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January 4, 2017
Revised May 21, 2019

FINAL REPORT

DOSEMM v190429: A Model for Assessment of Airborne Releases and Multimedia Terrestrial Transport and Dose Assessment

RAC Report No. 01-2017-FINAL

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CORPORATION

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DOSEMM v190429: A Model for Assessment of Airborne Releases, Terrestrial Transport, and Dose Assessment

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Executive Summary

The DOSEMM model was designed for assessment of multi-year releases of radionuclides to ambient air, their subsequent movement and transfer in the terrestrial environment, and the resulting radiation doses to humans from inhalation, ingestion, and external exposure pathways. The model does not include a module for computing atmospheric transport of radionuclides released to the air, but instead uses dispersion and deposition factors calculated from any suitable atmospheric dispersion model as input, along with the release history from sources that emit radionuclides to the air. Computations are performed across a model domain discretized into a uniform Cartesian grid, where dispersion and deposition factors are required to be provided by the external atmospheric transport model at each grid node. Discrete locations may also be added. The dispersion and deposition factors may have annual, biannual, quarterly, or monthly time resolution. The product of the source term and the dispersion factor provides an estimate of air concentration at a given grid node or discrete location. Likewise, the product of the source term and deposition factor provides an estimate of the deposition flux at a given grid node or discrete location. Radionuclides that deposit on soil may be resuspended back into the air using a time-dependent resuspension function. Radionuclide inventories in a surface and subsurface soil compartment are tracked over time. Decay, progeny ingrowth, and leaching of radionuclides are accounted in the soil model. Only parent decay is addressed during atmospheric transport. A steady-state food chain model is used to calculate radionuclide concentrations in food products including leafy vegetables and other produce, milk, meat, and wild game. A specific activity model is used to address food product concentrations of tritium and ^{14}C. For emissions of radon, the working-level month (WLM) is calculated. The user specifies locations where air, soil, and food product concentrations are calculated, along with age-specific inhalation and ingestion rates. The model allows for the use of age-specific dose coefficients for inhalation and ingestion; thereby, doses to an individual as they age over time may be calculated. Parametric uncertainty is assessed using a Monte Carlo routine coupled with simple random sampling. The overall model was verified and benchmarked using the Annual Site Environmental Report for the Idaho National Laboratory. This report is an update reflecting changes made for v190429. These changes include a reworking of the equations for accumulation in soil and resuspension and radioactive progeny ingrowth.

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Introduction

Numerous models have been developed over the last 40 years to assess radiological doses from radionuclide releases to the atmosphere. Most assessment models use an annual characterization of meteorological conditions commonly expressed as a joint frequency distribution of wind speed, wind direction, and stability class, coupled with a straight-line Gaussian plume model to calculate annual average concentrations and deposition near the site. Terrestrial transport models are then used to calculate radionuclides in soil and food products (and in some cases, water). An exposure scenario that describes the intake rates of air, soil, and food products, and the time spent at locations for an individual is used to calculate intakes of radionuclides and total external exposure. A dose coefficient library is then used to calculate doses to the individual.

Most models include the atmospheric dispersion model, which is coupled to environmental pathway, exposure scenario, and dose models. Thus, the user is tied to using the model's built-in atmospheric transport model, which may not be appropriate for the situation being modeled. Although these models are useful for future assessment purposes, they do not offer the flexibility of using alternative atmospheric transport models, and moreover, they typically assume a constant release over the assessment period.

The origins of DOSEMM are from dose reconstruction studies (Rood et al. 2002, 2008), and thus DOSEMM was designed primarily as a tool for dose reconstruction, but it has found application to prospective cases as well. DOSEMM was designed specifically to decouple the atmospheric transport model from the environmental pathway, exposure, and dose models. This allows any suitable model to be used in the assessment. Furthermore, DOSEMM allows the source term to change over time. That is, releases can reflect changes in air emissions from the source (i.e., facility, contaminated land, remediation activities, etc.) over multiple years of operations.

The atmospheric transport model results are entered into DOSEMM through atmospheric transport and deposition factors. These factors typically take the form of concentration (X) divided by source term (Q), or X/Q values, and deposition (ψ) divided by the source term Q (ψ/Q). These values are calculated using historical meteorological data and may have monthly, quarterly, biannual, or annual time resolution. Receptors can be defined anywhere in the model domain and can move from location to location over time. Parametric uncertainty is addressed through a built-in Monte Carlo sampling routine employing simple random sampling of various model parameters and uncertainty factors, thereby providing distributions of predicted concentrations in environmental media and radiological doses.

This report describes the conceptual and mathematical model, computational methods, input file construction, and code execution and output files. It reflects changes made to the soil and resuspension models made in version 190429. The software design description and configuration management plan are presented in Appendix A, and the code verification problem used to benchmark the code is presented in Appendix B.

Conceptual Model

The generalized conceptual model for DOSEMM is illustrated in Figure 1. Emission sources release radionuclides to air. Radionuclide concentrations in air are calculated by the product of the dispersion factor (X/Q) and the emission rate. Radionuclide deposition on the surface soil and on vegetation is calculated by the product of the deposition factor (ψ/Q) and the emission rate. Dispersion and deposition factors are calculated with an external atmospheric transport model. Radionuclides in surface soil may be resuspended and depleted from the layer due to leaching and decay. Radionuclides in the subsurface may be transferred to food crops and animal feed via root uptake, and also be depleted from the layer through leaching and decay. The radionuclide concentrations in the air from direct emissions and resuspension are used to calculate inhalation and air submersion doses. Radionuclide concentrations in surface soil, produce, and animal products are used to calculate doses from ingestion pathways.

A flow chart of the inputs and outputs is illustrated in Figure 2. Dispersion (X/Q) and deposition (ψ/Q) factors are read into DOSEMM via ASCII files. The X/Q and ψ/Q values need to be calculated on a uniform spatial grid that covers the model domain. Additional discrete receptors may also be added. Any Cartesian coordinate system may be used provided that the units of measure are in meters. The source term is tabulated in an ASCII file and read in for each source. The source term includes the time history of release for each radionuclide simulated. DOSEMM allows 10 radionuclides per run, so if more radionuclides are required for the simulation, then multiple runs may be performed. Each source has unique X/Q and ψ/Q values, and up to 30 separate sources may be simulated in a run.

Environmental transport parameters, radionuclide and element-specific values, and dose coefficients are read in via ASCII text files. These files along with X/Q and ψ/Q files, the computational grid and discrete receptors, soil leaching and resuspension parameters, and receptor and exposure assessment parameters are input via a parameter definition file that is read at the beginning of a DOSEMM simulation.

For a deterministic run, most output is sent to the list file. Gridded output of environmental concentrations and doses calculated across the model domain may be generated and are written to separate files that may be read directly by the Surfer® mapping and contouring software.

Concentrations in environmental media by radionuclide, source, year, and receptor are reported in the list file. Radiation doses are summed across sources and reported by radionuclide, year, organ, and receptor. The doses are then summed across all years of exposure and all radionuclides and reported by receptor.

