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Pacific Northwest National Laboratory
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Multimedia Environmental Pollutant Assessment System (MEPAS): Exposure Pathway Module Description

D. L. Strenge
M. A. Smith

October 2006

Prepared for
Engineer Research and Development Center
U.S. Army Corps of Engineers
Vicksburg, MS
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Summary

This report represents one of the three documents that have been derived from the original Multimedia Environmental Pollutant Assessment System (MEPAS) Exposure Pathway and Human Health Impact Assessment document (Strenge and Chamberlain 1995) and describes the exposure 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. 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. 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. The exposure pathway analysis starts with pollutant concentration in a transport medium and estimates the average concentration in the exposure medium from contact with the transport medium or a secondary medium contaminated by the transport medium.

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 concentration of the exposure medium. Models for the exposure-pathway assessment 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.

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 Pollutant Assessment System
PNNL	Pacific Northwest National Laboratory
SAF	soil accumulation factor

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1.0 Introduction

The exposure-pathway module uses pollutant concentrations in transport media to estimate pollutant concentration in exposure media. The concentration values are then used in the receptor intake module to estimate the average daily intake of pollutant in the exposure media for exposed individuals from contact with the medium.

Each exposure-pathway analysis in the Multimedia Environmental Pollutant Assessment System (MEPAS) involves the definition of a transport medium (or medium of measurement), an exposure route for transfer of pollutant from the transport medium to man, and exposure conditions for the individual receiving the pollutant.

The pollutant concentration in the transport medium is the starting point for the exposure analysis. This concentration is generally represented within MEPAS as an average value over the exposure duration. Generally, the average value is calculated from input time series of concentrations in the transport medium and 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 to irrigate agriculture crops, the exposure medium is not the well water, but the foods produced. For agricultural pathways, models are used 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.

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 the purpose of transport medium usage (e.g., domestic water, aquatic foods).

Ingestion pathways include ingesting drinking water, water while showering, agricultural products (leafy vegetables, other vegetables, meat, and milk), aquatic foods (fin fish and shellfish), water or sediment while participating in aquatic recreational activities (swimming, boating, or shoreline use), and soil. Dermal pathways include contact with soil, shoreline sediments, and water (while swimming or showering). Inhalation pathways include inhaling air transported from the release site to the exposure location, resuspended particulate material from prior deposition to soil, and 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).

Four major transport pathways are considered in MEPAS, including special pathways for handling exposure to measured pollutant levels in soils. Table 2.1 lists these transport pathways and their associated exposure pathways. 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 transport pathways leading to the exposure pathway and the special transfers and processes considered in determining the pollutant concentration in the exposure medium.

Table 2.1. Transport- and Exposure-Pathway Summary

Transport Pathway	Contaminated Medium	Exposure Route	Exposure Pathways
Ground Water	Water at well location	Ingestion	Drinking water
		Ingestion	Water while showering
		Dermal	Shower Water contact
		Inhalation	Indoor air
	Soil at location of 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	Indoor air
	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
	Air at location of agricultural production	Ingestion	Leafy vegetable
		Ingestion	Other vegetables
		Ingestion	Meat
		Ingestion	Milk
	Soil at location of people	Ingestion	Soil
		Dermal	Soil contact
		Inhalation	Soil resuspension
		External	Soil

Table 2.1 (Contd)

Transport Pathway	Contaminated Medium	Exposure Route	Exposure Pathways
Measured Soil	Soil at location of people	Ingestion Dermal Inhalation External	Soil Soil contact Soil suspension Soil
	Soil at location of agricultural production	Ingestion Ingestion Ingestion Ingestion	Leafy vegetables Other vegetables Meat Milk

2.1 Drinking-Water Ingestion

Using 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.

Transport Medium:

- Water concentration, C_{dwi}, Bq/L, or mg/L, expressed as an average value over the exposure duration

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)

Exposure Factors:

- Exposure duration

The domestic water supply may come from either groundwater or surface-water sources.

The exposure concentration for the drinking-water pathway for groundwater transport is evaluated as follows for pollutants:

$$C_{dwi} = \left[C_{gwi} TF_i e^{(-\lambda_{gi} TH_{dw})} \right] \tag{1}$$

where C_{gwi} = concentration of pollutant i at the well for the domestic water supply (mg/L or Bq/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)
λ_{gi} = $\lambda_{di} + \lambda_{gi}$.
TH_{dw} = holdup time in transfer of water from the pumping station or well to the consumer (d)
C_{dwi} = average exposure concentration in drinking water (mg/L or Bq/L)

The exposure concentration for the drinking-water pathway for surface water transport is evaluated as follows for chemical pollutants:

$$C_{dwi} = \left[C_{swi} TF_i e^{(-\lambda_{gi} TH_{dw})}\right] \tag{2}$$

where C_{swi} is the concentration of pollutant i at the surface water pumping station for the domestic water supply (mg/L or Bq/L), and other terms are as previously defined.

2.2 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. Figure 2.1 shows the paths by which pollutants in transport media may reach the crops.

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}, Bq/L, or mg/L, expressed as an 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 from soil by leaching and 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

