^{-3}\ A_{wd}\ TE_{w}\ FE_{sw}\ F_{wd}\ ED_{wd} / (BW_{wc} \tag{A.33}$$

where

SIF$_{wdc}$ = summary intake factor for the swimming water dermal contact exposure pathway for carcinogenic chemicals [L·h/(kg·d·cm)].

Radionuclides

$$SIF_{wdr} = 10^{-3}\ A_{wd}\ TE_{w}\ FE_{sw}\ F_{wd}\ ED_{wd}\ 365.2 \quad (A.34)$$

where

SIF$_{wdr}$ = summary intake factor for the swimming water dermal contact exposure pathway for radionuclides (L·h).

Exposure Pathway: Shoreline Dermal Contact

Noncarcinogenic Chemicals

$$SIF_{hdn} = 10^{-6}\ A_{hd}\ AD\ FE_{sl}\ F_{hd} / BW_{hd} \quad (A.35)$$

where

SIF$_{hdn}$ = summary intake factor for the shoreline sediment dermal contact exposure pathway for noncarcinogenic chemicals

[kg·ev/(kg·d)].

Carcinogenic Chemicals

$$SIF_{hdc} = 10^{-6}\ A_{hd}\ AD\ FE_{sl}\ F_{hd}\ ED_{hd} / (BW_{hd} \quad (A.36)$$

where

SIF$_{hdc}$ = summary intake factor for the shoreline sediment dermal contact exposure pathway for carcinogenic chemicals

[kg·ev/(kg·d)].

Radionuclides

$$SIF_{hdr} = 10^{-6}\ A_{hd}\ AD\ FE_{sl}\ F_{hd}\ ED_{hd}\ 365.2 \quad (A.37)$$

where

SIF$_{hdr}$ = summary intake factor for the shoreline sediment dermal contact exposure pathway for radionuclides (kg·ev).

Exposure Pathway: Shoreline Sediment Ingestion

Noncarcinogenic Chemicals

$$SIF_{hsn} = 10^{-3}\ U_{hs}\ TE_{1}\ FE_{s1}\ F_{hs} / BW_{hs} \qquad (A.38)$$

where

SIF_{hsn} = summary intake factor for the shoreline sediment inadvertent ingestion exposure pathway for noncarcinogenic chemicals [kg/(kg·d)].

Carcinogenic Chemicals

$$SIF_{hsc} = 10^{-3}\ U_{hs}\ TE_{1}\ FE_{s1}\ F_{hs}\ ED_{hs} / (BW_{hs} \qquad (A.39)$$

where

SIF_{hsc} = summary intake factor for the shoreline sediment inadvertent ingestion exposure pathway for carcinogenic chemicals [kg/(kg·d)].

Radionuclides

$$SIF_{hsr} = 10^{-3}\ U_{hs}\ TE_{1}\ FE_{s1}\ F_{hs}\ ED_{hs}\ 365.2 \qquad (A.40)$$

where

SIF_{hsr} = summary intake factor for the shoreline sediment inadvertent ingestion exposure pathway for radionuclides (kg).

Exposure Pathway: Soil Ingestion, Air Deposition

Noncarcinogenic Chemicals

$$SIF_{dsn} = 10^{-6}\ U_{ds}\ F_{ds} / (t_{dd}\ \rho_{dd}\ BW_{ds}) \qquad (A.41)$$

where

SIF_{dsn} = summary intake factor for the soil ingestion following air deposition exposure pathway for noncarcinogenic chemicals [m^2/(kg·d)].

Carcinogenic Chemicals

$$SIF_{dsc} = 10^{-6}\ U_{ds}\ F_{ds}\ ED_{ds} / (t_{dd}\ \rho_{dd}\ BW_{ds} \qquad (A.42)$$

where

SIF_{dsc} = summary intake factor for the soil ingestion following air deposition exposure pathway for carcinogenic chemicals [m^2/(kg·d)].

Radionuclides

$$SIF_{dsr} = 10^{-6}\ U_{ds}\ F_{ds}\ ED_{ds}\ 365.25 / (t_{dd}\ \rho \qquad (A.43)$$

where

SIF_{dsr} = summary intake factor for the soil ingestion following air deposition exposure pathway for radionuclides (m^2).

Exposure Pathway: Soil Ingestion, Measured Soil

Noncarcinogenic Chemicals

$$SIF_{dsn} = 10^{-3} U_{ds} F_{ds} / BW_{ds} \qquad (A.44)$$

where

SIF_{dsn} = summary intake factor for the soil ingestion of measured soil exposure pathway for noncarcinogenic chemicals

[kg/(kg·d)].