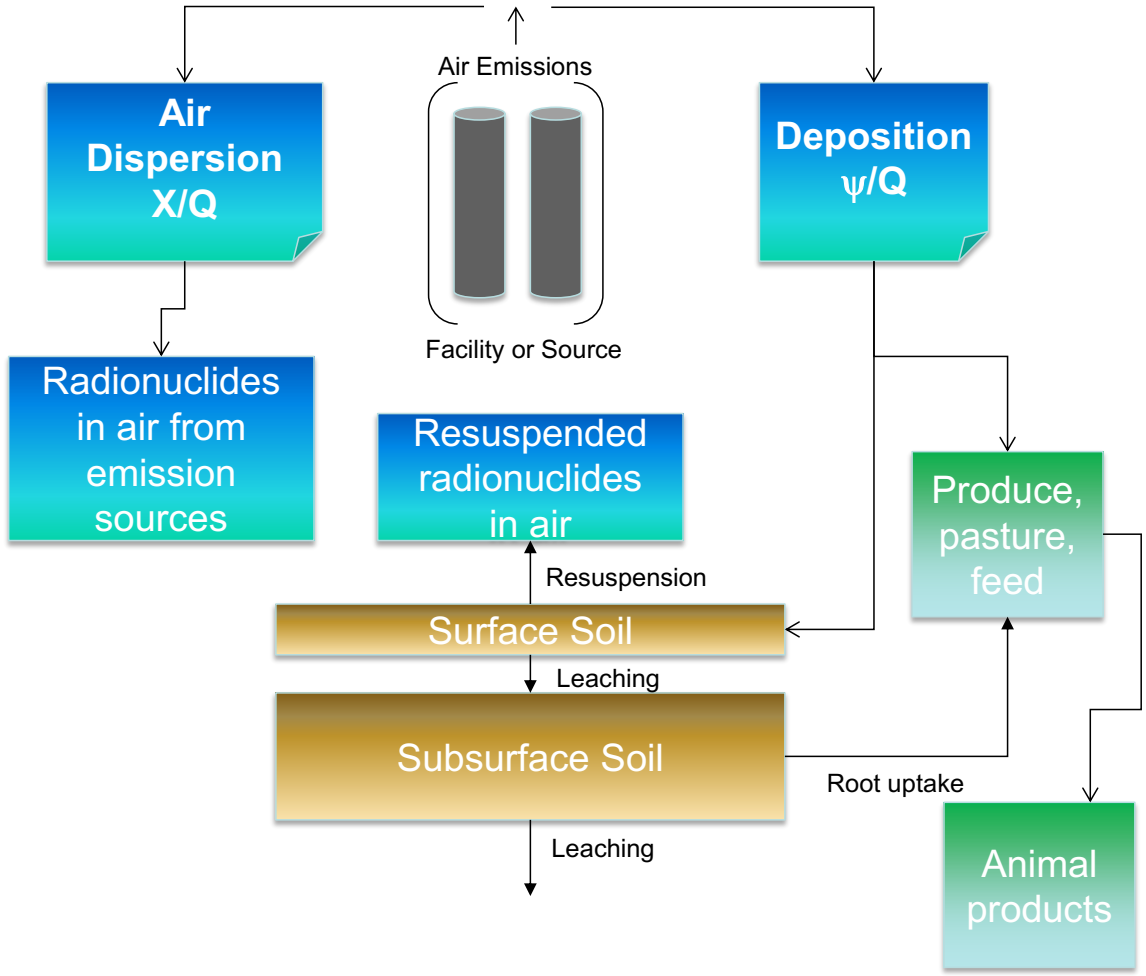

Figure 1. Generalized conceptual model for DOSEMM showing environmental media in which radionuclide concentrations are calculated. Exposure and dose are calculated based on the radionuclide concentrations in the environmental media.

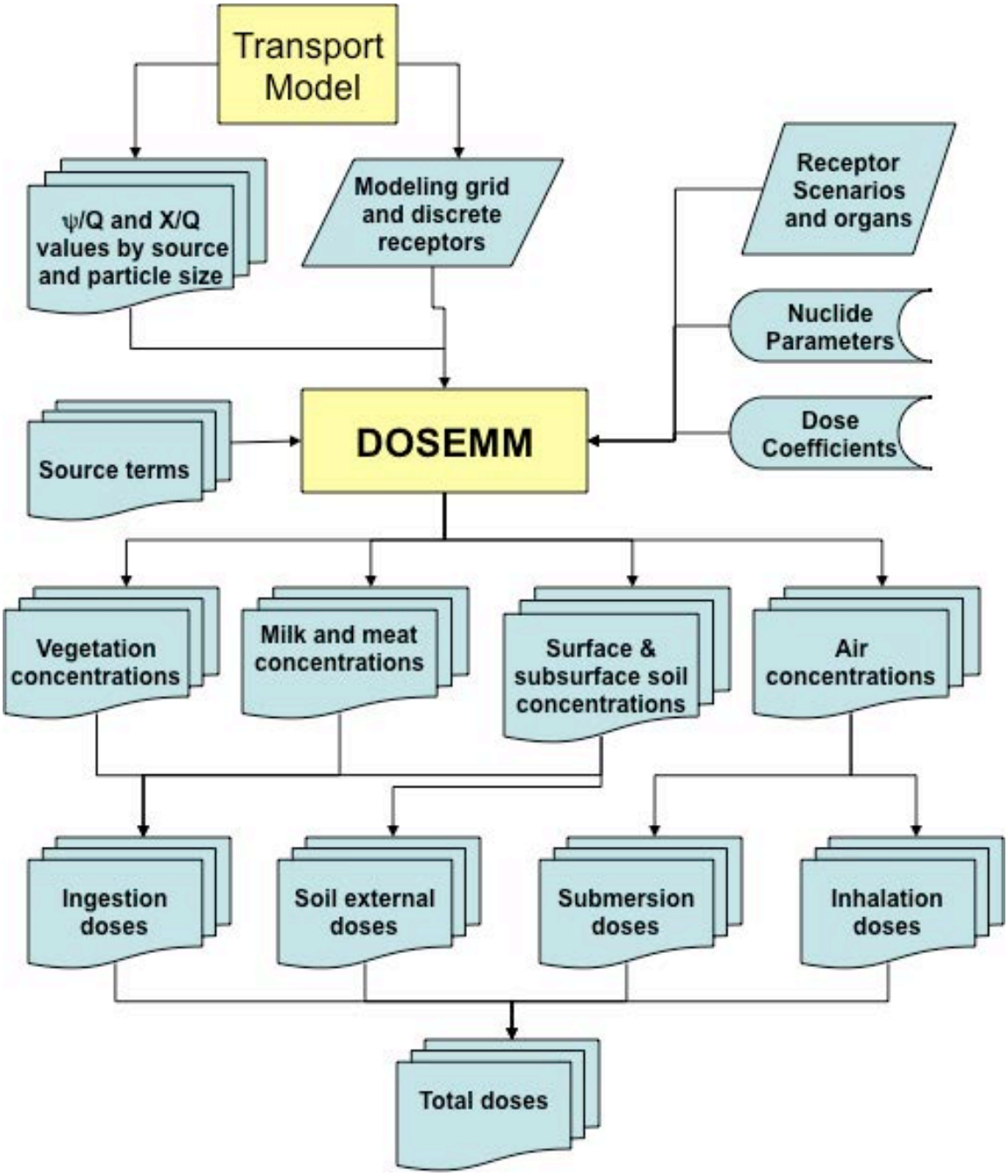

Figure 2. Computational flow chart for the DOSEMM model. The yellow boxes indicate an executable code. Blue boxes are data and output files. Additional output files are produced for Monte Carlo uncertainty analysis.

Mathematical Model

The estimated air concentration consists of contributions from direct emissions to air from the emitting sources and resuspension of radionuclides that have deposited on the soil surface. The model calculates each of these components separately for each source for the period of time

the receptor is assumed present at a given location. The air concentrations are then summed across all sources on an annual basis, providing a time-integrated air concentration from direct air emissions and resuspension.

Air Concentrations from Direct Emissions

The time-integrated concentration at a receptor for a year and a single source (i.e., at stack, vent, area, etc.) is computed by:

$$\chi_{i,j,k,n} = \sum_{m=1}^{np} \left(\chi / Q_{i,j,m} \right) Q_{j,k,m,n} \, UQ_{j,k} UM_k \, dt_m DF \tag{1}$$

where

$\chi_{i,j,k}$	=	time-integrated concentration at receptor i and source j for year k (Ci-yr m^{-3})
$\chi/Q_{i,j,m}$	=	χ/Q value for receptor i, source j, and period m (s m^{-3} for point sources, s m^{-1} for area sources)
$Q_{j,k,m,n}$	=	source term for source j, year k, period m, and radionuclide n (Ci s^{-1} for point sources, Ci m^{-2} s^{-1} for area sources)
dt_m	=	time step for period m, equivalent to $1/np$ (year)
$UQ_{j,k}$	=	source term uncertainty factor for source j and year k (unitless)
UM_k	=	meteorology uncertainty for year k (unitless)
DF	=	decay factor for transit from source to receptor (unitless)
np	=	number of periods in a year
i	=	receptor index
j	=	source index
k	=	year index
n	=	radionuclide index
m	=	period index.

The source uncertainty factor is sampled once each realization. If the source uncertainty changes over the exposure period, then it is sampled every time the uncertainty distribution changes for each model realization. If the source uncertainty does not change over the exposure period, then a single sample of the source uncertainty is made for each model realization.

The decay factor accounts for radioactive decay during transport from source to receptor. For most contaminants, decay is negligible, and DF would be 1.0. However, transport time is important for ingrowth of radon progeny. Decay time is calculated by quotient of the transport distance to the average wind speed.

The number of periods in a year can be 1, 2, 3, 4, 6, and 12. If the number of periods is 1, then χ/Q values represent annual averages. If the number of periods is 4, then χ/Q values represent quarterly averages. If the number of periods is 12, the χ/Q values represent monthly averages.

The time-integrated concentration for multiple years of exposure is given by:

$$TIC_{i,j,n} = \left(\sum_{k=Y1}^{Y2} \chi_{i,j,k,n} \right) UD_{i,j} \tag{2}$$

where

$TIC_{i,j,n}$ = time integrated concentration for receptor i, source j, and radionuclide n (Ci-yr m^{-3})
$UD_{i,j}$ = dispersion uncertainty factor for receptor i and source j (unitless)
$Y1$ = starting year
$Y2$ = ending year.

For each model realization, the dispersion uncertainty factor is sampled once for each receptor and each source. The time-integrated exposure concentration for a receptor who has multiple exposure locations and from all sources is given by:

$$TICT_n = \sum_{i=1}^{NR} \sum_{j=1}^{NS} TIC_{i,j,n} \tag{3}$$

where

$TICT_n$ = time-integrated concentration for the individual exposure period (Ci-yr m^{-3})
NR = number of receptor locations
NS = number of sources.