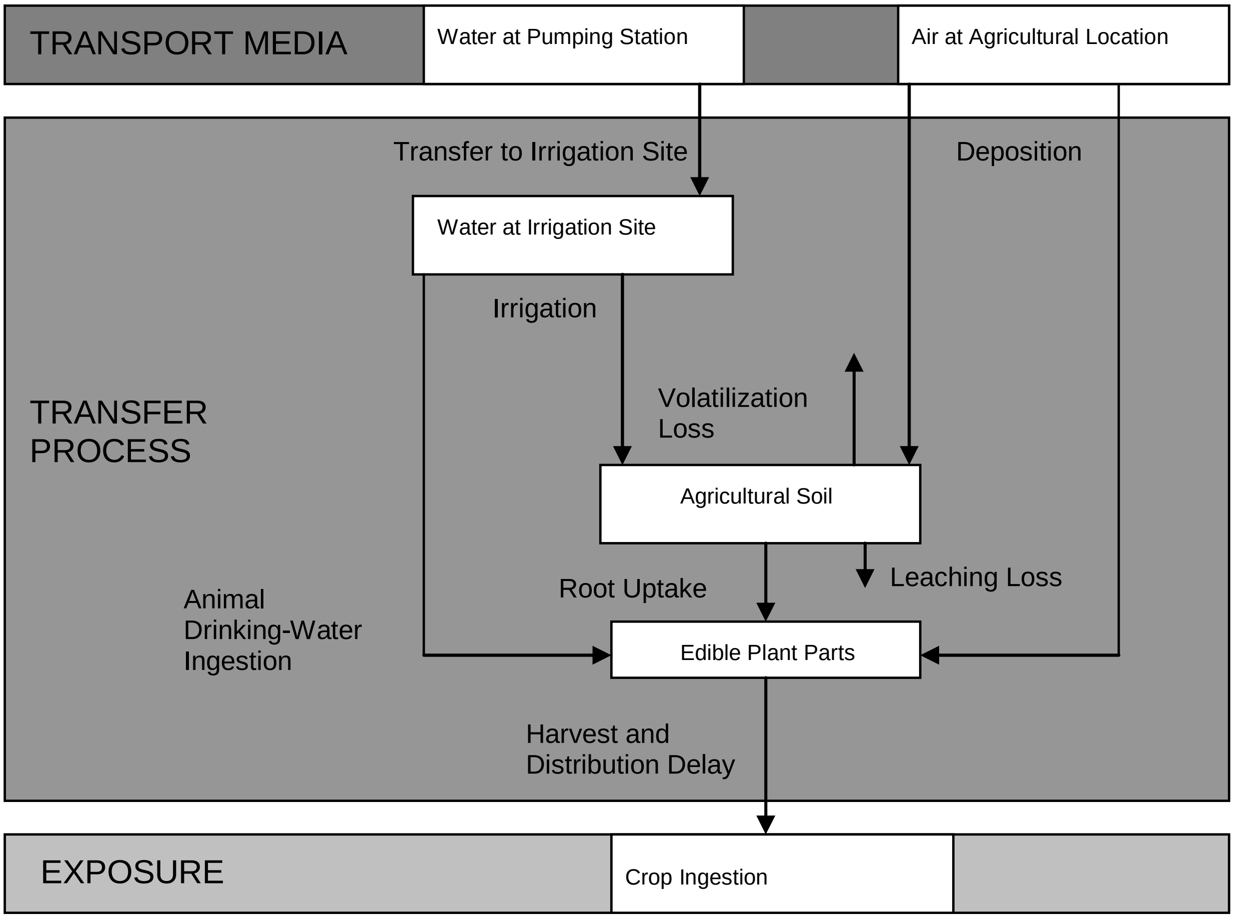

Figure 2.1. Pollutant Transfer to Edible Crops

Exposure Factors:

- Exposure duration

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

$$DP_{wi} = \frac{C_{iri} IR}{30} \tag{3}$$

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

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

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. 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:

$$\frac{dC_{awi}}{dt} = UD_{wi} - C_{awi}\lambda_{di} \tag{4}$$

and

$$SAF_i = \frac{\int_0^{ED_{kk}\,365.25} C_{awi}\,dt}{UD_{wi}ED_{kk}365.25} \tag{5}$$

where

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

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

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)

365.25 = units conversion factor (d/yr).

The environmental degradation constant includes losses from soil by leaching and volatilization.

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 member. The contributions from progeny chain members are evaluated similarly using the chain decay algorithms defined by Strenge (1997). Progeny chain members are assumed to have no quantity 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 pollutants 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 members 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:

$$CWD_{lvi} = DP_{wi}TV_{lv}r_{lv}\frac{\left[1-e^{-\lambda_{ei}TC_{lv}}\right]}{\lambda_{ei}Y_{lv}} \tag{6}$$

where CWD_{lvi} = pollutant i concentration in leafy vegetables at time of harvest from water deposition onto plants (mg/kg or Bq/kg)
DP_{wi} = rate of deposition of pollutant i in irrigation water to cropland soil and plants ($mg/m^2/d$ or $Bq/m^2/d$)
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)
λ_{ei} = effective weathering and decay constant for pollutant i (d^{-1})
λ_{ei} = $\lambda_{di} + \lambda_w$ λ_w = weathering decay constant for losses from plant surfaces (d^{-1})
TC_{lv} = duration of the crop growing period for leafy vegetables (d)
Y_{lv} = yield of leafy vegetables (kg/m^2).

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

$$CWR_{lvi} = \frac{FI_{lv} SAF_i B_{vi} DP_{wi}}{P} \tag{7}$$

where CWR_{lvi} = pollutant i concentration in edible parts of leafy vegetables at harvest from root uptake (mg/kg or Bq/kg)
DP_{wi} = rate of deposition of pollutant i in irrigation water to cropland soil and plants ($mg/m^2/d$ or $Bq/m^2/d$)
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)
SAF_i = soil accumulation factor for an exposure duration of ED_{kk} years for pollutant i (d).

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.

$$C_{lvi} = (CWD_{lvi} + CWR_{lvi}) e^{-\lambda_{gi} TH_{lv}} \tag{8}$$

where C_{lvi} = leafy vegetable plant concentration at time of consumption (mg/kg or Bq/kg)
CWD_{lvi} = pollutant i concentration in leafy vegetables at time of harvest from water deposition onto plants (mg/kg or Bq/kg)
CWR_{lvi} = pollutant i concentration in edible parts of leafy vegetables at harvest from root uptake (mg/kg or Bq/kg)
λ_{gi} = loss and decay rate constant for pollutant i in closed water systems, used to simulate loss during storage and distribution of vegetables (d^{-1})
TH_{lv} = holdup time between harvest of leafy vegetables and consumption by humans (d).

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.

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

Transport Medium:

- Air at agricultural production location, C_{ari}, Bq/m^3, or mg/m^3, expressed as an average value over the exposure duration

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:

- Exposure duration

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

$$DP_{ai} = 86400\, C_{ari}\ Vd_i \tag{9}$$

where
- DP_{ai} = rate of deposition of pollutant i from air to plants (mg/m^2/d or Bq/m^2/d)
- 86,400 = units conversion factor (s/d)
- C_{ari} = average concentration of pollutant i in air at the location of crop production (mg/m^3 or Bq/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 (4) and (5).

