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Pacific Northwest National Laboratory
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Multimedia Environmental Pollutant Assessment System (MEPAS): Receptor Intake Module Description

D. L. Strenge
M. A. Smith

October 2006

Prepared for
Engineer Research and Development Center
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Vicksburg, MS
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Summary

This report represents one of the three documents that have been derived from the original Multimedia Environmental Pollution Assessment System (MEPAS) Exposure Pathway and Human Health Impact Assessment document (Strenge and Chamberlain 1995) and describes the receptor-intake pathway module.

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 National Laboratory,[a] MEPAS is designed for site-specific assessments using readily available information. Endpoints are computed for chemical and radioactive pollutants. 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 receptor intake assessment. The receptor intake analysis starts with pollutant concentration in an exposure medium and estimates the average intake by an individual from contact with the exposure medium.

Reference

Strenge DL, and PJ Chamberlain. 1995. *Multimedia Environmental Pollutant Assessment System (MEPAS): Exposure Pathway and Human Health Impact Assessment Models*. PNL-10523, Pacific Northwest Laboratory, Richland, WA.

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Acronyms

EPA	U.S. Environmental Protection Agency
MEPAS	Multimedia Environmental Pollution Assessment System
PNNL	Pacific Northwest National Laboratory

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Contents

1.0 Introduction

This report represents one of the three documents that have been derived from the original Multimedia Environmental Pollution Assessment System (MEPAS) Exposure Pathway and Human Health Impact Assessment document (Strenge and Chamberlain 1995) and describes the receptor-intake pathway module.

The receptor intake module calculates the average daily intake rate to exposed individuals from contact with the transport medium or a secondary medium contaminated by the transport medium. The average daily intake rate is based on the concentration values transferred from the exposure pathway module. The average daily intake rate is then used to estimate a measure of health impact appropriate to the type of pollutant considered. The health-impact measure is evaluated in the Human Health Impact module.

The average daily intake rate 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 intake rate is described in the following sections with detailed applications to specific pathways.

2.0 Exposure Pathway-Intake Evaluation

The intake analysis for each exposure pathway is described in the following sections. The starting point is the medium concentration at the point of exposure. The output for chemical pollutants is the average daily intake rate averaged over the exposure duration, normalized to an averaging time. For radioactive pollutants, the output is the total intake for the radionuclide for inhalation, dermal, and inhalation pathways. For external pathways, the output is the effective concentration (or radiation dose for some external pathways) averaged over the exposure duration. The effective concentration or daily intake rate includes consideration of the fraction of the time that the individual is exposed to a particular pathway.

2.1 Drinking Water Ingestion

Using contaminated water as a source of domestic drinking water is evaluated based on the average water concentration over the exposure duration. The following exposure factors are used in the evaluation.

Exposure Factors:

- Water ingestion rate, exposure duration, and averaging time

The average daily intake rate for the drinking-water pathway for groundwater or surface-water transport is evaluated as follows for chemical pollutants:

$$D_{dwi} = MC_{di}\left(\frac{F_{dw}U_{dw}\ ED_{dw}}{BW_{dw}\ AT_{dwi}}\right) \tag{1}$$

where
D_{dwi} = average daily ingestion intake rate for the drinking-water pathway for chemical pollutant i (mg/kg/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)
MC_{di} = medium concentration for domestic drinking water (mg/L).

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 intake is evaluated as follows:

$$D_{dwi} = MC_{di}\left(U_{dw}F_{dw}ED_{dw}365.25\right) \tag{2}$$

where D_{dwi} = total lifetime intake for the drinking-water pathway for radionuclide i (Bq)
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)
365.25 = units conversion factor (d/yr)
MC_{di} = medium concentration for domestic drinking water (Bq/L).

2.2 Shower-Water Dermal Contact

Using 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. The following exposure factors are used in the evaluation.

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 the U.S. Environmental Protection Agency (EPA 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:

$$I_{shi} = MC_{di}\left(10^{-3}\ K_{pi}\ TE_s\right) \qquad (3)$$

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 Bq/cm^2/shower)
10^{-3} = units conversion factor (L/cm^3)
K_{pi} = skin absorption permeability constant for pollutant i (cm/h)
TE_s = duration of one shower (h/shower)
MC_{di} = medium concentration in domestic water (mg/L or Bq/L).