Carcinogenic Chemicals

$$SIF_{dsc} = 10^{-3} U_{ds} F_{ds} ED_{ds} / (BW_{ds} AT_{dsc}) \qquad (A.45)$$

where

SIF_{dsc} = summary intake factor for the soil ingestion of measured soil exposure pathway for carcinogenic chemicals

[kg/(kg·d)].

Radionuclides

$$SIF_{dsr} = 10^{-3}\ U_{ds}\ F_{ds}\ ED_{ds}\ 365.25 \qquad (A.46)$$

where

SIF_{dsr} = summary intake factor for the soil ingestion of measured soil exposure pathway for radionuclides (kg).

Exposure Pathway: Soil Dermal Contact, Air Deposition

Noncarcinogenic Chemicals

$$SIF_{ddn} = 10^{-9} \, FE_{dd} \, F_{dd} \, AD \, A_{dd} / (t_{dd} \, \rho_{dd} \, BW \qquad (A.47)$$

where

SIF$_{ddn}$ = summary intake factor for the soil dermal contact following deposition from air exposure pathway for noncarcinogenic chemicals [m^2·ev/(kg·d)].

Carcinogenic Chemicals

$$SIF_{ddc} = 10^{-9} \, FE_{dd} \, F_{dd} \, AD \, A_{dd} \, ED_{dd} / (t_{dd} \, \rho \qquad (A.48)$$

where

SIF$_{ddc}$ = summary intake factor for the soil dermal contact following deposition from air exposure pathway for carcinogenic chemicals [m^2·ev/(kg·d)].

Radionuclides

$$SIF_{ddr} = 10^{-9} \, FE_{dd} \, F_{dd} \, AD \, A_{dd} \, ED_{dd} \, 365.2 \qquad (A.49)$$

where

SIF$_{ddr}$ = summary intake factor for the soil dermal contact following deposition from air exposure pathway for radionuclides

(m^2·ev).

Exposure Pathway: Soil Dermal Contact, Measured Soil

Noncarcinogenic Chemicals

$$SIF_{ddn} = 10^{-6} \, FE_{dd} \, F_{dd} \, AD \, A_{dd} / BW_{dd} \qquad (A.50)$$

where

SIF$_{ddn}$ = summary intake factor for the soil dermal contact for measured soil exposure pathway for noncarcinogenic chemicals [kg·ev/(kg·d)].

Carcinogenic Chemicals

$$SIF_{ddc} = 10^{-6} \, FE_{dd} \, F_{dd} \, AD \, A_{dd} \, ED_{dd} / (BW_{dd} \qquad (A.51)$$

where

SIF_{ddc} = summary intake factor for the soil dermal contact for measured soil exposure pathway for carcinogenic chemicals [kg·ev/(kg·d)].

Radionuclides

$$SIF_{ddr} = 10^{-6}\ FE_{dd}\ F_{dd}\ AD\ A_{dd}\ ED_{dd}\ 365.2 \qquad (A.52)$$

where

SIF_{ddr} = summary intake factor for the soil dermal contact for measured soil exposure pathway for radionuclides (kg·ev).

Exposure Pathway: Special Foods

Noncarcinogenic Chemicals

$$SIF_{fdn} = U_{fd}\ F_{fd} / BW_{fd} \qquad (A.53)$$

where

SIF_{fdn} = summary intake factor for the special (measured) food ingestion exposure pathway for noncarcinogenic chemicals [kg/(kg·d)].

Carcinogenic Chemicals

$$SIF_{fdc} = U_{fd}\ F_{fd}\ ED_{fd} / (BW_{fd}\ AT_{fdc}) \qquad (A.54)$$

where

SIF_{fdc} = summary intake factor for the special (measured) food ingestion exposure pathway for carcinogenic chemicals [kg/(kg·d)].

Radionuclides

$$SIF_{fdr} = U_{fd}\ F_{fd}\ ED_{fd}\ 365.25 \qquad (A.55)$$

where

SIF_{fdr} = summary intake factor for the measured food ingestion exposure pathway for radionuclides (kg).

Exposure Pathway: Indoor Inhalation from Volatilization

Noncarcinogenic Chemicals

$$SIF_{ian} = U_{ia} \, F_{ia} \, K_c / BW_{ia} \tag{A.56}$$

where

SIF_{ian} = summary intake factor for the indoor air inhalation of volatile pollutants exposure pathway for noncarcinogenic chemicals [L/(kg·d)].