The concentration in edible parts of plants from airborne deposition is estimated by Equation (6), with parameters for the air pathway substituted for the irrigation pathway as follows:

$$CAD_{lvi} = DP_{ai} TV_{lv} r_{lv} \frac{\left|1 - e^{-\lambda_{ei} TC_{lv}}\right|}{\lambda_{ei} Y_{lv}} \tag{10}$$

where
- CAD_{lvi} = pollutant i concentration in leafy vegetables at time of harvest from atmospheric deposition onto plants (mg/kg or Bq/kg)
- DP_{ai} = rate of deposition of pollutant i from air to plants (mg/m^2/d or Bq/m^2/d)
- 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)
- λ_{ei} = effective weathering and decay constant for pollutant i (d^{-1})
- λ_{ei} = $\lambda_{di} + \lambda_w$, λ_w = weathering decay constant for losses from plant surfaces (d^{-1})
- TC_{lv} = duration of the growing period for leafy vegetables (d)
- Y_{lv} = yield of leafy vegetables (kg/m^2).

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

$$CAR_{lvi} = SAF_i B_{vi} \frac{DP_{si}}{P} \tag{11}$$

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

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

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)

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

The annual average deposition rate to soil (DP_{si}) is an output parameter from the atmospheric transport analysis and input to the MEPAS exposure module.

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:

$$C_{lvi} = (CAD_{lvi} + CAR_{lvi})e^{-\lambda_{gi} TH_{lv}} \tag{12}$$

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

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

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

λ_{gi} = loss and decay rate constant for pollutant i in closed water systems, used to simulate loss during storage and distribution of vegetables (d^{-1})

TH_{lv} = holdup time between harvest of leafy vegetables and consumption by humans (d).

For the measured soil-concentration pathway, two options are available to evaluate the average soil concentration over the exposure period. The first option uses the input soil concentration expressed as a function of time. For this option, the input data are used to determine the average soil concentration by numerical averaging of the data. The following considerations are included.

Transport Medium:

- Measured soil at the production location is expressed as a time series of concentration values, $C_{msi}(t)$, Bq/kg, or mg/kg

Special Processes:

- Uptake by roots from soil to edible portions of plants
- Loss of pollutants from plants following harvest before consumption by individuals

Exposure Factors:

- Exposure duration

The average soil concentration is evaluated by numerical integration of the input concentration time series information, divided by the exposure duration, as follows

$$SMF_i = \frac{1}{ED_{lv}} \int_0^{ED_{lv}} C_{msi}(t)dt \tag{13}$$

For the second option, the exposure evaluation is performed using the first concentration data point from the input file as the initial concentration (irrespective of the value of the time value provided). The average soil concentration is evaluated with the following considerations.

Transport Medium:

- Measured soil at the production location, $C_{msi}(0)$, Bq/kg, or mg/kg, expressed as the concentration at the start of the exposure period

Special Processes:

- Uptake by roots from soil to edible portions of plants
- Loss of pollutants from soil by volatilization
- Loss of pollutants from soil by leaching
- Loss of pollutants from soil by decay
- Loss of pollutants following harvest, before consumption by individuals

Exposure Factors:

- Exposure duration

The average concentration is evaluated as the time integral of the activity in the soil divided by the exposure duration as follows:

$$SMF_i = \frac{C_{msi}(0)}{ED_{lv}} \int_0^{ED_{lv}} e^{-\lambda_{ei}t} dt \tag{14}$$

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

$C_{msi}(0)$ = initial concentration of pollutant i in soil, Bq/kg dry soil or mg/kg dry soil

λ_{ei} = loss rate constant from soil, including volatilization and decay as appropriate for the pollutant i, (1/d)

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

and other terms are as previously defined.

The loss rate constant is the sum of the volatilization, leaching, and decay rate constants.

The average soil concentration is evaluated using Equation (14) for the first member of a decay chain and for non-decaying pollutants. For progeny pollutants, the average concentration from ingrowth during the exposure period is evaluated using the chain decay algorithms provided in Strenge (1997).

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

$$C_{lvi} = SMF_i B_{vi} \tag{15}$$

where C_{lvi} is the total concentration in leafy vegetables (mg/kg or Bq/kg), SMF_i is the average soil concentration for pollutant i over the exposure duration (mg/kg dry soil or Bq/kg dry soil), and B_{vi} is the soil-to-plant transfer factor for pollutant i (kg dry soil/kg wet weight plant).

2.3 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 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 (3) for irrigation deposition and Equation (9) for atmospheric deposition]. The soil accumulation factor is also applied to the other vegetable pathways, as defined by Equations (4) and (5).

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

$$CWD_{ovi} = DP_{wi} TV_{ov} r_{ov} \frac{\left[1 - e^{-\lambda_{ei} TC_{ov}}\right]}{\lambda_{ei} Y_{ov}} \tag{16}$$

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

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

$$CWR_{ovi} = \frac{FI_{ov} SAF_i B_{vi} DP_{wi}}{P} \tag{17}$$

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

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

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

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

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.

$$C_{ovi} = (CWD_{ovi} + CWR_{ovi}) e^{-\lambda_{gi} TH_{ov}} \tag{18}$$

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

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

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

λ_{gi} = loss and decay rate constant for pollutant i in closed water systems, used to simulate loss during storage and distribution of vegetables (d^{-1})

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

For the atmospheric-deposition pathway, the direct deposition of pollutants from air onto edible parts of plants is estimated by Equation (10), with parameters for the air pathway substituted for the irrigation pathway as follows:

$$CAD_{ovi} = DP_{ai} TV_{ov} r_{ov} \frac{\left[1 - e^{-\lambda_{ei} TC_{ov}}\right]}{\lambda_{ei} Y_{ov}} \tag{19}$$

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

DP_{ai} = deposition rate from air to plants for pollutant i (mg/m^2/d or Bq/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 soil accumulation factor is also applied to the atmospheric deposition to soil route, as defined by Equations (4) and (5). The plant concentration at the time of harvest for uptake from soil via roots following atmospheric deposition is estimated, as follows:

$$CAR_{ovi} = SAF_i B_{vi} \frac{DP_{si}}{P} \tag{20}$$

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

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

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 Bq/m^2/d)

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

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:

$$C_{ovi} = (CAD_{ovi} + CAR_{ovi})e^{-\lambda_{gi} TH_{ov}} \tag{21}$$

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

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

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

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

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

For the measured soil-concentration pathway, two options are available for evaluation of the average soil concentration over the exposure period. The first option uses the input soil concentration expressed as a function of time. For this option, the input data are used to determine the average soil concentration by numerical averaging of the data. The following considerations are included.