For organic chemicals, the EPA 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 EPA 1992) 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

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

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

$$DS_i = 0.001906\ l_{sc}\ 10^{-0.0061\ MW_i} \tag{5}$$

where MW_i is the 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:

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

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 $B < 0.1$, then $t^* = 2.4\ \tau$
For $0.1 \le B \le 1.17$, then $t^* = (8.4 + 6 \log B)\ \tau$
For $B > 1.17$, then

$$t^* = 6\tau\left(b - \sqrt{b^2 - c^2}\right) \tag{7}$$

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

$$b = \frac{2}{\pi}(1 + B)^2 - c \tag{8}$$

and

$$c = \frac{1 + 3B}{3} \tag{9}$$

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 $TE_s < t^*$,

$$I_{shi} = MC_{di}\left(2\times10^{-3}K_{pi}\sqrt{\frac{6\tau TE_s}{\pi}}\right) \tag{10}$$

and for $TE_s \geq t^*$,

$$I_{shi} = MC_{di}\left\{10^{-3}K_{pi}\left[\frac{TE_s}{1+B}+2\tau\left(\frac{1+3B}{1+B}\right)\right]\right\} \tag{11}$$

where I_{shi} is the dose absorbed per unit area per shower for pollutant i (mg/cm^2-shower), 10^{-3} is the units conversion factor (L/cm^3), and MC_{di} is the medium concentration in domestic water (mg/L or Bq/L).

The average daily dose, is given as follows:

$$D_{sdi} = I_{shi}A_{sd}FE_{sh}F_{sd}\frac{ED_{sd}}{\left(BW_{sd}AT_{sdi}\right)} \tag{12}$$

where D_{sdi} = average daily dose from chemical pollutant i via dermal absorption from water contact while showering (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).

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 body weight is 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:

$$D_{sdi} = I_{shi}\, A_{sd}\, FE_{sh}\, F_{sd}\, ED_{sd}\, 365.25 \tag{13}$$

where D_{sdi} = total intake via dermal absorption for radionuclide i (Bq)
I_{shi} = Absorption per unit area per shower for pollutant i (Bq/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)
365.25 = units conversion factor (d/yr).

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. The following exposure factors are used in the evaluation.

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:

$$D_{swi} = MC_{di}\left[\frac{U_{sw}TE_{s}FE_{sh}F_{sw}ED_{sw}}{\left(BW_{sw}AT_{swi}\right)}\right] \tag{14}$$

where D_{swi} = average daily ingestion dose for the shower ingestion pathway for pollutant i (mg/kg/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_{sw} = 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 individual exposed to shower-water ingestion pathway (kg)
AT_{swi} = averaging time for the shower-water ingestion pathway for exposure to pollutant i (yr)
MC_{di} = medium concentration in domestic water (mg/L).

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 intake is evaluated, as follows:

$$D_{dwi} = MC_{di}\left(U_{sw}\,TE_{s}\,FE_{sh}\,F_{sw}\,ED_{dw}\,365.25\right) \tag{15}$$

where D_{dwi} = total lifetime intake for the shower-water ingestion pathway for radionuclide i (Bq)
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_{sw} = fraction of days per year that showering occurs for the inadvertent shower ingestion pathway (dimensionless)
ED_{dw} = exposure duration for the shower-water ingestion pathway (yr)
365.25 = units conversion factor (d/yr)
MC_{di} = medium concentration for domestic water (Bq/L).

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 following exposure factors are used in the evaluation.

Exposure Factors:

- Rate of crop ingestion and exposure duration

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

$$D_{lvi} = C_{lvi}\left(U_{lv}\,\frac{F_{lv}ED_{lv}}{AT_{lvi}BW_{lv}}\right) \tag{16}$$

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)
C_{lvi} = average concentration in leafy vegetables over the exposure duration (mg/kg)
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 individual exposed by the leafy-vegetable 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 radioactive pollutants, the total lifetime ingestion intake is evaluated as follows:

$$D_{lvi} = C_{lvi}\left(U_{lv}F_{lv}ED_{lv}365.25\right) \tag{17}$$

where D_{lvi} = total intake from ingestion of leafy vegetables (Bq)
U_{lv} = ingestion rate of leafy vegetables by the exposed individual (kg/d)
C_{lvi} = average concentration in leafy vegetables over the exposure duration (Bq/kg)
F_{lv} = fraction of days per year that leafy vegetables are consumed (dimensionless)
ED_{lv} = exposure duration for the leafy-vegetable ingestion pathway (yr)
365.25 = units conversion factor (d/yr).

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 pathways are the same as those for the leafy-vegetable pathway. The equations are repeated here for completeness, with subscripts appropriate to the other vegetable pathways.

The following exposure factors are used in the evaluation.

Exposure Factors:

- Rate of crop ingestion and exposure duration

The average daily dose from ingestion of chemical pollutants in other vegetables is evaluated as follows:

$$D_{ovi} = C_{ovi}\left(U_{ov}F_{ov}\frac{ED_{ov}}{AT_{ovi}BW_{ov}}\right) \tag{18}$$

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)
C_{ovi} = average concentration of pollutant i in other vegetables over the exposure duration (mg/kg)
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 pathways for exposure to pollutant i (yr)
BW_{ov} = body weight of individual exposed by other vegetable-ingestion pathway (kg).