Deposition

Deposition is addressed in a similar fashion to Equation (3) where the ψ/Q value replaces the X/Q value.

$$\psi_{i,j,k,n} = \sum_{m=1}^{np} \left(\psi / Q_{i,j,m} \right) Q_{j,k,m,n} \; dt_m CF \, UQ_{j,k} UM_k DF \tag{4}$$

where

$\psi_{i,j,k,n}$ = deposition at receptor i from source j, year k, and radionuclide n (Ci m^{-2})
$\psi/Q_{i,j,m}$ = ψ/Q value for receptor i, source j, and month m (m^{-2})
CF = conversion factor from years to seconds (3.1536×10^7)
np = number of periods in a year
i = receptor index
j = source index
k = year index
n = radionuclide index
m = period index.

Total deposition from all sources at a receptor is given by:

$$DT_{i,n} = \sum_{j=1}^{NS} \left(\left(\sum_{k=Y1}^{Y2} \psi_{i,j,k,n} \right) UD_{i,j} \right) \tag{5}$$

Soil Concentrations in Surface and Subsurface Soil

Accumulation of activity in the surface and subsurface soil accounts for leaching and radioactive decay and ingrowth. The mass balance equation for the surface soil is described by the differential equation:

$$\frac{dQss_{i,n}}{dt} = DT_{i,n}(t) - (\lambda Ls_n + \lambda_n) Qss_{i,n} + \lambda_{n-1} Qss_{i,n-1} \tag{6}$$

where

$DT_{i,j,n,}(t)$ = time-variable deposition flux of radionuclide n at receptor i from source j equivalent to $\psi/Q \times Q$ (Ci m^{-2} yr^{-1})
$Qss_{i,n}$ = inventory of radionuclide n at receptor i in surface soil (Ci m^{-2})
λ_n = decay rate constant for radionuclide n (yr^{-1})
λLs_n = surface soil leach rate constant for radionuclide n (yr^{-1}).
i = receptor index
n = radionuclide index.

Accumulation in the subsurface (*QSB*) compartment is given by:

$$\frac{dQsb_{i,n}}{dt} = \lambda Ls_n Qss_{i,n} + \lambda_{n-1} Qsb_{i,n-1} - (\lambda Lb_n + \lambda_n) Qsb_{i,n} \tag{7}$$

where

$Qsb_{i,n}$ = inventory of radionuclide n at receptor i in subsurface soil (Ci m^{-2})
λLb_n = subsurface soil leach rate constant for radionuclide n (yr^{-1}).
i = receptor index
n = radionuclide index.

Equation 6 and 7 were solved analytically for a constant release rate (i.e., DT = constant) during the time step dt, initial condition of $Qsso$ and $Qsbo$ at t=0, and ignoring progeny ingrowth. For the surface compartment, the solution is

$$Qss_{i,n}(dt) = \frac{DT_{i,n}}{ks_n}\left[1 - e^{-ks_n\, dt}\right] + Qsso_{i,n} e^{-ks_n\, dt} \tag{8}$$

and for the subsurface compartment the solution is

$$\begin{aligned} Qsb_{i,n}(dt) = {} & \lambda Ls_n DT_{i,n}\left[\frac{1}{ks_n\, kb_n} + \frac{ks_n e^{-kb_n\, dt} - kbe^{-ks_n\, dt}}{ks_n\, kb_n\left(kb_n - ks_n\right)}\right] + \\ & \lambda Ls_n Qsso_{i,n}\left[\frac{e^{-ks_n\, dt} - e^{-kb_n\, dt}}{\left(ks_n - kb_n\right)}\right] + Qsbo_{i,n} e^{-kb_n\, dt} \end{aligned} \tag{9}$$

where

$$ks = \lambda_n + \lambda Ls_n$$

$$kb = \lambda_n + \lambda Lb_n$$

$Qsso_{i,n}$ = initial inventory of radionuclide n at receptor i in surface soil compartment (Ci m^{-2})

$Qsbo_{i,n}$ = initial inventory of radionuclide n at receptor i in subsurface soil compartment (Ci m^{-2}).

The soil inventories in the surface and subsurface compartments for each year (ignoring progeny ingrowth) in the assessment period is calculated iteratively by time step beginning from the start year of the simulation and sequentially calculating the gain and loss from the compartment using Equations 8 and 9. The surface and subsurface compartment inventories at year k are given by Equation 10 and 11 respectively.

$$QSS_{i,n,k} = \sum_{m=1}^{ns} \left(Qss_{i,n,k,m} + Qss_{i,n,k,m-1} e^{-kss\,dt} \right) \tag{10}$$

$$QSB_{i,n,k} = \sum_{m=1}^{ns} \left(Qsb_{i,n,k,m} + Qsb_{i,n,k,m-1} e^{-ksb\,dt} \right) \tag{11}$$

where

ns = $k \times np$

k = the number of years from the start of the simulation

m = period index

np = the number of periods in a year

$QSS_{i,n,k}$ = inventory of radionuclide n at receptor i and year k in surface soil compartment (Ci m^{-2})

$QSB_{i,n,k}$ = inventory of radionuclide n at receptor i and year k in subsurface soil compartment (Ci m^{-2})

The quantity Qsb and Qss in Equations (10) and (11) are Equations (8) and (9) respectively for an initial condition of zero inventory and indexed by time step. Progeny ingrowth is calculated by multiplying the inventories in each compartment at the end of the time step by the parent-to-progeny activity fraction. The activity fraction from parent (p) to the n^{th} progeny is given by (Scrable et al., 1974; Whicker and Schultz 1982):

$$q_n = q_p \left[\left(\prod_{i=1}^{n} \lambda_i \right) \sum_{i=1}^{n} \left(\frac{e^{-\lambda_i dt}}{\prod_{\substack{j \neq i \\ j=1}}^{n} \left(\lambda_j - \lambda_i \right)} \right) \right]$$

$$AF_{p-n} = BR_{p-n} \frac{q_n \lambda_n}{q_p \lambda_p} \tag{12}$$

$$A_n = \sum_{m=1}^{n-1} AF_{m-n} A_m$$

where

$AF_{p\text{-}n}$= activity fraction of parent (p) to progeny (n) after timestep dt
$BR_{p\text{-}n}$= branching ratio from parent to progeny
A_n = the activity of progeny n ingrown from parent m
n = the number in the decay chain series (i.e., 1, 2, 3 … n)
q_n = the number of atoms of progeny i (i=1 for parent)
q_p = the number of parent atoms at t = 0.
λ_p = decay constant for the parent (s^{-1})
λ_i = decay constant for the i^{th} progeny (s^{-1})
dt = timestep (s).

Equation 12 is implemented by assuming a unit activity of the parent and calculating a matrix of AF values. The inventory of the progeny that grows in from the parent during the timestep is computed and added to the progeny inventory at the end of each timestep.

The leach rate constant is given by:

$$\lambda Ls = \frac{I}{\theta Ts \left(1 + \frac{K_d \rho s}{\theta} \right)}$$

$$\lambda Lb = \frac{I}{\theta Tb \left(1 + \frac{K_d \rho b}{\theta} \right)} \tag{13}$$

where

I = infiltration rate (m yr^{-1})
θ = moisture content (unitless)
Ts, Tb = thickness of surface and subsurface soil layer, respectively (m)
ρs, ρb = bulk density of surface and subsurface soil, respectively (g cm^{-3})
K_d = linear sorption coefficient (mL g^{-1}).

The leach rate constant is based on the net infiltration through the cell and not the rainfall rate. The net infiltration can be estimated using the model for infiltration given in RESRAD:

$$I = (1 - C_e)[(1 - C_r)P_r] \tag{14}$$

where

C_e = evaporation coefficient (0.5 default value)
C_r = runoff coefficient (0.2 default value)
P_r = annual precipitation (m yr^{-1}).

The moisture content can be estimated using the model from Clapp and Hornberger (1978) as implemented in RESRAD:

$$\theta = \theta_T \left(\frac{I}{K_s} \right)^{\frac{1}{2b+3}} \tag{15}$$

where

θ_T = total porosity (m^3 m^{-3})
K_s = saturated hydraulic conductivity (m yr^{-1})
b = fitting parameter (unitless).

Resuspension

The air concentration from resuspension is given by the surface soil concentration (*QSS*, Ci m^{-2}) × the resuspension factor (*RF*, m^{-1}). The resuspension factor was calculated using an equation adapted from Reg Guide 3.51 (NRC 1982):

$$\begin{aligned} RF(t) &= RF_S e^{-\lambda R t} + RF_L \\ IRF &= \int_{t1}^{t2} RF(t)\,dt = \frac{RF_S}{\lambda R}\left(e^{-\lambda R t1} - e^{-\lambda R t2}\right) + RF_L(t2 - t1) \end{aligned} \tag{16}$$

where

λR = resuspension decay factor (yr^{-1})
RF_S = short-term resuspension factor (m^{-1})
RF_L = long-term resuspension factor (m^{-1})
IRF = time-integrated resuspension function (yr m^{-1}).