Carcinogenic Chemicals

$$SIF_{iac} = U_{ia} \, F_{ia} \, K_c \, ED_{ia} / (BW_{ia} \, AT_{iac}) \tag{A.57}$$

where

SIF_{iac} = summary intake factor for the indoor air inhalation of volatile pollutants exposure pathway for carcinogenic chemicals [L/(kg·d)].

Radionuclides

$$SIF_{iar} = U_{ia} \, F_{ia} \, K_r \, ED_{ia} \, 365.25 \tag{A.58}$$

where

SIF_{iar} = summary intake factor for the indoor air inhalation of volatile pollutants exposure pathway for radionuclides (L).

Exposure Pathway: Shower Air Inhalation

Noncarcinogenic Chemicals

$$SIF_{sin} = 10^3 \, U_{si} \, FE_{sh} \, F_{si} \, TE_s / (BW_{si} \, 24) \tag{A.59}$$

where

SIF_{sin} = summary intake factor for the shower air inhalation of volatile pollutants exposure pathway for noncarcinogenic chemicals [L/(kg·d)].

Carcinogenic Chemicals

$$SIF_{sic} = 10^3 \, U_{si} \, FE_{sh} \, TE_s \, F_{si} \, \frac{ED_{si}}{(BW_{si} \, AT_{sic}} \tag{A.60}$$

where

SIF_{sic} = summary intake factor for the shower air inhalation of volatile pollutants exposure pathway for carcinogenic chemicals [L/(kg·d)].

Radionuclides

$$SIF_{sir} = 10^3 \; U_{si} \; FE_{sh} \; TE_s \; F_{si} \; ED_{si} \; 365.25 \qquad (A.61)$$

where

SIF_{sir} = summary intake factor for the shower air inhalation of volatile pollutants exposure pathway for radionuclides (L).

Exposure Pathway: Air Inhalation

Noncarcinogenic Chemicals

$$SIF_{ain} = U_{ai} \; F_{ai} / BW_{ai} \qquad (A.62)$$

where

SIF_{ain} = summary intake factor for air inhalation exposure pathway for noncarcinogenic chemicals [m^2/(kg·d)].

Carcinogenic Chemicals

$$SIF_{aic} = U_{ai} \; F_{ai} \; ED_{ai} / (BW_{ai} \; AT_{aic}) \qquad (A.63)$$

where

SIF_{aic} = summary intake factor for air inhalation exposure pathway for carcinogenic chemicals [m^2/(kg·d)].

Radionuclides

$$SIF_{air} = U_{ai} \; F_{ai} \; ED_{ai} \; 365.25 \qquad (A.64)$$

where

SIF_{air} = summary intake factor for air inhalation exposure pathway for radionuclides (m^2).

A.15

Exposure Pathway: Inhalation of Resuspensed Soil

Noncarcinogenic Chemicals

$$SIF_{din} = U_{di}\ F_{di}\ RF / BW_{di} \tag{A.65}$$

where

SIF_{din} = summary intake factor for inhalation of resuspended soil following atmospheric deposition exposure pathway for non-carcinogenic chemicals [$m^2/(kg{\cdot}d)$].

Carcinogenic Chemicals

$$SIF_{dic} = U_{di}\ F_{di}\ RF\ ED_{di} / (BW_{di}\ AT_{dic}) \tag{A.66}$$

where

SIF_{dic} = summary intake factor for inhalation of resuspended soil following atmospheric deposition exposure pathway for carcinogenic chemicals [$m^2/(kg{\cdot}d)$].

Radionuclides

$$SIF_{dir} = U_{di}\ F_{di}\ RF\ ED_{di}\ 365.25 \tag{A.67}$$

where

SIF_{dir} = summary intake factor for inhalation of resuspended soil following atmospheric deposition exposure pathway for radionuclides (m^2).

Exposure Pathway: Inhalation of Suspended Soil

Noncarcinogenic Chemicals

$$SIF_{din} = U_{di}\ F_{di}\ ML / BW_{di} \tag{A.68}$$

where

SIF_{din} = summary intake factor for inhalation of suspended soil for measured soil exposure pathway for noncarcinogenic chemicals [$kg/(kg{\cdot}d)$].

Carcinogenic Chemicals

$$SIF_{dic} = U_{di}\ F_{di}\ ML\ ED_{di} / (BW_{di}\ AT_{dic}) \tag{A.69}$$

where

SIF_{dic} = summary intake factor for inhalation of suspended soil for measured soil exposure pathway for carcinogenic chemicals [kg/(kg·d)].