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

$$D_{ovi} = C_{ovi}\left(U_{ov}F_{ov}ED_{ov}365.25\right) \tag{19}$$

where D_{ovi} = total intake from ingestion of other vegetables (Bq)
U_{ov} = ingestion rate of other vegetables by the exposed individual (kg/d)
C_{ovi} = average concentration of pollutant i in other vegetables over the exposure duration (Bq/kg)
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)
365.25 = units conversion factor (d/yr).

2.6 Meat Ingestion

Animals fed contaminated crops or water can be expected to produce contaminated meat. The following exposure factors are used in the evaluation.

Exposure Factors:
- Rate of meat ingestion and exposure duration

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

$$D_{mti} = C_{mti}\left(U_{mt}\,\frac{F_{mt}ED_{mt}}{AT_{mti}BW_{mt}}\right) \tag{20}$$

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)
C_{mti} = average concentration of pollutant i in meat over the exposure duration (mg/kg)
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 individual exposed by the meat-ingestion pathway (kg).

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

$$D_{mti} = C_{mti}\left(U_{mt}F_{mt}ED_{mt}\,365.25\right) \tag{21}$$

where D_{mti} = total intake from ingestion of meat (Bq)
U_{mt} = ingestion rate of meat by the exposed individual (kg/d)
C_{mti} = average concentration of pollutant i in meat over the exposure duration (Bq/kg)
F_{mt} = fraction of days per year that meat is eaten (dimensionless)
ED_{mt} = exposure duration for the meat-ingestion pathway (yr)
365.25 = units conversion factor (d/yr).

2.7 Milk Ingestion

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

Exposure Factors:

- Rate of milk ingestion and exposure duration

The average daily dose received by individuals consuming the contaminated milk is evaluated as follows for chemical pollutants.

$$D_{mki} = C_{mki}\left(U_{mk}\,\frac{F_{mk}ED_{mk}}{AT_{mki}BW_{mk}}\right) \qquad (22)$$

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)
- C_{mki} = average concentration of pollutant i in milk over the exposure duration (mg/L)
- 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 individual exposed by the milk-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 radioactive pollutants, the total lifetime intake is evaluated, as follows:

$$D_{mki} = C_{mki}\left(U_{mk}F_{mk}ED_{mk}\,365.25\right) \qquad (23)$$

where
- D_{mki} = total intake from ingestion of milk (Bq)
- D_{mki} = average daily dose from ingestion of milk (mg/kg/d)
- U_{mk} = ingestion rate of milk by the exposed individual (L/d)
- C_{mki} = average concentration of pollutant i in milk over the exposure duration (Bq/L)
- F_{mk} = fraction of days per year that milk is ingested (dimensionless)
- ED_{mk} = exposure duration for the milk-ingestion pathway (yr)
- 365.25 = units conversion factor (d/yr).

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. 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 exposure factors are used in the evaluation.

Exposure Factors:

- Rate of fin fish ingestion and exposure duration

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

$$D_{ffi} = C_{ffi}\left(U_{ff}\,\frac{F_{ff}\,ED_{ff}}{AT_{ffi}\,BW_{ff}}\right) \tag{24}$$

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)
C_{ffi} = average concentration of pollutant i in fin fish over the exposure duration (mg/kg)
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 individual exposed by the fin-fish ingestion pathway (kg).

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

$$D_{ffi} = C_{ffi}\left(U_{ff}\,F_{ff}\,ED_{ff}\,365.25\right) \tag{25}$$

where
D_{ffi} = total intake from ingestion of fin fish for radionuclide i (Bq)
U_{ff} = ingestion rate of fin fish by the exposed individual (kg/d)
C_{ffi} = average concentration of pollutant i in fin fish over the exposure duration (Bq/kg)
F_{ff} = fraction of days per year that fish are eaten (dimensionless)
ED_{ff} = exposure duration for the fin-fish ingestion pathway (yr)
365.25 = units conversion factor (d/yr).

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 following exposure factors are used in the evaluation.

Exposure Factors:

- Rate of shellfish ingestion and exposure duration

The transport medium, special processes, and exposure considerations are the same as those for the fin-fish ingestion pathway as defined in Subsection 2.8, except that the exposure medium is contaminated shellfish.

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

$$D_{sfi} = C_{sfi}\left(U_{sf}\,\frac{F_{sf}ED_{sf}}{AT_{sfi}BW_{sf}}\right) \tag{26}$$

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)
- C_{sfi} = average concentration of pollutant i in shellfish over the exposure duration (mg/kg)
- 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 individual exposed by the shellfish-ingestion pathway (kg).