Reg Guide 3.51 uses a resuspension decay factor equivalent to a 50-day half-life (5.06 yr^{-1}) for uranium mill operations. The Reactor Safety Study (NRC 1975) uses a halftime of 373 days, and Linsley (1978) used a 69-d half time. More recent work by Maxwell and Anspaugh (2011) presents a double exponential form having a short-term factor of ~10^{-5} m^{-1} with half-time ~10 d, and a longer term decay factor having a half-time of ~370 d. The DOSEMM code is not designed to address acute fallout, and thus the NRC formation was considered more than adequate to address this process for the time-scales considered. Resuspension is applied to the surface soil

compartment, and the depth of the surface soil compartment ranges from 1 to 3 cm. The short-term resuspension factor is given in NRC (1982) as 10^{-5}, although it can range from ~10^{-5} m^{-1} to ~10^{-6} m^{-1} (Peterson 1983). The 10^{-5} m^{-1} value is appropriate for desert environments or pavement with vehicle traffic, whereas the 10^{-6} m^{-1} value is appropriate for well-vegetated soils. The long-term resuspension factor is given in NRC (1982), NRC (1975), and Maxwell and Anspaugh (2011) as 10^{-9} m^{-1} The time-integrated concentration from resuspension (*TICRS*) over multiple years of deposition is found by convolution of the resuspension function, decay and leaching functions, and source terms.

$$TICRS_{i,n}(t) = pmf \int_0^t QSS_{i,n}(\tau) RF(t-\tau) d\tau \cong pmf \sum_{k=Y1}^{Y2} \sum_{m=1}^{np} Qss_{i,n,k,m}(dt) IRF_{Y2-k} \qquad (17)$$

where

$Qss_{i,n}$ = the time-dependent inventory in the surface soil compartment (Ci m^{-2})
$t-\tau$ = the age of the deposit
IRF_{Y2-k} = integrated resuspension factor from time *Y2-k* to *Y2-k*+1(m^{-1})
pmf = particle size modification factor
i = receptor index
m = period index.
n = radionuclide index.
k = the year index from the start of the simulation

When the number of periods (*np*) is greater than 1 then there is an option to set the integration limits for the short-term resuspension factor to account for the age of the deposit *within* the 1-year period. In this case, the integration limits are $Y2 - k$ to $Y2 - k + m \times dt$.

The particle size modification factor (*pmf*) accounts for the limited ability of large particles to resuspend. The *pmf* takes the value between 0 and 1.0. This correction is consistent with NRC (1982) which uses the ratio of the default deposition velocity (0.01 m s^{-1}) for small particles that the resuspension factor is based on to the deposition velocity of a large particle as the *pmf*.

Because the resuspension and leaching functions are independent of receptor, the time-integrated concentrations from resuspension are calculated once for each source, radionuclide, and output time using a unit ψ/Q value. These values are then scaled according to the ψ/Q values at the specific receptor. Radioactive ingrowth is addressed in a similar fashion as the surface and subsurface soil model (see Equation 12).

Food Chain Modeling

The food chain model employs a model similar to that used in the CAP88 model, which is based on U.S. NRC Regulatory Guide 1.109. The model considers ingestion of leafy vegetables and other produce, beef, milk, and a special case of wild game. Special specific activity models for ^{14}C and ^{3}H are also embedded.

The equations for food product concentrations are provided in a general form and do not include the source, location, or radionuclide indexes. Two general equations for vegetation are provided. The first equation assumes build-up of radionuclides in soil for a user-provided time period assuming an annual average deposition rate. The radionuclide build-up term accounts for radioactive decay but does not account for leaching, and it is used to calculate root uptake. This

equation is what is used in Regulatory Guide 1.109 and CAP88 and is provided for consistency with these regulatory models. The second equation uses the radionuclide inventories in soil calculated in Equation (11) to calculate root uptake, so the soil inventories reflect all emissions from the year calculated to the modeled start of operations of the facility. This equation provides a more realistic assessment of food product concentrations. The general equation for radionuclide concentration in leafy vegetables, produce, pasture, stored feed, and natural forage for the NRC/CAP88 model is given in Equation (18):

$$Cv_k = \psi_k \left(\frac{fi\ fw\left(1-\exp\left[\left(\lambda+\lambda_w\right)t_e\right]\right)}{Y\left(\lambda+\lambda_w\right)} + \frac{B_{iv}\left(1-\exp\left[\lambda t_b\right]\right)}{P\lambda} \right) \exp\left[-\lambda t_h\right] \qquad (18)$$

where

Cv_k = concentration in vegetation for year k (Ci kg^{-1})
ψ_k = annual average deposition rate for year k (Ci m^{-2} d^{-1})
fi = vegetation interception fraction (unitless)
fw = fraction of radioactivity remaining after washing (unitless)
λ_w = weathering rate constant (d^{-1})
t_e = time crops or vegetation are exposed (d)
B_{iv} = concentration ratio (unitless)
t_b = time of long-term buildup in soil (d)
t_h = hold-up time from harvest to consumption (d)
Y = agriculture yield (kg m^{-2})
P = surface soil density (kg m^{-2}).

In the case of wild game, the deposition term in Equation (18) is the average deposition over the model domain for the given year. The vegetation is assumed to be natural forage. The concentration ratio and agriculture yield should be in wet weight for leafy vegetables and produce, and in dry weight for animal feeds and forage.

The equation for vegetation concentrations using actual soil inventories is given by:

$$Cv_k = \left[\psi_k \left(\frac{fi\ fw\left(1-\exp\left[\left(\lambda+\lambda_w\right)t_e\right]\right)}{Y\left(\lambda+\lambda_w\right)} \right) + \frac{B_{iv}\left(QSS_k + QSB_k\right)}{P\lambda} \right] \exp\left[-\lambda t_h\right] \qquad (19)$$

where

QSS_k = radionuclide inventory in surface soil for year k (Ci m^{-2})
QSB_k = radionuclide inventory in subsurface soil for year k (Ci m^{-2}).

Once the concentration in pasture, animal feed, and forage is calculated, the concentration in milk, beef, and wild game can be calculated. The concentration in beef and wild game (assuming dry-weight consumption rates of animal feed) is given by:

$$Cm_k = FmQf\left[fp\ fs\ Cp_k + \left(1-fp\right)Csf_k + fp\left(1-fs\right)Csf\right]\exp\left[-\lambda t_h\right] \qquad (20)$$

where

Cm_k = radionuclide concentration in milk for year k (Ci L^{-1})

Fm = milk transfer coefficient (d L^{-1})
Qf = daily milk cow feed ingestion rate (dry weight kg d^{-1})
fp = fraction of year animals graze on fresh pasture
fs = fraction of animal feed that is fresh pasture
Cp_k = radionuclide concentration in pasture calculated with Equation (18) or Equation (19) (Ci kg^{-1} dry weight)
Csf_k = radionuclide concentration in stored feed calculated with Equation (18) or Equation (19) (Ci kg^{-1} dry weight)
t_h = hold-up time from milk production to consumption (d).

The concentration in beef and wild game flesh is given by:

$$Cb_k = FbQf\left[fp\,fs\,Cp_k + (1-fp)Csf_k + fp(1-fs)Csf\right]\exp\left[-\lambda t_h\right] \quad (21)$$

where

Fb = beef transfer coefficient (d kg^{-1}).

Note that when calculating pasture concentrations, t_h is set to zero in Equation (18) and Equation (19).

Wet-Weight or Dry-Weight?

Equations (18) and (19) can be used to calculate concentrations in leafy vegetables, produce, and animal feed on either a wet- or dry-weight basis. What is important is that the units of agriculture yield and intake are consistent with the units of concentration ratio. Concentration ratios such as those provided in IAEA (1994) are on a dry-weight basis, so biomass and intake rates must also be on a dry-weight basis. Human intake rates of fruits and vegetables are typically expressed in terms of wet weight, often referred to as fresh weight, thus it can be convenient to calculate leafy vegetable and produce concentrations on a wet-weight basis. A simple means to adjust concentrations in leafy vegetables and produce reported on a dry weight basis is to divide the dry-weight concentration by the dry-to-wet-weight ratio. This can be accomplished in the code by using the vegetable modification factor. Dry-to-wet ratios range from 0.05 for lettuce, to 0.059 for tomatoes, to 0.22 for potatoes, to 0.17 for cherries and pears, to ~0.9 for grains, and to ~0.2 for forage.

^{3}H and ^{14}C Food Chain Modeling

A specific activity model used to calculate ^{3}H and ^{14}C concentrations in vegetation and animal products was adapted from the NCRP screening model (NCRP 1996), which is similar in form to the specific activity model in NRC Regulatory Guide 1.109 (NRC 1977). The ^{3}H concentration in vegetation is given by:

$$CH3v_k = \frac{\chi_k\, fw \exp\left[-\lambda th\right]}{H} \quad (22)$$

where

$CH3v_k$ = ^{3}H concentration in vegetation for year k (Ci kg^{-1})

χ_k = average ^{3}H concentration in the form of HTO in ambient air (Ci m^{-3})
H = absolute humidity in ambient air (kg m^{-3})
fw = fraction of vegetation that is water (unitless).

Mean absolute humidity ranges from 4.9 g m^{-3} in arid environments, to 8.4 g m^{-3} in semiarid regions, and to 13.8 g m^{-3} in humid environments (Till 1983).