Transport Medium:

- Measured soil at the production location is expressed as a time series of concentration values, $C_{msi}(t)$, Bq/kg, or mg/kg

Special Processes:

- Uptake by roots from soil to edible portions of plants
- Loss of pollutants from plants following harvest prior to consumption by individuals

Exposure Factors:

- Exposure duration

The average soil concentration is evaluated by numerical integration of the input concentration time series information, divided by the exposure duration, as given by Equation (13).

For the second option, the exposure evaluation is performed using the first concentration data point from the input file as the initial concentration (irrespective of the value of the time value provided). The average soil concentration is evaluated with the following considerations.

Transport Medium:

- Measured soil at the production location, $C_{msi}(0)$, Bq/kg, or mg/kg, expressed as the concentration at the start of the exposure period

Special Processes:

- Uptake by roots from soil to edible portions of plants
- Loss of pollutants from soil by volatilization
- Loss of pollutants from soil by leaching
- Loss of pollutants from soil by decay
- Loss of pollutants following harvest, before consumption by individuals

Exposure Factors:

- 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 (14).

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

$$C_{ovi} = SMF_i B_{vi} \qquad (22)$$

where C_{ovi} is the concentration of pollutant i in other vegetable crops at the time of consumption (mg/kg or Bq/kg), SMF_i is the average soil concentration for pollutant i over the exposure duration (mg/kg dry soil or Bq/kg dry soil), and B_{vi} is the soil-to-plant transfer factor for pollutant i (kg dry soil/kg wet weight plant).

2.4 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 waterborne 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. Figure 2.2 shows the paths by which pollutants in transport media may reach animals.

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}, Bq/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
- 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 before consumption by humans

Intake Factors:

- 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 (3). The soil accumulation factor is also applied to the analysis, as given by Equations (4) and (5). The concentration of pollutants in feed-crop plants at the time of feeding to animals is evaluated as follows for irrigation deposition onto plants:C

$$CWD_{fti} = DP_{wi} TV_{ft} r_{ft} \frac{\left[1 - e^{-\lambda_{ei} TC_{ft}}\right]}{\lambda_{ei} Y_{ft}} \tag{23}$$

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

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

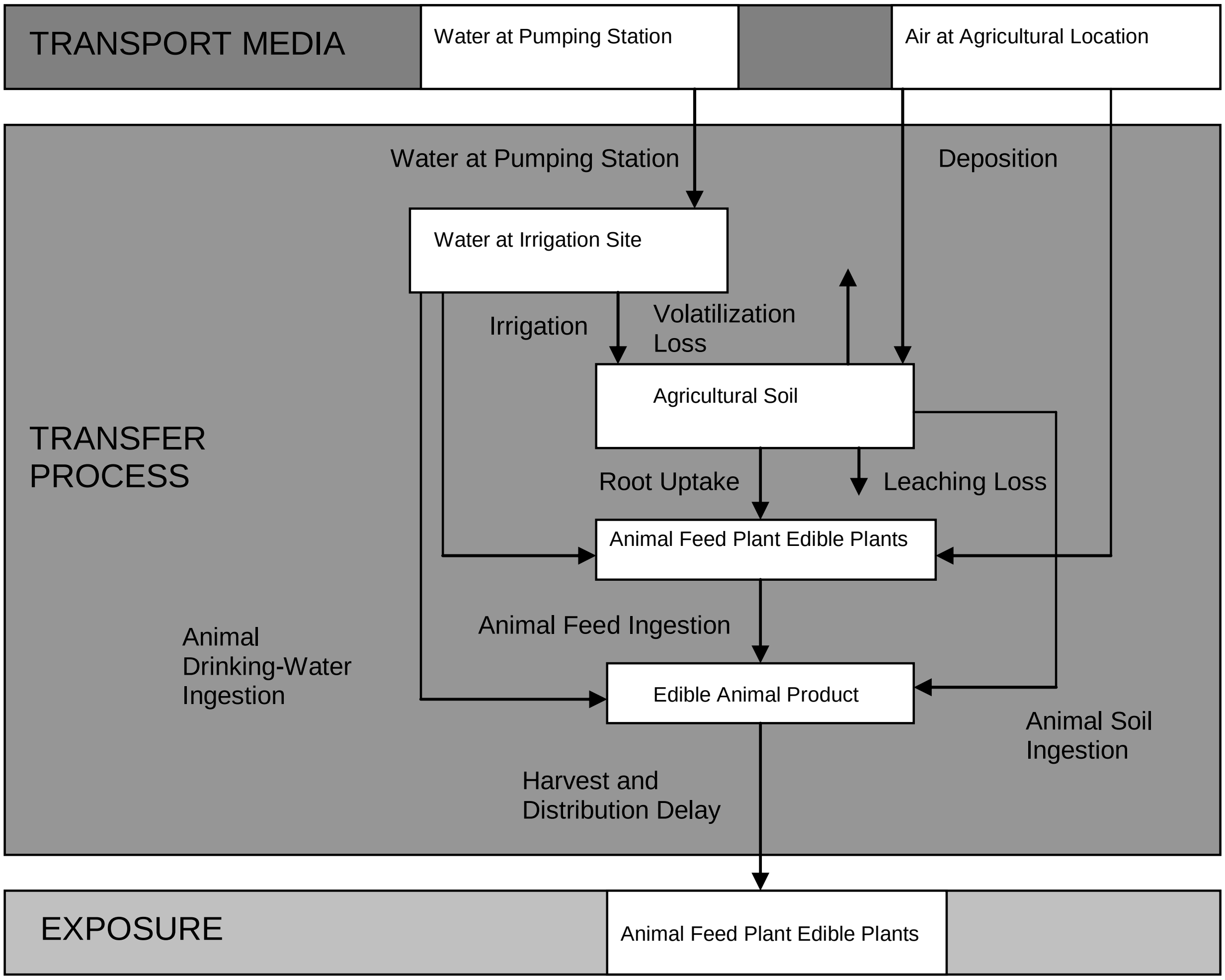

Figure 2.2. Pollutant Transfer to Animal Products

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

$$CWR_{fti} = \frac{FI_{mt} SAF_i B_{vi} DP_{wi}}{P} \tag{24}$$

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 Bq/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)

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

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

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 (4) and (5). The soil concentration is evaluated as follows:

$$CWS_{fti} = \frac{FI_{mt} SAF_i DP_{wi}}{P} \tag{25}$$

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

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)

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

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

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

$$C_{mti} = FM_{mti}\{ FC_{ft}\left[(CWD_{fti} + CWR_{fti})Q_{ft} + CWS_{fti}Q_{st}\right] + C_{iri}FC_{wt}Q_{wt} \}e^{-\lambda_{gi}TH_{mt}} \tag{26}$$

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

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

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 Bq/kg)

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 Bq/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).