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

$$D_{sfi} = C_{sfi}\left(U_{sf}F_{sf}ED_{sf}\,365.25\right) \tag{27}$$

where
- D_{sfi} = total intake from ingestion of shellfish for radionuclide i (Bq
- U_{sf} = ingestion rate of shellfish by the exposed individual (kg/d)
- C_{sfi} = average concentration of pollutant i in shellfish over the exposure duration (Bq/kg)
- F_{sf} = fraction of days per year that shellfish is eaten (dimensionless)
- ED_{sf} = exposure duration for the shellfish-ingestion pathway (yr).

2.10 Swimming-Water Ingestion

Individuals may inadvertently ingest small amounts of water while swimming. The following exposure factors are used in the evaluation.

Exposure Factors:
- Swimming frequency, time, and inadvertent ingestion rate

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 pathway is evaluated as follows:

$$D_{wwi} = C_{swi}\left(TE_{w}FE_{sw}U_{ww}\,\frac{F_{ww}ED_{ww}}{AT_{wwi}BW_{ww}}\right) \tag{28}$$

where	D_{wwi}	=	average daily dose from pollutant i from inadvertent ingestion of water while swimming (mg/kg/d)
	C_{swi}	=	average concentration of pollutant i in surface water over the exposure duration (mg/L)
	TE_w	=	duration of an average swimming event (h/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 intake for radionuclide pollutants from the swimming-water ingestion pathway is evaluated as follows:

$$D_{wwi} = C_{swi}\left(TE_w FE_{sw} U_{ww} F_{ww} ED_{ww} 365.25\right) \tag{29}$$

where	D_{wwi}	=	total intake of radionuclide pollutant i from inadvertent ingestion of water while swimming (Bq)
	C_{swi}	=	average concentration of pollutant i in surface water over the exposure duration (Bq/L)
	TE_w	=	duration of one swimming event (h/event)
	FE_{sw}	=	frequency of swimming events (events/day)
	U_{ww}	=	rate of inadvertent ingestion of water while swimming (L/h)
	F_{ww}	=	fraction of days per year that swimming occurs (dimensionless)
	ED_{wd}	=	exposure duration for the swimming dermal-contact pathway (yr)
	365.25	=	units conversion factor (d/yr).

2.11 Swimming Dermal Contact

Individuals swimming will be exposed to contaminated water via the dermal-absorption pathway from contact with water. The following exposure factors are used in the evaluation.

Exposure Factors:

- Area of skin exposed, swimming frequency, swimming event time, and exposure duration

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 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:

$$I_{swi} = C_{swi}\left(10^{-3} K_{pi} TE_w\right) \tag{30}$$

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 Bq/cm^2/event)
10^{-3} = units conversion factor (L/cm^3)
C_{swi} = average concentration of pollutant i in surface water over the exposure duration (mg/L or Bq/L)
K_{pi} = skin absorption permeability constant for pollutant i (cm/h)
TE_w = duration of one swimming event (h/event).

For organic pollutants, the absorption per event is evaluated using the six-step process described in Subsection 2.2 by Equations (4) through (11). 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 pathway is evaluated as follows:

$$D_{wdi} = I_{swi}\left(A_{wd} FE_{sw} \frac{F_{wd} ED_{wd}}{AT_{wdi} BW_{wd}} \right) \tag{31}$$

where D_{wdi} = average daily dose from chemical pollutants via dermal absorption from water contact while swimming, equivalent (mg/kg/d)
I_{swi} = amount of pollutant absorbed through the skin during one swimming event per unit area of skin contacted (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 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).

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 for radionuclides is as follows:

$$D_{wdi} = I_{swi}\left(A_{wd}FE_{sw}F_{wd}ED_{wd}365.25\right) \tag{32}$$

where
D_{wdi} = total intake from radionuclide pollutant i via dermal absorption from water contact while swimming (Bq)
I_{swi} = amount of pollutant absorbed through the skin during one swimming event per unit of skin contacted (Bq/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 pathway (yr)
365.25 = units conversion factor (d/yr).

I_{swi} is evaluated using Equation (3) for inorganic chemicals and radionuclides and Equations (10) and (11) for organic chemicals.

2.12 Shoreline Pathways

The shoreline pathways involve interaction with contaminated sediments during shoreline recreational activities. The pollutants in the sediment may result in exposure by dermal contact with sediments, inadvertent ingestion of sediments, and external exposure to radionuclides in sediments. These pathways are described in the following sections.

2.12.1 Shoreline Dermal Contact

For the dermal-contact with sediment pathway, the following exposures factors are used in the evaluation.