The ^{14}C concentration in vegetation is given by:

$$CC14v_k = \frac{\chi_k \, fc \exp[-\lambda th]}{Cc} \tag{23}$$

where

$CC14v_k$ = ^{14}C concentration in vegetation for year k (Ci kg^{-1})
χ_k = average ^{14}C concentration in ambient air (Ci m^{-3})
Cc = concentration of stable carbon in atmosphere (kg of C m^{-3})
fc = fraction of carbon in vegetation.

The fraction of stable carbon in the atmosphere is given in RG 1.109 as 0.16 g m^{-3}. Till (1983) and NCRP (1996) give a value of 330 ppm (0.18 g m^{-3}), and this value in recent times has been increasing due to anthropogenic sources of CO_2 emitted to the atmosphere. In RG 1.109, the concentration of ^{3}H and ^{14}C in milk and meat are calculated using transfer coefficients and feed ingestion rates. In DOSEMM, ^{3}H and ^{14}C concentrations in milk and meat are calculated assuming equilibrium with the air as done in NCRP (1996). Thus, ^{3}H concentrations in milk and meat are calculated using Equation (22), substituting for fw the fraction of milk that is water and the fraction of meat that is water, respectively. Likewise, the ^{14}C concentrations in milk and meat are calculated using Equation (23), substituting for fc the fraction of milk that is carbon and the fraction of meat that is carbon, respectively. Water and carbon fractions from various sources are provided in Table 1. The ^{14}C concentration in milk and meat calculated with the NCRP (1996) model and the RG 1.109 model were compared. Model parameters for this comparison were a feed ingestion rate of 50 kg d^{-1} wet weight, milk transfer coefficients of 0.012 d L^{-1}, and 0.031 d kg^{-1} for beef. The ratio of the ^{14}C concentrations calculated with NCRP model to that of the RG 1.109 model were 0.74 for meat and 0.985 for milk. Thus, the NCRP model and RG 1.109 models provide similar ^{14}C concentrations in milk and meat.

Table 1. Fraction of Carbon and Water in Various Food Types and Grams of C per kg Fresh Weight

Food type	Reference	Fraction of carbon	Fraction water equivalent
Vegetables	Moore et al. (1979)	0.339	0.824
Meat	Moore et al. (1979)	0.491	0.623
Milk	Moore et al. (1979)	0.169	0.875
All vegetation (RG 1.109)	NRC (1977)	0.11	0.75
Vegetables	NCRP (1996)	0.2	1.0
Meat	NCRP (1996)	0.23	1.0
Milk	NCRP (1996)	0.067	1.0

Food type	Reference	Fraction of carbon	Fraction water equivalent
	g of C per kg fresh weight (IAEA 2010)		
Food type		Geometric Mean	Maximum	Minimum
Leafy and non-leafy vegetables		30	65	18
Root crops		46	95	22
Tubers		103	130	86
Grass, fodder, pasture		100	160	40
Milk, cow		65	69	62
Meat, beef		200	290	160

Dose Calculations

The annual inhalation dose from direct emissions and resuspension for a single radionuclide is calculated using:

$$DINH_{i,k} = \sum_{j=1}^{NS} \left(TIC_{i,j,k} + TICR_{i,j,k}\right) I_k ET_i EF_i DC_{j,k} \left(ICF_i \times fin_i + 1 - fin_i\right) \quad (24)$$

where

$DINH$ = the annual dose from inhalation pathways (rem)
$TIC_{i,j,k}$ = time-integrated concentration at receptor i, source j, and year k (Ci-yr m^{-3})
$TICR_{i,j,k}$ = time-integrated concentration from resuspension at receptor i, source j, and year k (Ci-yr m^{-3})
I_k = inhalation rate for year k (m^3 hr^{-1})
ET_i = exposure time at receptor i (hr d^{-1})
EF_i = exposure frequency at receptor i (d yr^{-1})
$DC_{j,k}$ = dose coefficient for source j and age at year k (rem Ci^{-1})
ICF_i = indoor air correction factor (set to 1.0 for no correction)
fin_i = fraction of time spent indoors (set to zero for no time indoors).

Note that the dose coefficient is selected by source because each source has a specific particle size associated with it. Age-specific breathing rates are given in Table 2 and were derived from the work of Roy and Courtay (1991) and Layton (1993) as described in Rood and Grogan (1999). Breathing rates are linearly interpolated for the age of the receptor at the time of exposure. Also note that partial year exposure is considered because the time-integrated concentration integrates over the partial year as defined in the exposure scenario.

The general equation for ingestion doses from soil, vegetables, milk, and meat for a single radionuclide is calculated using:

$$DING_{i,k} = \sum_{j=1}^{NS} CF_{i,j,k} ING_k DCING_k imf_i \quad (25)$$

where

$CF_{i,j,k}$ = the concentration in soil or food products receptor i, source j, and year k (Ci kg^{-1} or Ci L^{-1} for milk)
ING_k = annual ingestion of soil or food product for year k (kg or L yr^{-1})

$DCING_k$ = ingestion dose coefficient for age at year k (rem Ci^{-1})
imf_i = ingestion modification factor (unitless).

The ingestion modification factor may be used to account for specific changes in ingestion rates that are outside the age-specific values provided in the code input. For soil ingestion, the exposure time and exposure frequency are needed to calculate the annual intake. Soil concentrations are calculated from the surface soil inventory divided by the product of the bulk density and the surface layer thickness. The exposure time for soil ingestion is adjusted for partial exposure as described later in this section.

Table 2. Age-Specific Breathing Rates (from Roy and Courtay [1991] and Layton [1993])

Age	Male breathing rate (m^3 hr^{-1})	Female breathing rate (m^3 hr^{-1})
0	0.22	0.16
1	0.32	0.28
5	0.45	0.43
10	0.62	0.59
15	0.88	0.79
20	1.06	0.74
>20[a]	0.93	0.75

[a] Breathing rates for ages greater than 20 linearly change to the values listed on this line over a 100-year period.

External exposure from radionuclides deposited on soil is calculated for surface soil and subsurface soil separately and then summed. The dose from external exposure from radionuclides in soil at a receptor is given by:

$$DEXT_{i,k} = \left(QSS_{i,k}\ DCESS + \frac{QSB_{i,k}}{Tb} DCESB \right) ET_i\ EF_i \left(ESF \times fin_i + 1 - fin_i \right) \frac{3600\ \text{s}}{\text{hour}} \quad (26)$$

where

$DEXT_{i,k}$ = the annual dose from external exposure from soil (rem)
$QSS_{i,k}$ = surface soil concentration at receptor i and year k (Ci m^{-2})
$QSB_{i,k}$ = subsurface soil concentration at receptor i and year k (Ci m^{-2})
Tb = thickness of subsurface layer (m)
$DCESS$ = external dose coefficient for surface plane (rem-m^{-2} [Ci-s]$^{-1}$)
$DCESS$ = external dose coefficient for volume (rem-m^{-3} [Ci-s]$^{-1}$)
ET_i = exposure time at receptor i (hr d^{-1})
EF_i = exposure frequency at receptor i (d yr^{-1})
ESF = indoor external shielding factor (set to 1.0 for no shielding)
fin_i = fraction of time spent indoors.

The indoor shielding factor is the ratio of the exposure rate indoors to the exposure rate outdoors. For external exposure from soil and air, dose coefficients are not age specific. The submersion dose is given by:

$$DSUB_{i,k} = \left(TIC_{i,k} + TICR_{i,k}\right) DCSUB\ ET_i\ EF_i \left(SSF \times fin_i + 1 - fin_i\right) \frac{3600\ \text{s}}{\text{hour}} \tag{27}$$

where

$DSUB_{i,k}$ = the annual dose from air submersion (rem)
$TIC_{i,k}$ = time-integrated concentration from direct emissions at receptor i and year k (Ci-yr m^{-3})
$TICR_{i,k}$ = time-integrated concentration from resuspension at receptor i and year k (Ci-yr m^{-3})
$DCSUB$ = external dose coefficient for air submersion (rem-m^{-3} [Ci-s]$^{-1}$)
ET_i = exposure time at receptor i (hr d^{-1}),
EF_i = exposure frequency at receptor i (d yr^{-1})
SSF = indoor air submersion shielding factor (set to 1.0 for no shielding)
fin_i = fraction of time spent indoors.

The indoor shielding factor is the ratio of the submersion exposure rate indoors to the submersion exposure rate outdoors.

The exposure frequency is adjusted for partial years of exposure and only makes a difference when the number of periods is greater than 1. For soil ingestion and external exposure, the exposure frequency is modified by the multiplicative factor

$$EF_{MF} = \frac{EY + \frac{EP}{nP} - \left(SY + \frac{(SP-1)}{nP}\right)}{EY - SY + 1} \tag{28}$$

where

EF_{MF} = exposure frequency modification factor (unitless)
EY = end year
EP = end period
SY = start year
SP = start period
nP = number of periods in a year.