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

Transport Medium:

- Air at agricultural production location, C_{ari}, Bq/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 before consumption by humans

Exposure Factors:

- Exposure duration

The deposition rate from air to plants is given by Equation (9). The soil accumulation factor, as defined by Equations (4) and (5), is also applied to this pathway.

The concentration of pollutants in edible parts of plants from atmospheric deposition is estimated by Equation (23) with parameters for the air pathway substituted for the irrigation pat400hway, as follows:

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

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

DP_{ai} = deposition rate from air to plants for pollutant i (mg/m^2/d or Bq/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 meat animal feed plant concentration at the time of harvest for uptake from soil via roots is estimated as follows:

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

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

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 wet weight plant)

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

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

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

$$C_{mti} = FM_{mti}\left(CAD_{fti} + CAR_{fti}\right)FC_{mt}Q_{ft}e^{-\lambda_{gi}TH_{mt}} \tag{29}$$

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

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

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

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

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

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

Q_{ft} = meat animal ingestion rate of feed (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_{mt} = holdup time between harvest (slaughter) and consumption of animal meat by humans (d).

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}, Bq/kg, or mg/kg, expressed as the concentration at the start of the exposure period, or as a function of time

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 before consumption of animal products by individuals

Exposure Factors:

- 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 (13 or 14), and the plant concentration is evaluated using Equation (15). The animal may also ingest soil. The soil concentration ingested by the meat animal is equal to the average soil concentration given by Equation (13 or 14). The concentration in the animal product is evaluated as follows:

$$C_{mti} = FM_{mti}FC_{ft}\left[C_{fti}Q_{ft} + SMF_iQ_{st}\right]e^{-\lambda_{gi}TH_{mt}} \tag{30}$$

where C_{mti} = concentration of pollutant i in meat at time of consumption by humans (mg/kg or Bq/kg)
C_{fti} = concentration in meat animal feed for pollutant i (mg/kg wet weight feed or Bq/kg wet weight feed)
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)
SMF_i = average soil concentration for pollutant i over the exposure duration (mg/kg dry soil or Bq/kg dry soil)
Q_{st} = meat animal intake 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_{mt} = holdup time between harvest (slaughter) and consumption of animal meat by humans (d).

2.5 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 2.4, 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. 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 2.4, 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 (3). The soil accumulation factor is also applied to the analysis as given by Equations (4) and (5). 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:

$$CWD_{fki} = DP_{wi} TV_{fk} r_{fk} \frac{\left[1 - e^{-\lambda_{ei} TC_{fk}}\right]}{\lambda_{ei} Y_{fk}} \qquad (31)$$

where CWD_{fki} = pollutant i concentration in milk animal feed crops at time of feeding from water deposition onto plants (mg/kg or Bq/kg)
DP_{wi} = deposition rate of pollutant i in irrigation water to crops (mg/m^2/d or Bq/m^2/d)
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).

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

$$CWR_{fki} = \frac{FI_{mk} SAF_i B_{vi} DP_{wi}}{P} \tag{32}$$

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 Bq/kg)
FI_{mk} = fraction of year that milk animal feed crops are irrigated (dimensionless)
SAF_i = soil accumulation factor for the milk ingestion exposure duration for pollutant i (d)
B_{vi} = soil-to-plant transfer factor for pollutant i (kg dry soil/kg wet weight plant)
DP_{wi} = deposition rate of pollutant i in irrigation water to crops (mg/m^2/d or Bq/m^2/d)
P = area soil density of farmland (kg dry soil/m^2 farmland).

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

$$C_{mki} = FM_{mki}\{FC_{fk}\left[(CWD_{fki} + CWR_{fki})Q_{fk} + CWS_{fki}Q_{sk}\right] + C_{iri}FC_{wk}Q_{wk}e^{-\lambda_{gi}TH_{mk}} \tag{33}$$

where C_{mki} = concentration of pollutant i in milk at time of consumption by humans (mg/L or Bq/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)
CWD_{fki} = pollutant i concentration in milk animal feed crops at time of feeding from water deposition onto plants (mg/kg or Bq/kg)
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 Bq/kg)
CWS_{fti} = average soil concentration for pollutant i eaten by meat animals along with feed (mg/kg dry soil or Bq/kg dry soil)
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)
C_{iri} = average concentration of pollutant i in irrigation water (mg/L or Bq/L)
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 milk (d^{-1})
TH_{mk} = holdup time between harvest (milking) and consumption of animal milk by humans (d).

For airborne-transport pathways, the milk ingestion exposure evaluation is performed with the same considerations as defined for the meat-ingestion pathway of Subsection 2.4.

The deposition rate from air to plants is given by Equation (9). The soil accumulation factor, as defined by Equations (4) and (5), is also applied to this pathway.

The concentration of pollutants in feed crop plants is estimated by Equation (31) with parameters for the air pathway substituted for the irrigation pathway, as follows:

$$CAD_{fki} = DP_{ai} TV_{fk} r_{fk} \frac{\left[1 - e^{-\lambda_{ei} TC_{fk}}\right]}{\lambda_{ei} Y_{fk}} \tag{34}$$

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

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

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)

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

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

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

$$CAR_{fki} = SAF_i B_{vi} \frac{DP_{si}}{P} \tag{35}$$

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 Bq/kg)

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

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 Bq/m^2/d)

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

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

$$C_{mki} = FM_{mki}(CAD_{fki} + CAR_{fki}) FC_{mk} Q_{fk} e^{-\lambda_{gi} TH_{mk}} \tag{36}$$

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

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

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

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 Bq/kg)
FC_{mk} = fraction of milk-animal feed that is contaminated (dimensionless)
Q_{fk} = milk-animal ingestion rate of feed (kg/d)
λ_{gi} = rate constant for decay and loss in confined water system, used to simulate loss during storage and distribution of milk (d^{-1})
TH_{mk} = holdup time between harvest (milking) and consumption of animal milk by humans (d).

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 pathway.