Exposure Factors:

- Area of skin exposed, shoreline event frequency, and exposure duration

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:

$$D_{hdi} = C_{ssi}\left(10^{-6}FE_{sl}AD\,A_{hd}AB_{di}\,\frac{F_{hd}ED_{hd}}{AT_{hdi}BW_{hd}}\right) \tag{33}$$

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)
C_{ssi} = average shoreline sediment concentration for pollutant i at the location of recreational shoreline use over the exposure duration (mg/kg or Bq/kg)
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).

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

$$D_{hdi} = C_{ssi}\left(10^{-6} FE_{sl} AD\, A_{hd} AB_{di} F_{hd} ED_{hd} 365.25\right) \tag{34}$$

where

D_{hdi}	=	intake of radionuclide pollutant i from dermal contact with shoreline sediment (Bq)
10^{-6}	=	units conversion factor (kg/mg)
C_{ssi}	=	average shoreline sediment concentration for pollutant i at the location of recreational shoreline use over the exposure duration (Bq/kg)
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)
365.25	=	units conversion factor (d/yr).

2.12.2 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 2.12.1. For the shoreline-sediment ingestion pathway, the following exposures factors are used in the evaluation.

Exposure Factors:

- Ingestion rate of sediments, shoreline event frequency, and exposure duration

This sediment concentration is used to estimate the average daily dose to chemical pollutants as follows:

$$D_{hsi} = C_{ssi}\left(10^{-3} FE_{sl} TE_{l} U_{hs} \frac{F_{hs} ED_{hs}}{AT_{hsi} BW_{hs}}\right) \tag{35}$$

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} = average shoreline sediment concentration for pollutant i at the location of recreational shoreline use over the exposure duration (mg/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 intake of radionuclide pollutants from inadvertent ingestion of shoreline sediments is estimated as follows:

$$D_{hsi} = C_{ssi}\left(10^{-3} FE_{sl} TE_l F_{hs} U_{hs} ED_{hs} 365.25\right) \quad (36)$$

where D_{hsi} = intake of radionuclide pollutant i from ingestion of shoreline sediment (Bq)
10^{-3} = units conversion factor (kg/g)
C_{ssi} = average shoreline sediment concentration for pollutant i at the location of recreational shoreline use over the exposure duration (Bq/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)
365.25 = units conversion factor (d/yr)

2.12.3 Shoreline Sediment External Radiation Exposure

The 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 the sediment over the exposure duration for the shoreline activities. The following exposure factors are used in the evaluation.

Exposure Factors:

- Shoreline event frequency, time per event, and exposure duration

The concentration to which individuals are exposed is provided as input to the receptor module where it is used to estimate the total lifetime exposure to radionuclide pollutants. This is calculated as follows:

$$D_{hei} = \frac{C_{ssi} F_{he} FE_{sl} TE_l}{24} \quad (37)$$

where D_{hei} = average sediment concentration at the exposure location over the exposure duration (Bq/kg)
C_{ssi} = average concentration of radionuclide i in shoreline sediment over the shoreline exposure duration (Bq/kg)
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)
24 = units conversion factor (h/d).

2.13 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). MEPAS has 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 (described above) is treated separately from the soil-ingestion pathway.

The following exposure factors are used in the evaluation.

Exposure Factors:

- Ingestion rate of soil, event frequency, and exposure duration

The average daily dose for chemical pollutants from soil ingestion is evaluated as follows:

$$D_{dsi} = C_{dsi}\left[U_{ds}F_{ds}\left(\frac{ED_{ds}}{AT_{dsi}BW_{ds}}\right)\right] \tag{38}$$

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)
F_{ds} = fraction of days per year that soil ingestion occurs (dimensionless)
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)
C_{dsi} = average concentration of pollutant i in soil over the exposure duration (mg/g).

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

$$D_{dsi} = C_{dsi}\left(U_{ds}F_{ds}ED_{ds}365.25\right) \tag{39}$$

where D_{dsi} = total intake of radionuclide pollutant i from ingestion of soil (Bq)
C_{dsi} = average concentration of pollutant i in soil over the exposure duration (Bq/g)
U_{ds} = ingestion rate for soil (g/d)
F_{ds} = fraction of days per year that soil ingestion occurs (dimensionless)
ED_{ds} = exposure duration for the soil-ingestion pathway (yr)
365.25 = units conversion factor (d/yr).

2.14 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 following exposure factors are used in the evaluation.