Radon Assessment

Radon is assessed in DOSEMM using a radon emission rate, the χ/Q values for atmospheric dispersion, annual average wind speed to the receptor, and an adaptation of the radon dosimetry model described in NCRP (1984) to calculate indoor and outdoor radon progeny concentrations and the attached and unattached fractions. Two isotopes of radon are present in the environment; ^{222}Rn is formed by the decay of ^{226}Ra and has a 3.82-day half-life. Radon-220 is formed by the decay of ^{224}Ra and has a 55-second half-life. Radon-220 is generally not as important as ^{222}Rn. Thus, only ^{222}Rn is addressed in DOSEMM, and radon generically refers to ^{222}Rn. The average wind speed is used to compute the decay and ingrowth of radon progeny during transport from source to receptor. As a starting point, the initial fractions of ^{218}Po, ^{214}Pb, and ^{214}Bi (the radon progeny of interest) are provided by the user. Because the decay chain and its members are fixed, a simple analytical solution to the ordinary differential equations is hard wired into the code. The

decay and ingrowth of radon and its progeny for a transit time t are given by (Killough et al. 1998):

$$
\begin{aligned}
&^{222}\mathrm{Rn}: A_1 = c_{11}e^{-\lambda_1 t} \\
&^{218}\mathrm{Po}: A_2 = c_{21}e^{-\lambda_1 t} + c_{22}e^{-\lambda_2 t} \\
&^{214}\mathrm{Pb}: A_3 = c_{31}e^{-\lambda_1 t} + c_{32}e^{-\lambda_2 t} + c_{33}e^{-\lambda_3 t} \\
&^{214}\mathrm{Bi}: A_4 = c_{41}e^{-\lambda_1 t} + c_{42}e^{-\lambda_2 t} + c_{43}e^{-\lambda_3 t} + c_{44}e^{-\lambda_4 t}
\end{aligned}
\tag{29}
$$

where

$\lambda_1 .. \lambda_4$ = decay rate constant for ^{222}Rn (2.10×10^{-6} s^{-1}), ^{218}Po (3.79×10^{-3} s^{-1}), ^{214}Pb (4.31×10^{-4} s^{-1}), and ^{214}Bi (5.86×10^{-4} s^{-1}), respectively

$A_1 .. A_4$ = the activities of ^{222}Rn and progeny, respectively

t = transport time (s).

The coefficients ($c_{i,j}$) are given by (Killough et al. 1998):

$$
\begin{aligned}
&c_{11} = A_1^0 \\
&c_{21} = \frac{\lambda_2 c_{11}}{\lambda_2 - \lambda_1}, c_{22} = A_2^0 - c_{21} \\
&c_{31} = \frac{\lambda_3 c_{21}}{\lambda_3 - \lambda_1}, c_{32} = \frac{\lambda_3 c_{22}}{\lambda_3 - \lambda_2}, c_{33} = A_3^0 - c_{31} - c_{32} \\
&c_{41} = \frac{\lambda_4 c_{31}}{\lambda_4 - \lambda_1}, c_{42} = \frac{\lambda_4 c_{32}}{\lambda_4 - \lambda_2}, c_{43} = \frac{\lambda_4 c_{33}}{\lambda_4 - \lambda_3}, c_{44} = A_4^0 - c_{41} - c_{42} - c_{43}
\end{aligned}
\tag{30}
$$

where $A_1{}^0 .. A_4{}^0$ are the initial activities of radon and progeny, respectively. The outdoor radon and progeny air concentrations can be calculated using the decay and ingrowth equations and a transit time that is estimated from the average wind speed and the distance between the source and receptor.

Indoor radon concentrations are a function of the outdoor concentration, building ventilation rate, and removal processes. Radon dosimetry is sensitive to the attached and unattached fractions of radon progeny. When radon decays, the ^{218}Po progeny is a positively charged ion and rapidly attaches (about 100 seconds indoors) to an aerosol particle. A small percentage remains unattached in air. Ambient air always contains some fraction of unattached ^{218}Po from recent decay of ^{222}Rn.

The unattached fraction has higher dose consequences compared to the attached fraction. However, the unattached fraction is removed from the air more rapidly compared to the attached fraction. The indoor radon model accounts for removal of the attached and unattached fractions. Note that the indoor radon and progeny concentration reflects only the outdoor concentration from an external source distant from the receptor and does not consider the diffusion of radon from the soil into the structure. The rate constant that describes the rate of attachment for ^{218}Po ions is given by (NCRP 1984):

$$\lambda att = \frac{n\pi D^2 \upsilon}{4} \tag{31}$$

where

λatt = attachment rate constant (s^{-1})
N = number concentration of condensation nuclei (cm^{-1}): indoor counts typically range from 15,000 to 120,000 condensation nuclei cm^{-3} (NCRP 1984)
D = diameter corresponding to the mean surface area of condensation nuclei (cm); a value of 0.125 μm is considered typical for environmental air (NCRP 1984)
υ = average velocity of unattached ^{218}Po ions (NCRP [1984] value of 1.38 $\times 10^4$ cm s^{-1}).

The unattached fractions of ^{214}Pb and ^{214}Bi are not explicitly calculated in the NCRP dose model and are treated as attached. The removal of attached and unattached fractions is a function of the deposition velocity and the indoor surface-to-volume ratio. The attached fraction deposition velocity has a nominal value of 0.2 m h^{-1} (Knutson 1988). For the unattached fraction, deposition velocities are in the range of 5–10 m h^{-1} with a nominal value of 8 m h^{-1} (Knutson 1988). The rate constant that describes the removal of the attached and unattached fractions is given by:

$$\lambda a = \frac{\upsilon att\ As}{V}, \lambda u = \frac{\upsilon uatt\ As}{V} \tag{32}$$

where

λa = removal rate constant for the attached fraction (s^{-1})
λu = removal rate constant for the unattached fraction (s^{-1})
υatt = attached fraction deposition velocity (m s^{-1})
$\upsilon uatt$ = unattached fraction deposition velocity (m s^{-1})
As/V = indoor surface-to-volume ratio (m^{-1}).

The building ventilation rate constant (λE) is essentially the ventilation rate divided by the building volume. Murray and Burmaster (1995) compiled a survey of residences in the United States by climatic region. Ranges of ventilation rate constants from 0.14 h^{-1} to 1.38 h^{-1} were reported for the northeast United States. The indoor air concentrations for radon and progeny are given as follows (Killough et al. 1998):

$$\begin{aligned}
&^{222}\mathrm{Rn}: [A_1]_{in} = \lambda_E [A_1]_{out} (\lambda_1 + \lambda_E)^{-1} \\
&^{218}\mathrm{Po\ (unattached)}: [A_2^*]_{in} = \left(\lambda_2 [A_1]_{in} + \lambda_E [A_2^*]_{out}\right)(\lambda_2 + \lambda_E + \lambda_{att} + \lambda_u)^{-1} \\
&^{218}\mathrm{Po\ (attached)}: [A_2^-]_{in} = \left(\lambda_{att} [A_2^*]_{in} + \lambda_E [A_2^-]_{out}\right)(\lambda_2 + \lambda_E + \lambda_a)^{-1} \\
&^{214}\mathrm{Pb}: [A_3]_{in} = \left(\lambda_3 \left([A_2^*]_{in} + [A_2^-]_{in}\right) + \lambda_E [A_3]_{out}\right)(\lambda_3 + \lambda_E + \lambda_a)^{-1} \\
&^{214}\mathrm{Bi}: [A_4]_{in} = \left(\lambda_4 [A_3]_{in} + \lambda_E [A_4]_{out}\right)(\lambda_4 + \lambda_E + \lambda_a)^{-1}
\end{aligned} \tag{33}$$

where

$[A_i]_{in}$ = the indoor air concentration of radon (i=1) or progeny (i=2 to 4)
$[A^*_2]$ = unattached fraction of ^{218}Po
$[A^-_2]$ = attached fraction of ^{218}Po
$[A_i]_{out}$ = the outdoor air concentration of radon (i=1) or progeny (i=2 to 4).

The NCRP (1984) model also contains coefficients to convert from air concentrations of radon progeny to absorbed dose to the tracheobronchial epithelium for adult male and female and a 10-year-old-child. These dose coefficients are not used in DOSEMM; instead, a simpler method used in RESRAD (Yu et al. 2001) is employed to estimate the effective dose from the working level month (WLM). The WLM is a cumulative exposure term historically applied to uranium miners. It is the product of the working level (WL) and the duration of exposure normalized to a 170-hour working month. The working level is defined as any combination of short-lived radon progeny in one liter of air that will result in emission of 1.3×10^5 MeV of potential alpha energy. One WL is equivalent to 3,700 Bq L^{-1} or 100 pCi L^{-1} of radon and daughters in equilibrium in air. Radon is seldom in equilibrium with its progeny in air. A convenient measure to describe the mixture of radon and progeny concentration in air is the equilibrium equivalent concentration (EEC). This is the radon concentration in equilibrium with its short-lived progeny that would have the same potential alpha energy per unit volume as the existing mixture. Numerically, it is defined as (NCRP 1988):

$$EEC = 0.105[A] + 0.516[B] + 0.379[C] \tag{34}$$

where [A], [B], and [C] are the air concentrations of ^{218}Po, ^{214}Pb, and ^{214}Bi, respectively. If the air concentrations are expressed in pCi L^{-1}, then WL = EEC/100 (for Bq m^{-3}, WL=EEC/3,700). The WLM calculation uses the user-defined exposure scenario that considers indoor and outdoor air.

$$WLM = \left(\frac{EEC_{outdoor}}{100}(1 - fin) + \frac{EEC_{indoor}}{100} fin \right) \frac{EF\ ET}{170 \text{ hours}} \tag{35}$$

where

ET = exposure time at receptor (hr d^{-1})
EF = exposure frequency at receptor (d yr^{-1})
fin = fraction of time spent indoors.