Transport Medium:

- Measured soil at the production location, C_{msi}, Bq/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 before consumption of animal products by individuals

Exposure Factors:

- 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 (13 or 14), and the plant concentration is evaluated using Equation (15). The animal may also ingest soil. The soil concentration ingested by the milk animal is equal to the average soil concentration given by Equation (13). The concentration in the animal product is evaluated as follows:

$$C_{mki} = FM_{mki} FC_{fk} \left[C_{fki} Q_{fk} + SMF_i Q_{sk} \right] e^{-\lambda_{gi} TH_{mk}} \tag{37}$$

where C_{mki} = concentration of pollutant i in milk at time of consumption by humans (mg/L or Bq/L)
C_{fki} = concentration in milk animal feed for pollutant i (mg/kg wet weight feed or Bq/kg wet weight feed)
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)
SMF_i = average soil concentration for pollutant i over the exposure duration (mg/kg dry soil or Bq/kg dry soil)
Q_{fk} = milk-animal ingestion rate of feed (kg/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 milk (d^{-1})
TH_{mk} = holdup time between harvest (milking) and consumption of animal milk by humans (d).

2.6 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 2.7. 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}, Bq/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, before consumption by individuals

Exposure Factors:

- Duration of ingestion

The loss of pollutants during transport in the surface water body is evaluated using Equation (2). 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:

$$C_{ffi} = C_{swi} B_{fi} e^{-\lambda_{gi} TH_{ff}} \qquad (38)$$

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

C_{swi} = average concentration of pollutant i in surface water in which fin fish are grown (mg/L or Bq/L)

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

2.7 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 2.6, except that the exposure medium, is contaminated shellfish.

The loss of pollutants during transport in the surface water body is evaluated using Equation (2). 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:

$$C_{sfi} = C_{swi} B_{si} e^{-\lambda_{gi} TH_{sf}} \tag{39}$$

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

C_{swi} = average concentration of pollutant i in surface water in which shellfish are grown (mg/L or Bq/L)

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

2.8 Shoreline Pathways

The shoreline-exposure pathways involve interaction 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, and external exposure to radionuclides in sediments. 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.

2.8.1 Shoreline Dermal Contact

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}, Bq/L, or mg/L

Special Process:
- Transfer of pollutant from water to shoreline sediment
- Accumulation of pollutant in sediment over time
- Contact of individuals with shoreline sediment

Exposure Factors:
- Exposure duration

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 (Bq/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:

$$CS_i = 100 \ln(2) C_{swi} \frac{1 - e^{-\lambda_{si} \frac{\mathrm{TE}_1 365.25}{2}}}{\lambda_{si}} \tag{40}$$

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

The shoreline accumulation period is set to the midpoint of the exposure duration to provide an average sediment concentration. The loss rate constant for loss from sediment is approximated using the loss-rate constant for surface water.

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 must be converted to a sediment-mass concentration using the sediment density and an assumed sediment thickness, as follows:

$$C_{ssi} = \frac{CS_i 10^{-6} 10^3}{t_{ss} \rho_{ss}} \tag{41}$$

where
C_{ssi} = shoreline sediment concentration for pollutant i at the location of recreational shoreline use (mg/kg or Bq/kg)
CS_i = surface concentration of pollutant i in shoreline sediment (mg/m^2 or Bq/m^2)
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).

2.8.2 Shoreline Sediment Ingestion

The sediment concentration for this exposure pathway is evaluated in the same manner as described above for the dermal contact with sediment pathway. For this pathway, the following considerations are given to the exposure evaluation.

Transport Medium:

- Surface water concentration in the water at the shoreline location, C_{swi}, Bq/L, or mg/L

Special Process:

- Transfer of pollutant from water to shoreline sediment
- Accumulation of pollutant in sediment over time
- Contact of individuals with shoreline sediment

Exposure Factors:

- Exposure duration

The sediment concentration is evaluated as described above using Equations (40) and (41).

2.8.3 Shoreline Sediment External Exposure

The sediment concentration for this exposure pathway is evaluated in the same manner as described above for the dermal contact with sediment pathway. For this pathway, the following considerations are given to the exposure evaluation.

Transport Medium:

- Surface water concentration in the water at the shoreline location, C_{swi}, Bq/L, or mg/L

Special Process:

- Transfer of pollutant from water to shoreline sediment
- Accumulation of pollutant in sediment over time
- Contact of individuals with shoreline sediment

Exposure Factors:

- Shoreline width, Exposure duration

The sediment surface contamination level is estimated as follows:

$$CS_i = 100 \ln(2) C_{swi} SW \frac{1 - e^{-\lambda_{si} \frac{\mathrm{TE_1\,365.25}}{2}}}{\lambda_{si}} \qquad (42)$$

where
CS_i = surface concentration of pollutant i in shoreline sediment (mg/m^2 or Bq/m^2)
100 = empirical constant for transfer of pollutants from water to sediment (L/m^2/d)
C_{swi} = surface water concentration of pollutant i at the location of the shoreline (mg/L or Bq/L)
SW = shoreline width factor (dimensionless)

λ_{si} = loss or decay rate constant for pollutant i from sediment (d^{-1})
TE_l = period over which shoreline sediment has accumulated (yr)
365.25 = units conversion factor (d/yr).

The surface sediment concentration must be converted to a sediment mass concentration as described by Equation (41).

2.9 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 U.S. Environmental Protection Agency (EPA) Andelman (1990) indoor inhalation model. The MEPAS shower inhalation model is described first, followed by the EPA 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 estimating the 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}, Bq/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:

- 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 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 as follows:

$$C_{sai} = 10^3 C_{dwi} TF_i e^{-\lambda_{gi} TH_{dw}} \left[\frac{H_i}{RT} \right] \tag{43}$$

where C_{sai} = concentration of pollutant i in shower air (mg/m^3 or Bq/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 Bq/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 (atm-m^3/mol)
R = gas law constant (atm-m^3/mol-°K)
T = average absolute water temperature in the shower (°K).

Equation (43) will predict relatively high air concentrations for highly volatile contaminants; therefore, a mass balance must be performed to confirm 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

$$C_{sai} V_a \leq C_{wi} V_w \tag{44}$$

where C_{sai} = concentration of pollutant i in the shower air (mg/m^3 or Bq/m^3)
C_{wi} = concentration of pollutant i in the shower water (mg/L or Bq/L)
V_a = volume of air in the shower stall (m^3)
V_w = volume of water used during the shower (L).