Exposure Factors:

- Soil contact event frequency and exposure duration

The amount of a pollutant 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:

$$D_{ddi} = C_{dsi}\left(10^{-3} F_{dd} FE_{dd} AD\ A_{dd} AB_{di} \frac{ED_{dd}}{AT_{ddi} BW_{dd}}\right) \tag{40}$$

where D_{ddi} = average daily dose for chemical pollutant i from dermal contact with soil, equivalent to ingestion intake (mg/kg/d)
10^{-3} = units conversion factor (g/mg)
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)
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)
f_{li} fraction of pollutant i absorbed in passing through the GI tract following ingestion (dimensionless)
C_{dsi} average concentration of pollutant i in soil over the exposure duration (mg/g).

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

$$D_{ddi} = C_{dsi}\left(10^{-3} F_{dd} FE_{dd} AD\ A_{dd} AB_{di} ED_{dd} 365.25\right) \tag{41}$$

where D_{ddi} = total intake for radionuclide pollutant i from soil dermal contact (Bq)
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)
ED_{dd} = exposure duration for the soil dermal-contact pathway (yr)
10^{-3} = units conversion factor (g/mg)
C_{dsi} = average concentration of pollutant i in soil over the exposure duration (Bq/g)
365.25 = units conversion factor (d/yr).

2.15 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 intake from indoor inhalation of volatile pollutants: the MEPAS shower inhalation model and the EPA Andelman indoor inhalation model.

The MEPAS shower inhalation model is described first, followed by the EPA Andelman (1990) 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.

The following exposure factors are used in the evaluation.

Exposure Factors:

- Inhalation rate, shower duration, shower frequency, and exposure duration

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

$$D_{sii} = C_{sai}\left[\left(\frac{U_{si} F_{si} FE_{sh} TE_s}{24}\right)\left(\frac{ED_{si}}{BW_{si} AT_{si}}\right)\right] \quad (42)$$

where D_{sii} = average daily inhalation dose from chemical pollutant i for the shower inhalation pathway (mg/kg/d)
C_{sai} = average concentration of pollutant i in shower air over the exposure duration (mg/m^3)
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 individual exposed via the shower inhalation pathway (kg)
AT_{si} = 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 intake is evaluated as follows:

$$D_{sii} = C_{sai}\left(\frac{F_{si}U_{si}FE_{sh}TE_s}{24}ED_{si}365.25\right) \tag{43}$$

where
- D_{sii} = total lifetime intake from radionuclide i for the shower inhalation pathway (Bq)
- C_{sai} = average concentration of pollutant i in shower air over the exposure duration (Bq/m^3)
- F_{si} = fraction of days per year that showering occurs (dimensionless)
- U_{si} = inhalation rate while showering (m^3/d)
- 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)
- 365.25 = units conversion factor (d/yr).

The second model available for estimation of exposure from indoor inhalation of volatile pollutants is the EPA model (EPA 1991) based on work by Andelman (1990). The following exposure factors are used in the evaluation.

Exposure Factors:
- Inhalation rate and exposure duration

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

$$D_{iai} = C_{iai}\left(U_{ia}\frac{F_{ia}ED_{ia}}{BW_{ia}AT_{iai}}\right) \tag{44}$$

where
- D_{iai} = average daily inhalation dose from chemical pollutant i for the indoor-air inhalation pathway (mg/kg/d)
- C_{iai} = average concentration of pollutant i in indoor air over the exposure duration (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 indoor-air pathway (yr)
- BW_{ia} = body weight of individual exposed via the indoor inhalation pathway (kg)
- AT_{iai} = averaging time for indoor air 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.

Equations (42) and (44) result in an average daily intake rate (mg/kg/d) for inhalation of chemicals and are to be used when health impacts are evaluated based on slope factors $(mg/kg/d)^{-1}$ or reference doses (mg/kg/d).

Equations (42) and (44) have been the standard approach for computing health impacts until recently. EPA now recommends that inhalation health impacts be based on inhalation unit risk factors [lifetime risk/(mg/m^3)] or reference concentrations (mg/m^3). The analysis is performed as described in Equations (42) and (44), except that the inhalation rate and body weight are eliminated from the equation, producing a "normalized" concentration (C_{naii}), using Equation (44) as an example.

$$C_{naii} = D_{aii}\, BW_{ai} / U_{ai} = C_{ari}\, F_{ai}\, ED_{ai} / AT_{aii} \tag{45}$$

This results in a concentration (mg/m^3) that takes the place of an intake rate (mg/kg/day) (i.e., inhalation dose). In the event that the analysis requires a reference concentration and only a reference dose is available, EPA recommends using a "typical" body weight and an inhalation rate to convert between a reference concentration, (RfC_{aii}) and a reference dose (RfD_{aii}):

$$RfC_{aii} / RfD_{aii} = (70 \text{ kg}) / (20 \text{ m}^3/\text{d}) \tag{46}$$

where the typical body weight (BW_{ai}) is assumed as 70 kg, and the typical inhalation rate (U_{ai}) is assumed as 20 m^3/d. Because this conversion normalizes to the typical body weight and inhalation rate, different health-impact results may be obtained, depending on the method employed, as noted below.