The WLM is computed separately for each receptor location and represents the accumulated WLM for the year. The conversion from WLM to organ or effective dose is not computed in DOSEMM because it depends on exposure scenario assumptions that may not be accounted for in the code. A summary of the dose coefficients for the equivalent dose to the lung and effective dose as summarized in Marsh et al., (2010) are presented in Table 3. The difference between dose coefficients for mine and home reflect different breathing rates and environmental conditions. In DOSEMM, the WLM, indoor and outdoor radon progeny concentrations, and attached and unattached fractions are provided. It is left to the user to compute lung and effective doses based on the models and methodology that best represent the situation to be assessed.

Table 3. Summary of Dose Coefficients for Equivalent Dose to Lung and Effective Dose from Radon Exposure

Publication	Exposure scenario	Lung Equivalent dose (mSv WLM^{-1})	Effective dose (mSv WLM^{-1})[a]
ICRP 50 (1987)	Indoors	53	6.4
	Outdoors	74	8.9
UNSCEAR (2000)	Indoors and outdoors	48	5.7
Harely et al. (1996)	Indoors and mines	80	9.6
Porstendöfer (2001)	Home (no cigarettes)	67	9

Publication	Exposure scenario	Lung Equivalent dose (mSv WLM^{-1})	Effective dose (mSv WLM^{-1})[a]
	Workplace	96	11.5
	Outdoors	88	10.6
Winkler-Heil and Hoffman (2002)	Home	63	7.6
Winkler-Heil et al. (2007)	Mine[b]	69–98	8.3–11.8
Marsh and Birchall (2000)	Home	125	15
James et al. (2004)	Mine	174	20.9
	Home	176	21.1
Marsh et al. (2005)	Mine	104	12.5
	Home	108	12.9
Marsh et al., (2010)	All persons	55	6.6
	Workers	41	5

a. Effective dose is calculated from the lung dose by multiplying be the lung tissue weighting factor of 0.12
b. The range of values presented represent different dosimetry models

Uncertainty Evaluation

Uncertainty in predicted concentrations and radiation doses uses Monte-Carlo parametric uncertainty analysis coupled with simple random sampling. Uncertainty in atmospheric dispersion, deposition, meteorology, and source term is accomplished through the sampling of a multiplicative uncertainty factor as discussed in the mathematical model section. Uncertainty in the dose coefficients is also addressed through a multiplicative uncertainty factor that is sampled once on every realization. The dose coefficient uncertainty factor can be correlated across radionuclides, or sampled independently for each radionuclide. Likewise, the source uncertainty factor can be sampled once and applied to all years of release (i.e., correlated from year to year) or sampled independently for each year of release (i.e., uncorrelated from year to year). The process for including correlation is discussed in the uncertainty files.

Uncertainty in the soil and biota transfer parameters and resuspension factors are addressed by defining distributions for each parameter. Distributions for soil sorption coefficients, concentration ratios, and milk and beef transfer coefficients are defined by the element such that the same sampled value is used across all radionuclides of the same element. These values are sampled once for each model realization.

Parameter distributions are limited to normal, lognormal, triangular, and uniform. Normal and lognormal distributions may be truncated. Specification of the distribution type and parameters is discussed in the uncertainty files section under code implementation.

Monte Carlo output files are written for time-integrated concentration in air from emissions, time-integrated concentration in air from resuspension, deposition, and total dose. For the time-integrated concentrations in air and deposition amount, time-integrated results over the model simulation time are presented by radionuclide, receptor, and model realization Results are summarized at the end of the file by the percentiles of the output distribution. For the dose output, inhalation dose by receptor, radionuclide, organ, year, and model realization are provided in one file. A second file has the inhalation and total dose summed across all radionuclides, years, and

receptor locations for each model realization and also contains a summary in terms of percentiles of the output distribution.

Code Implementation

DOSEMM is written in Fortran 77 and 95 and can be compiled using the gfortran compiler available on Linux, Unix, and Mac OS X operating systems. The code has been compiled using the Lahey Fortran compiler for Windows© operating systems. Execution of DOSEMM is conducted by constructing ASCII input files that contain model parameter values, χ/Q and ψ/Q values, dose coefficients, radionuclide specific data, and uncertainty specifications. The primary input file is the parameter definition file. The parameter definition file defines the model domain and grid, model options, source definition, radionuclides and organs of interest, output options, other input data files, and receptor scenario definition.

Parameter Definition File

The parameter definition file is a free-format ASCII file constructed with a text editor. The structure of the parameter definition file is described in Table 4. Blank lines are accepted and comments may be inserted by placing a dollar sign ($) in the first column of the line. File formats for the other files are provided in Table 5 through Table 10. The description provided in Table 4 is for Version 180510 and later, which added the capability to use geographic (i.e., latitude and longitude) coordinate system instead of a Cartesian coordinate system (i.e., UTM). Version 180510 will run a parameter definition file from earlier version of the code.

Table 4. **Parameter Definition File for DOSEMM**

Record	Code variable	Type/Format	Units	Description
1	title	CHAR/A80	---	Title of run
2	debug	LOGICAL	---	Set to TRUE for detailed output for debugging purposes, otherwise set to FALSE
2	lgame	LOGICAL	---	Set to TRUE for calculation of wild game ingestion doses, otherwise set to FALSE
2	fmodel	CHAR*5	---	Food chain model option: SFOOD = steady state model, NONE = no food chain calculations
3	nx	INT/*	---	Number of x (east-west) nodes
3	ny	INT/*	---	Number of y (north-south) nodes
3	dx	REAL/*	m or degrees	Node spacing of grid
3	xsw	REAL/*	m or degrees	X-coordinate of southwest corner of domain
3	ysw	REAL/*	m or degrees	Y-coordinate of southwest corner of domain
3	ndiscrete	INT/*	---	Number of discrete receptors
3	gtype	CHAR*3	---	Type of grid coordinates, LL = latitude-longitude, UTM = Universal Transverse

Table 4. Parameter Definition File for DOSEMM

Record	Code variable	Type/Format	Units	Description
				Mercator, USR = user defined
3	utmzone	INT/*	---	UTM zone. If the zone is outside the range of 3-19, UTM conversion from latitude and longitude is not performed.
Record 4 is read ndiscrete times				
4	utmd(i,1)	REAL/*	m or degrees	X-coordinate of discrete receptor *i*
4	utmd(i,2)	REAL/*	m or degrees	Y-coordinate of discrete receptor *i*
5	nsrcs	INT/*	---	Number of sources
5	nresol	INT/*	---	Time resolution (must be a multiple of 12)
5	byear	INT/*	---	Year starting simulation (*yyyy*)
5	npartsize	INT/*	---	Number of particle sizes considered for sources
6	partsize(i)	REAL/*	μm	Particle size, npartsize values read
7	partmod(i)	REAL/*	---	Particle size modifier for resuspension, npartsize values read
			---	
Record 8, 9, 10, 11, 12 and 13 is read nscrs times				
8	srcname(i)	CHAR*12/*	---	Name of source for i^{th} source
8	srctype(i)	CHAR*1/*	---	Source type for i^{th} source; P for point, A for area
8	partindx(i)	INT/*	---	Index of particles sizes applied to i^{th} source
9	utms(i,1)	REAL/*	m or degrees	X-coordinate of i^{th} source
9	utms(i,2)	REAL/*	m or degrees	Y-coordinate of i^{th} source
10	filechiq(i)	CHAR*80	---	X/Q file for i^{th} source
11	filepsiq(i)	CHAR*80	---	ψ/Q file for i^{th} source
12	filesrc(i)	CHAR*80	---	Source release file for i^{th} source
13	soption(i)	INT/*	---	Source plotting option. Set to 1 to include in plotting, to 0 to exclude
14	ncontam	INT/*	---	Number of contaminants in simulation
14	ctype	CHAR*2/*	---	Contaminant type. RA for radionuclide, RN for radon. If RN, then nconam must be 1
14	norgans	INT/*	---	Number of organs to calculate doses
Record 15–21 read only if ctype=RA				
15	organ(i)	CHAR*20/*	---	Organ names, norgan values read. Names must match names in dose coefficient files. If organ(1) = NONE, then only environmental concentrations are calculated
Records 16–21 read only if organ(1)≠ NONE				
16	dcffile(1)	CHAR*80	---	Inhalation dose coefficient file. Only read