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 the above equation and solving for the Henry's law constant, the maximum allowable Henry's law constant is found to be 2.4×10^{-3} m^3-atm/g-mole.

The second model available for estimating the exposure from indoor inhalation of volatile pollutants is the EPA model (EPA 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:

- Average water concentration at water-treatment plant, C_{swi} or C_{gwi}, Bq/L, or mg/L

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)
- Volatilization of pollutants from the hot shower water to the indoor air, circulated throughout the house

Exposure Factors:

- Exposure duration

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

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.

$$C_{iai} = C_{dwi} TF_i e^{\left(-\lambda_{gi} TH_{dw}\right)} K_c \tag{45}$$

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)
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).

For radionuclides, the indoor air concentration is evaluated using Equation (45) with the Andelman factor defined for radionuclides as follows:

$$C_{iai} = C_{dwi} TF_i e^{\left(-\lambda_{gi} TH_{dw}\right)} K_r \tag{46}$$

where C_{iai} = concentration of radionuclide i in indoor air from volatilization from domestic water uses (Bq/m^3)
C_{dwi} = concentration of pollutant i at the pumping station or well for domestic water supply (Bq/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_r = Andelman volatilization factor for radionuclide pollutants (L/m^3).

2.10 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 soil resuspension pathway is not included for irrigation deposition to soil. The soil concentration is used as the starting point in the resuspension model to estimate the air concentration in the inhaled air.

Transport Medium:

- Soil concentration at the location of the exposed individual, C_{asi}, Bq/m^2, or mg/m^2, expressed as an annual deposition accumulation value

Special Process:

- Resuspension of pollutants in soil to air

Exposure Factors:

- Exposure duration

The soil concentration is evaluated for the atmospheric-transport pathways using the soil accumulation factor for air deposition evaluated the same as for irrigation water deposition, as defined by Equations (4) and (5). The air concentration above the soil is evaluated using a resuspension factor as follows.

$$C_{rsi} = DP_{si} SAF_i RF \tag{47}$$

where C_{rsi} = concentration of pollutant i in air from resuspended soil (mg/m^3, or Bq/m^3)
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)
RF = resuspension factor (m^{-1}).

For the measured-soil pathway, the soil concentration is expressed per unit mass of soil (rather than per unit area of soil as for the atmospheric-transport pathway). The air concentration is evaluated 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 soil on the ground.

The air concentration from resuspension, for the measured-soil pathway, is evaluated using the average soil concentration described above, as follows:

$$C_{mli} = SMF_i ML \tag{48}$$

where C_{mli} is the concentration of pollutant i in soil for external exposure (mg/m^3 or Bq/m^3), SMF_i is the average soil concentration of pollutant i (mg/kg or Bq/kg), and ML is the mass loading factor for airborne particulate material (kg/m^3).

2.11 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 soil external radiation pathway is not included for irrigation deposition to soil.

The considerations given to estimating the soil concentration for external radiation dose from exposure to radionuclides in soil from atmospheric transport and deposition is as follows.

Transport Medium:

- Atmospheric deposition rate to soil concentration at the location of the exposed individual

Special Process:

- Accumulation of radionuclides in soil over the exposure duration for the soil external pathway
- Thickness and density of soil receiving atmospheric deposition

Exposure Factors:

- Exposure duration

The soil accumulation factor for air deposition is the same as for irrigation-water deposition, as defined by Equations (4) and (5). The average soil concentration is evaluated using the soil accumulation factor, as follows.

$$C_{asi} = DP_{si} SAF_i \frac{10^{-6} 10^3}{t_{dd} \rho_{dd}} \tag{49}$$

where C_{asi} = concentration of radionuclide i in soil from atmospheric deposition (Bq/kg)
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)
10^{-6} = units conversion factor (m^3/cm^3)
10^3 = units conversion factor (g/kg)
$t_{dd=}$ = thickness of soil receiving atmospheric deposition (m)
ρ_{dd} = density of soil receiving atmospheric deposition (g/cm^3).

The considerations given to estimating the external radiation dose from exposure to radionuclides in soil when the 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}, Bq/kg

Special Processes:

- Decay of pollutants over time following the measurement of contamination levels
- Loss of pollutants by leaching or other mechanisms from the soil

Exposure Factors:

- Exposure duration

The average soil concentration for the measured-soil pathway is evaluated using the average soil concentration described above, as described earlier for the two options for specification of soil concentration. The first option uses the input soil concentration expressed as a function of time. For this option, the input data are used to determine the average soil concentration by numerical averaging of the data. The average soil concentration for this option is defined by Equation (13).

For the second option, the soil-concentration evaluation is performed using the first concentration data point from the input file as the initial concentration (irrespective of the value of the time value provided). The average soil concentration for this option is defined by Equation (14).

For both options, the accumulation of pollutants in soil is estimated using the deposition and accumulation equations described earlier. The average concentration in soil is set to the previously evaluated average soil concentration as follows:

$$C_{asi} = SMF_i \tag{50}$$

where C_{asi} is the concentration of radionuclide i in contaminated ground to depth of interest (Bq/kg), and SMF_i is the average measured soil concentration for radionuclide i (Bq/kg).

2.12 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 or when the individual is protected from inhalation exposure. The exposure for this pathway is estimated with the following considerations.

Transport Medium:

- Air concentration at the exposure location Bq/m^3

Special Process:

- None (the transport component accounts for special processes during downwind transport)

Exposure Factors:

- Exposure duration

The air concentration for the external radiation dose analysis is set equal to the average air concentration over the exposure duration, as follows:

$$C_{aei} = C_{ari} \tag{51}$$

where C_{ari} is the average concentration of radionuclide i in air at the location of crop production (Bq/m^3), and C_{aei} is the average concentration of radionculide i in air for the external radiation-dose pathway (Bq/m^3).

2.13 Carbon-14 Plant Model

The concentrations of carbon-14 in environmental media (soil, plants, and animal products) are assumed to have the same specific activity as the contaminating medium. The transfer of carbon-14 from water to plants is based on the ratio of grams of carbon-14 to grams of total carbon in soil and the amount of carbon that plants obtain from soil. The carbon-14 model present here is taken from Napier et al (1988).