Carcinogenic impacts are evaluated using an inhalation slope factor or an inhalation unit risk concentration. If the analysis requires an inhalation unit risk concentration and only an inhalation slope factor is available, EPA recommends using a "typical" body weight and an inhalation rate to convert between the inhalation slope factor (SF_{hi}), and the inhalation unit risk concentration (UC_{hi}) as follows.

$$UC_{hi} / SF_{hi} = (20 \text{ m}^3/\text{d}) / (70 \text{ kg}) \tag{47}$$

Non-Carcinogenic Health Impact Based on Dose:

If the health impact is based on an average daily dose and a

1. reference dose value is available, then Equations (42) and (44) are used, accounting for any modifications to body weight (BW_{ai}) and intake rate (U_{ai}).
2. reference concentration value is available, then
    a. a reference dose is computed using Equation (46).
    b. Equations (42) and (44) are used, accounting for any modifications to body weight (BW_{ai}) and intake rate (U_{ai}).

Non-Carcinogenic Health Impact based on Concentration:

If the health impact is based on a concentration, and a

1. reference concentration value is available, then Equation (45) is used.
2. reference dose value is available, then
    a. a reference concentration is computed using Equation (46).
    b. Equation (45) is used.

Note that this will result in a health impact value, which differs from the values computed based on dose by the following factor:

$$(70 \text{ kg} / BW_{ai})\, [(U_{ai} / (20 \text{ m}^3/\text{d})] \tag{48}$$

Carcinogenic Health Impact based on Dose:

If the health impact is based on a slope factor and an

1. inhalation slope factor value is available, then Equations (42) and (44) are used, accounting for any modifications to body weight (BW_{ai}) and intake rate (U_{ai}).
2. inhalation unit risk concentration value is available, then
   a. an inhalation slope factor is computed using Equation (47).
   b. Equations (42) and (44) are used, accounting for any modifications to body weight (BW_{ai}) and intake rate (U_{ai}).

Carcinogenic Health Impact based on Concentration:

If the health impact is based on a concentration, and an

1. inhalation unit risk concentration value is available, then Equation (45) is used.
2. inhalation slope factor is available, then
   a. an inhalation unit risk concentration is computed using Equation (47).
   b. Equation (45) is used.

Note that this will result in a health impact value, which differs from the values computed based on dose by the factor defined by Equation (48).

The total lifetime intake from inhalation of radionuclides in indoor air is evaluated as follows:

$$D_{iai} = C_{iai}\left(U_{ia} F_{ia} ED_{ia} 365.25\right) \tag{49}$$

where

D_{iai} = total intake from radionuclide i for the indoor-air inhalation pathway (Bq)
C_{iai} = average concentration of pollutant i in indoor air over the exposure duration (Bq/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 indoor-air inhalation pathway (yr)
365.25 = units conversion factor (d/yr).

2.16 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. The following exposure factors are used in the evaluation.

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:

$$D_{aii} = C_{ari}\left(U_{ai}F_{ai}\frac{ED_{ai}}{BW_{ai}AT_{aii}}\right) \tag{50}$$

where D_{aii} = average daily inhalation dose from chemical pollutant i for the air inhalation pathway (mg/kg/d)
C_{ari} = average concentration of pollutant i in air at the point of inhalation over the exposure duration (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.

Equation (50) results in an average daily intake rate (mg/kg/d) for inhalation of chemicals and is to be used when health impacts are evaluated based on inhalation unit risk factors [lifetime risk/(mg/m^3)] or reference concentrations (mg/m^3). The discussion describing the calculation of impacts based on average concentrations presented in Section 2.15 on inhalation of indoor air applies to this inhalation pathway also.

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

$$D_{aii} = C_{ari}\left(U_{ai}F_{ai}ED_{ai}365.25\right) \tag{51}$$

where D_{aii} = total intake from radionuclide i for the air inhalation pathway (Bq)
C_{ari} = average concentration of radionuclide i in air at the point of inhalation over the exposure duration (Bq/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)
365.25 = units conversion factor (d/yr).

2.17 Inhalation of Re-suspended 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 following exposure factors are used in the evaluation.

Exposure Factors:

- Inhalation rate, event frequency, and exposure duration

The concentration in the air above the contaminated soil is provided as input to the receptor intake module. The average daily dose for chemical pollutants from inhalation of resuspended pollutants following atmospheric transport and deposition is evaluated as follows:

$$D_{dii} = C_{rsi}\left[U_{di}\left(\frac{F_{di}ED_{di}}{AT_{dii}BW_{di}}\right)\right] \tag{52}$$

where D_{dii} = average daily dose for chemical pollutant i from inhalation of resuspended pollutants (mg/kg/d)
C_{rsi} = average concentration of pollutant i in air from resuspended soil over the exposure duration (mg/m^3)
U_{di} = inhalation rate of air for the resuspension pathway (m^3/d)
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).