Radionuclides

$$SIF_{dir} = U_{di}\ F_{di}\ ML\ ED_{di}\ 365.25 \qquad (A.70)$$

where

SIF_{dir} = summary intake factor for inhalation of suspended soil for measured soil exposure pathway for radionuclides (kg).

Exposure Pathway: Swimming External Radiation

Radionuclides

$$SIF_{wer} = TE_{w}\ FE_{sw}\ F_{we}\ ED_{we}\ 365.25 \qquad (A.71)$$

where

SIF_{wer} = summary intake factor for external exposure while swimming exposure pathway for radionuclides (h).

Exposure Pathway: Boating External Radiation

Radionuclides

$$SIF_{ber} = SB\ TE_{b}\ FE_{bt}\ F_{be}\ ED_{be}\ 365.25 \qquad (A.72)$$

where

SIF_{ber} = summary intake factor for external exposure while boating exposure pathway for radionuclides (h).

Exposure Pathway: Shoreline External Radiation, Surface Water

Radionuclides

$$SIF_{her} = SW\ TE_{l}\ FE_{sl}\ F_{he}\ ED_{he}\ 365.25 \qquad (A.73)$$

where

SIF_{her} = summary intake factor for external exposure from shoreline sediment activity exposure pathway for radionuclides (h).

Exposure Pathway: Soil External Radiation, Air Deposition

Radionuclides

$$SIF_{der} = U_{de} \left[SH_h \; FT_h + SH_o \; FT_o \right] F_{de} \; ED_{de} \; 3 \tag{A.74}$$

where

SIF_{der} = summary intake factor for external exposure to ground contamination from airborne deposition exposure pathway for radionuclides (h).

Exposure Pathway: Ground External Radiation, Measured Soil

Radionuclides

$$SIF_{der} = U_{de} \left[SH_h \; FT_h + SH_o \; FT_o \right] F_{de} \; ED_{de} \; 3 \tag{A.75}$$

where

SIF_{der} = summary intake factor for external exposure to ground contamination for measured soil exposure pathway for radionuclides (h).

Exposure Pathway: Air External Radiation

Radionuclides

$$SIF_{aer} = U_{ae} \; F_{ae} \; ED_{ae} \; 365.25 \tag{A.76}$$

where

SIF_{aer} = summary intake factor for external exposure to airborne contamination exposure pathway for radionuclides (h).

Exposure Pathway: Measured Direct Radiation

Radiation Fields

$$SIF_{drr} = U_{dr}\ F_{dr}\ \frac{1 - e^{-\lambda_{dr}\ ED_{dr}\ 365.25}}{\lambda_{dr}} \tag{A.77}$$

where

SIF_{drr} = summary intake factor for external exposure measured radiation fields soil exposure pathway (h).

APPENDIX B

RADIONCULIDE DECAY ALGORITHMS

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. The general analytical solution is 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 system 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 appendix includes chain decay with branching explicitly in the equations (Kennedy and Strenge 1992).

The general radioactive-decay-chain problem is illustrated in Figure B.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.

This appendix presents four applications of the general solution for the compartmental system of Figure B.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.

FIGURE B.1. A Representation of the General Radioactive-Decay-Chain Problem

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 B.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 as follows.

$$\frac{d A_c(t)}{dt} = - L_c \; A_c(t) - \lambda_{rc} \; A_c(t) + \sum_{n=1}^{c-1} d_{nc} \lambda_{rn} \; A_n(t) \qquad \text{(B.1)}$$

where

L_c = total rate constant for all physical transfers of chain member c 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}).

The first term on the right side of Equation (B.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.

$$A_c(t) = \sum_{i=1}^{c} K_{ci} e^{-\lambda_{ei} t} \qquad \text{(B.2)}$$

$$K_{11} = A_1(0) \qquad \text{(B.3)}$$

$$K_{cn} \; (n = 1 \rightarrow c-1) = \frac{\sum_{i=n}^{c-1} d_{ic} \lambda_{ri} K_{in}}{\lambda_{ec} - \lambda_{en}} \qquad \text{(B.4)}$$

and

$$K_{cc} = A_c(0) - \sum_{n=1}^{c-1} K_{cn} \qquad \text{(B.5)}$$

The previous discussion and equations describe quantities of radionuclides expressed in units of atoms. Equations (B.2) through (B.5) can be easily converted to units of activity, such as Bq or Ci, using the general relationship between atom and activity units:

$$Q_c(t) = k \; A_c(t) \, \lambda_{rc} \qquad \text{(B.6)}$$

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 (B.6) into Equations (B.2) through (B.5), with the terms slightly simplified, results in the following general solution with quantities expressed in activity units:

$$Q_c(t) = \lambda_{rc} \sum_{n=1}^{c} K_{cn} e^{-\lambda_{en} t} \qquad \text{(B.7)}$$

$$K_{11} = \frac{Q_1(0)}{\lambda_{r1}} \qquad \text{(B.8)}$$

$$K_{cn}\ (n = 1 \rightarrow c-1) = \frac{\sum_{i=n}^{c-1} d_{ic} \lambda_{ri} K_{in}}{\lambda_{ec} - \lambda_{en}} \tag{B.9}$$

and

$$K_{cc} = \frac{Q_c(0)}{\lambda_{rc}} - \sum_{n=1}^{c-1} K_{cn} \tag{B.10}$$

The forms of Equations (B.7) through (B.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 (B.8) and (B.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 (B.2) through (B.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 (B.4) and (B.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 has 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 (B.2) and (B.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 (B.7) illustrates these steps:

$$\int_0^t Q_c dt = \int_0^t \lambda_{rc}\left[\sum_{n=1}^{c} K_{cn} e^{-\lambda_{en}t}\right]dt = \lambda_{rc}\sum_{n=1}^{c} K_{cn}\left[\int_0^t e^{-\lambda_{en}}dt\right]$$

$$= \lambda_{rc}\sum_{n=1}^{c} K_{cn}\left[\frac{e^{-\lambda_{en}t}}{-\lambda_{en}}\right]_0^t = \lambda_{rc}\sum_{n=1}^{c} K_{cn}\left[\frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}}\right] \tag{B.11}$$

The general solution for the time integral now uses the following formula with Equations (B.8), (B.9), and (B.10):

$$\int_0^t Q_c dt = \lambda_{rc}\sum_{n=1}^{c} K_{cn}\left[\frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}}\right] \tag{B.12}$$

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 (B.1), with an added term representing the constant rate of deposition of chain member c to the medium, R_c.

$$\frac{dA_c(t)}{dt} = R_c - (L_c + \lambda_{rc})A_c(t) + \sum_{n=1}^{c-1} d_{nc} \tag{B.13}$$

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:

$$A_c(t) = \lambda_{rc}\sum_{n=1}^{c} K_{cn}\left[\frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}}\right] \tag{B.14}$$

$$K_{11} = \frac{D_1}{\lambda_{r1}} \tag{B.15}$$

$$K_{cn}\ (n=1 \rightarrow c-1) = \frac{\sum_{i=n}^{c-1} d_{ic}\lambda_{ri}K_{in}}{\lambda_{ec} - \lambda_{en}} \tag{B.16}$$

and

$$K_{cc} = \frac{D_c}{\lambda_{rc}} - \sum_{n=1}^{c-1} K_{cn} \tag{B.17}$$

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 (B.11) and (B.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 (B.11), works as follows:

$$\begin{aligned}
\int_0^t Q_c\,dt &= \int_0^t \left[\lambda_{rc} \sum_{n=1}^{c} K_{cn} \left(\frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}} \right) \right] dt \\
&= \lambda_{rc} \sum_{n=1}^{c} K_{cn} \left[\int_0^t \frac{1 - e^{-\lambda_{en}}}{\lambda_{en}}\,dt \right] \\
&= \lambda_{rc} \sum_{n=1}^{c} K_{cn} \left[\frac{t}{\lambda_{en}} - \frac{e^{-\lambda_{en}t}}{-\lambda^2_{en}} \right]_0^t \\
&= \lambda_{rc} \sum_{n=1}^{c} \frac{K_{cn}}{\lambda_{en}} \left[t - \frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}} \right]
\end{aligned} \tag{B.18}$$

or

$$\int_0^t Q_c\,dt = \lambda_{rc}\sum_{n=1}^{c}\frac{K_{cn}}{\lambda_{en}}\left[t - \frac{1 - e^{-\lambda_{en}t}}{\lambda_{en}}\right] \qquad (B.19)$$

The general solution to the time integral of deposition at a constant rate with accumulation uses Equation (B.19) [in place of Equation (B.14)], and Equations (B.15), (B.16), and (B.17). These equations can be put in terms of atom units by using Equation (B.6), as illustrated earlier.

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