The concentration of carbon-14 in plants from irrigation is evaluated as follows.

$$C_{ci} = 30 C_w IR \frac{0.1}{0.01 P \lambda_{sC}} \left[1 - e^{-\lambda_{sC} T_{irr}} \right] \tag{52}$$

where C_{ci} = concentration of carbon-14 in crop type c from irrigation deposition and soil uptake (Bq/kg wet-weight)
30 = units conversion factor (d/mo)
C_w = irrigation water concentration (Bq/L)
IR = irrigation rate, L/m^2/mo
0.1 = assumed uptake of 10% of plant carbon from soil
0.01 = average fraction of soil that is carbon
P = areal soil density for agricultural soil (kg/m^2 of farmland)
λ_{sC} = effective removal rate constant for carbon from soil (d^{-1})
T_{irr} = irrigation period for crops (d).

The concentration in plants from direct transfer from air is evaluated as follows.

$$C_{ca} = C_{air} FC_c / PC \tag{53}$$

where C_{ca} = concentration of carbon-14 in crop type c from direct transfer from air (Bq/kg wet weight)
C_{air} = concentration of carbon-14 in air (Bq/m^3)
PC = fraction of carbon in air (dimensionless)
FC_c = fraction of crop c that is carbon (dimensionless).

The concentration in plants from soil uptake is evaluated as follows.

$$C_{cs} = C_s \frac{0.1 FC_c}{0.01} \tag{54}$$

where C_{cs} = concentration of carbon-14 in crop type c from uptake from soil (Bq/kg wet weight)
C_s = average soil concentration over the growing period (Bq/kg dry soil)
FC_c = fraction of crop c that is carbon (dimensionless)
0.1 = assumed uptake of 10% of plant carbon from soil
0.01 = average fraction of soil that is carbon.

The concentration of carbon-14 in animal products is evaluated as follows

$$C_m = FC_m\left(\frac{C_c Q_{mc} FF_m + C_w Q_{wm} FW_m}{FC_c Q_{cm} + FC_w Q_{mw}}\right) \tag{55}$$

where C_m = concentration of carbon-14 in animal product m, (Bq /kg wet-weight meat) or (Bq/kg milk)
FC_m = fraction of carbon in animal product m (dimensionless)
C_c = concentration of carbon in crop c used for animal feed (Bq /kg wet-weight)
Q_{mc} = intake rate of feed crop by animal for animal type m, (kg/d)
FF_m = fraction of animal m feed intake that is contaminated (dimensionless)
C_w = concentration of carbon-14 in animal m drinking water (Bq /L)
Q_{mw} = animal m intake rate of water (L/day)
FW_m = fraction of animal m drinking water that is contaminated (dimensionless)
FC_c = fraction of crop c that is carbon (dimensionless)
FC_w = fraction of carbon in animal drinking water (dimensionless).

Table 2.2 presents parameter values for the carbon-14 model. Values are from Napier et al. (1988).

Table 2.2. Parameter Values for Carbon-14 Model

Parameter	Value
Fraction of leafy vegetables that is carbon	0.09
Fraction of other vegetables that is carbon	0.09
Fraction of forage that is carbon	0.40
Fraction of forage that is carbon	0.09
Fraction of carbon in animal meat	0.24
Fraction of carbon in animal milk	0.07
Fraction of carbon in animal drinking water	2.0×10^{-5} kg/L
Concentration of carbon in air	1.6×10^{-4} kg/m^3

2.14 Tritium Plant Model

A special model is used to evaluate the concentration of tritium in plant and animal products. The model is based on the assumption that the food type has the same specific activity as the contaminating medium. Tritium uptake is not evaluated for the measured-soil pathway as tritium is generally lost rapidly from soil, and residual levels would be small. The tritium model present here is taken from Napier et al. (1988).

The concentration of tritium in plants is evaluated based on equilibrium between water and the plant's moisture concentration, as follows.

$$C_{cT} = 9C_{wT} FHP_c \tag{56}$$

where C_{cT} = concentration of tritium in plant type c (Bq /kg wet weight)
9 = conversion from soil water to soil hydrogen based on molecular components of water (kg water in soil/kg hydrogen in soil)
C_{wT} = concentration of tritium in irrigation water (Bq /L)
FHP_c = fraction of hydrogen in total vegetation crop type c (kg hydrogen in plant/kg wet-weight plant).

Table 2.3 gives the values for the hydrogen fraction.

Table 2.3. Plant Type and Hydrogen Fraction (FHP_c)

Plant Type	Hydrogen Fraction
Leafy Vegetables	0.1
Other Vegetables	0.1
Meat Animal Feed (grain)	0.068
Milk Animal Feed (forage)	0.1

The concentration in animal products is evaluated based on tritium concentration in animal feed and animal drinking water, as follows.

$$C_{mtT} = \frac{(C_{mT} Q_{mc} FF_m + C_{wmT} Q_{mw} FW_m) FHM_m}{FHP_c Q_{mc} + Q_{mw} / 9} \tag{57}$$

where C_{mtT} = concentration of tritium in animal product m, (meat or milk) from animal intake of contaminated plants and drinking water (Bq /kg wet-weight)
C_{mT} = concentration of tritium in animal m feed plant, (grain or forage) (Bq /kg wet-weight)
Q_{mc} = intake rate of feed crop by animal for animal type m, (kg/d)
FF_m = fraction of animal m feed intake that is contaminated (dimensionless)
C_{wmT} = concentration of tritium in animal m drinking water (Bq /L)
Q_{mw} = animal m intake rate of water (L/day)
FW_m = fraction of animal m drinking water that is contaminated
FHM_m = fraction of animal product m that is hydrogen (dimensionless)
FHP_c = fraction of hydrogen in total vegetation crop type c (kg hydrogen in plant/kg wet-weight plant).
9 = conversion from soil water to soil hydrogen based on molecular components of water (kg water in soil/kg hydrogen in soil).

For meat, the hydrogen fraction is 0.1, and the meat animal feed is assumed to be all grain. For milk, the hydrogen fraction is 0.11, and the milk animal feed is assumed to be all forage. The animal feed plant concentration is evaluated using Equation (56).

Parameter values are from Napier et al. (1988).

3.0 Conclusions

This document describes mathematical formulations used in the MEPAS exposure-assessment module. The exposure-pathway analysis starts with pollutant concentration in a transport medium and estimates the average concentration in the exposure medium from contact with the transport medium or a secondary medium contaminated by the transport medium. 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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