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

Equation (53) results in an average daily intake rate (mg/kg/d) for inhalation for chemicals and is to be used when health impacts are evaluated based on inhalation unit risk factors [lifetime risk/(mg/m^3)] or reference concentrations (mg/m^3). The discussion describing the calculation of impacts based on average concentrations presented in Section 2.15 on inhalation of indoor air applies to this inhalation pathway also.

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

$$D_{dii} = C_{rsi}\left(U_{di}F_{di}ED_{di}365.25\right) \tag{53}$$

where D_{dii} = total intake for radionuclide pollutant i from inhalation of resuspended pollutants (Bq)
C_{rsi} = average concentration of pollutant i in air from resuspended soil over the exposure duration (Bq/m^3)
U_{di} = inhalation rate of air for the resuspension pathway (m^3/d)
F_{di} = fraction of days per year that resuspension inhalation exposure occurs (dimensionless)
ED_{di} = exposure duration for the pollutant resuspension pathway (yr)
365.25 = units conversion factor (d/yr).

2.18 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. The following exposure factors are used in the evaluation.

Exposure Factors:

- Frequency of swimming exposure and exposure duration

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

$$D_{wei} = \frac{C_{swi} F_{we} FE_{sw} TE_w}{24} \tag{54}$$

where D_{wei} = effective average water concentration for radionuclide pollutant i from swimming in contaminated surface water (Bq/L)
C_{swi} = average concentration of radionuclide i in surface water at the swimming location over the exposure duration (Bq/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)
24 = units conversion factor (h/d).

2.19 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. The following exposure factors are used in the evaluation.

Exposure Factors:

- Frequency of boating exposure and exposure duration

The total lifetime exposure from external exposures to radionuclides while boating is evaluated as follows:

$$D_{bei} = \frac{C_{swi} SBF_{be} FE_{be} TE_b}{24} \tag{55}$$

where D_{bei} = effective average water concentration for radionuclide pollutant i from boating in contaminated surface water (Bq/L)

C_{swi} = average concentration of pollutant i in surface water at the boating location over the exposure duration (Bq/L)

SB = shielding factor for boating exposures (dimensionless)

F_{be} = fraction of days per year that boating occurs (dimensionless)

FE_{be} = average frequency of boating events (events/d)

24 = units conversion factor (h/d).

2.20 Soil External Radiation

Soils contaminated with radioactive material provide a potential for external exposure to nearby individuals. The following exposure factors are used in the evaluation.

Exposure Factors:

- Exposure time to soil, and exposure duration

The soil concentration provided as input to the receptor module for this pathway is expressed as an areal concentration, per unit area of soil. The total lifetime exposure for radionuclides is evaluated as follows:

$$D_{dei} = C_{asi}\left[\frac{U_{de}\left(SH_h FT_h + SH_o FT_o\right)F_{de}}{24}\right] \tag{56}$$

where D_{dei} = effective soil concentration for external exposure for radionuclide pollutant i in soil (Bq/kg)

C_{asi} = average soil concentration over the exposure duration (Bq/kg)

U_{de} = exposure time to contaminated ground (h/d)

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)

24 = units conversion factor (h/d).

2.21 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 factors for this pathway are as follows.

Exposure Factors:

- Exposure rate and exposure duration

The air concentration is used to estimate the total lifetime exposure for the air external pathway for atmospheric transport for radionuclides as follows:

$$D_{aei} = C_{ari} \frac{U_{ae} F_{ae}}{24} \tag{57}$$

where
D_{aei} = average concentration of radionuclide i for the air external pathway (Bq/m^3)
C_{ari} = average concentration of radionuclide i in air over the exposure duration (Bq/m^3)
U_{ae} = daily exposure time (h/d)
F_{ae} = fraction of days per year external exposure to air occurs (dimensionless)
ED_{ae} = exposure duration for the air external pathway (yr)
24 = units conversion factor (h/d).

3.0 Conclusions

This document describes mathematical formulations used in the MEPAS receptor intake assessment. The receptor intake analysis starts with pollutant concentration in an exposure medium and estimates the average intake by an individual from contact with the exposure medium. The pathways include ingestion, inhalation, dermal contact, and external radiation routes of exposure. Developed by Pacific Northwest National Laboratory, MEPAS is designed for site-specific assessments using readily available information. Endpoints are computed for chemical and radioactive pollutants. 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.

4.0 References

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