Table 4. Parameter Definition File for DOSEMM

Record	Code variable	Type/Format	Units	Description
				if organ(1)≠ NONE
17	dcffile(2)	CHAR*80	---	Ingestion dose coefficient file. Only read if organ(1)≠ NONE
18	dcffile(3)	CHAR*80	---	Surface plane external dose coefficient file. Only read if organ(1)≠ NONE
19	dcffile(4)	CHAR*80	---	Air submersion dose coefficient file. Only read if organ(1)≠ NONE
20	dcffile(5)	CHAR*80	---	Ground volume external dose coefficient file. Only read if organ(1)≠ NONE
21	subcut	REAL/*	hours	Half-life cutoff to include progeny dose coefficient in parents for submersion
21	extcut	REAL/*	years	Half-life cutoff to include progeny dose coefficients in parents for surface and ground volume external doses
22	cnames(i)	CHAR*8/*	---	Array of contaminant names to be modeled, ncontam names read
Record 23–31 read only if ctype<>RN				
23	bratio(i)	REAL/*	---	Array of branching ratios for radionuclides, ncontam values read
Records 24 read only if organ(1)≠ NONE				
24	adtype(i,j)	CHAR*1/*	---	Array inhalation solubility class for each radionuclide and source. ncontam values read per line, nsrcs lines read. Read only if ctype=RA. If solubility class = N then inhalation dose coefficient not read and set to zero
25	filenuc	CHAR*80/*	---	Radionuclide or contaminant data file
26	filelement	CHAR*80/*	---	Stable element data file
27	rflt	REAL/*	m^{-1}	Long-term resuspension factor (1E-9)
27	rfst	REAL/*	m^{-1}	Short-term resuspension factor (1E-5)
27	thkres	REAL/*	m	Thickness of resuspension layer (0.03)
27	thklch	REAL/*	m	Thickness of leaching layer (0.15)
27	infil	REAL/*	m yr^{-1}	Net infiltration rate
27	theta	REAL/*	m^3 m^{-3}	Moisture content
27	strc	REAL/*	yr^{-1}	Short-term resuspension decay constant
27	rho	REAL/*	g cm^{-3}	Bulk density
27	aws	REAL/*	m s^{-1}	Average wind speed
27	iflag	LOGICAL	---	If true integration limits for resuspension represent the age of the deposit *within* the year, otherwise, a 1-year integration limits are applied. Not applicable when nresol=1.
Record 28–31 read only if fmodel=SFOOD				

Table 4. Parameter Definition File for DOSEMM

Record	Code variable	Type/Format	Units	Description
28	dd1	REAL/*	---	Fraction of contamination retained on vegetation after washing (0.5)
28	fsubg	REAL/*	---	Fraction of produce grown in garden (1.0)
28	fsubl	REAL/*	---	Fraction of leafy vegetables grown in garden (1.0)
28	fsubp	REAL/*	---	Fraction of year animals are on pasture (0.4)
28	fsubs	REAL/*	---	Fraction of feed that is pasture when animals are on pasture (0.43)
28	lamw	REAL/*	d^{-1}	Weathering rate constant from vegetation surface (0.0696)
28	p	REAL/*	kg m^{-2}	Effective surface soil density (215)
29	qsubf	REAL/*	kg d^{-1}	Dry weight consumption of animal feed or forage (15.6)
29	r1	REAL/*	---	Fallout interception fraction for pasture (0.57)
29	r2	REAL/*	---	Fallout interception faction for vegetables and produce (0.2)
29	th1	REAL/*	d	Time delay for ingestion of pasture grass by animals (0)
29	th2	REAL/*	d	Time delay for ingestion of stored feed by animals (90)
29	th3	REAL/*	d	Time delay for ingestion of leafy vegetables (14)
29	th4	REAL/*	d	Time delay for ingestion of other produce (14)
30	tsubB	REAL/*	years	Build-up time of deposits in soil. (0 to 100 years)
30	tsubE1	REAL/*	d	Period of exposure for pasture (30)
30	tsubE2	REAL/*	d	Period of exposure for vegetables and produce (60)
30	tsubF	REAL/*	d	Delay time from animal feed to milk consumption (2)
30	tsubS	REAL/*	d	Delay time from animal slaughter to consumption (20)
30	ysubV1	REAL/*	kg m^{-2}	Pasture and forage yield (dry weight) (0.28)
30	ysubV2	REAL/*	kg m^{-2}	Leafy vegetable yield (wet weight) (1.9)
30	ysubV3	REAL/*	kg m^{-2}	Other produce yield (wet weight) (0.57)
31	absH	REAL/*	g m^{-3}	Absolute humidity (8 for arid environment)
31	concC	REAL/*	g m^{-3}	Atmospheric concentration of carbon (0.18)

Table 4. Parameter Definition File for DOSEMM

Record	Code variable	Type/Format	Units	Description
31	fw	REAL/*	---	Fraction of vegetation that is water
31	fc	REAL/*	---	Fraction of vegetation that is carbon
31	fwb	REAL/*	---	Fraction of meat that is water
31	fwm	REAL/*	---	Fraction of milk that is water
31	fcb	REAL/*	---	Fraction of meat that is carbon
31	fcm	REAL/*	---	Fraction of milk that is carbon
Record 32 and 33 is read only if ctype=RN				
32	lambdaE	REAL/*	s^{-1}	Air exchange rate constant between building and outside (0.14-1.38 hr^{-1})
	Dbar	REAL/*	cm	Diameter of condensation nuclei (~0.125 μm)
	vbar	REAL/*	cm s^{-1}	Average velocity of unattached RaA ions (8 m hr^{-1})
	cnuc	REAL/*	nuclei cm^{-3}	Condensation nuclei concentration (15,000-120,000)
	vuatt	REAL/*	m hr^{-1}	Deposition velocity for unattached RaA on interior surfaces (8 m hr^{-1})
	vat	REAL/*	m hr^{-1}	Deposition velocity for attached RaA on interior surfaces (0.2 m hr^{-1})
	stvol	REAL/*	m^{-1}	Surface-to-volume ratio of building interior (1 to 3 m^{-1})
	aws	REAL/*	m s^{-1}	Average wind speed
33	afrac(i)	REAL/*	---	Initial fraction of equilibrium of each radon progeny at the source
34	coption(i)	INT/*	---	Option to plot (1) or not to plot (0) for i^{th} contaminant, ncontam values read
35	poption(i)	INT/*	---	Plot-type option: (i=1), plot time-integrated concentration; (i=2), plot average concentration; (i=3), plot deposition. Set poption to 1 to plot or 0 not to plot
Note: Default units are given in column 4 for records 36 to 42. Set cf to 1.0 to retain default units.				
36	cf(1)	REAL/*	Ci m^{-3}	Conversion factor for air concentration
	unitslabel(1)	CHAR*20/*	---	Units label for converted air concentration
37	cf(2)	REAL/*	Ci m^{-2}	Conversion factor for annual deposition
	unitslabel(2)	CHAR*20/*	---	Units label for converted deposition
38	cf(3)	REAL/*	Ci m^{-2}	Conversion for soil surface concentration
	unitslabel(3)	CHAR*20/*	---	Units label for converted surface soil
39	cf(4)	REAL/*	Ci kg^{-1}	Conversion factor for vegetable concentrations
	unitslabel(4)	CHAR*20/*	---	Units label for converted vegetable
40	cf(5)	REAL/*	Ci L^{-1}	Conversion factor for milk concentrations

Table 4. Parameter Definition File for DOSEMM

Record	Code variable	Type/Format	Units	Description
	unitslabel(5)	CHAR*20/*	---	Units label for converted milk
41	cf(6)	REAL/*	Ci kg^{-1}	Conversion factor for beef concentrations
	unitslabel(6)	CHAR*20/*	---	Units label for converted beef
42	cf(7)	REAL/*	Ci m^{-2}	Conversion factor for subsurface soil concentration
	unitslabel(7)	CHAR*20/*	---	Units label for converted subsurface soil
Record 43 is read only if organ(1) <> to NONE				
43	fileexp	CHAR*80/*	---	File containing media intake rates (i.e., air, soil, food)
44	nrecept	INT/*	---	Number of receptors. If nrecept is less than or equal to zero, then one receptor is read and the scenario as applied to all computational nodes in the model domain
Records 45 and 46 are read nrecept times				
45	utmr(i, 1)	REAL/*	m or degrees	X-coordinate of ith receptor
	utmr(i,2)	REAL/*	m or degrees	Y-coordinate of ith receptor
46	syr(i)	INT/*	year	Start year of exposure
	spr(i)	INT/*	---	Start period of exposure (see nresol)
	eyr(i)	INT/*	year	End year of exposure
	epr(i)	INT/*	---	End period of exposure (see nresol)
	yob(i)	INT/*	year	Year of birth
47	fi(i)	REAL/*	---	Fraction of time spent indoors
	ef(i)	REAL/*	hr d^{-1}	Exposure frequency
	et(i)	REAL/*	d yr^{-1}	Exposure time
	inhm(i)	REAL/*	---	Inhalation modification factor
	ingsm(i)	REAL/*	---	Soil ingestion modification factor
	ingvm(i)	REAL/*	---	Vegetable ingestion modification factor
	ingbm(i)	REAL/*	---	Beef ingestion modification factor
	ingmm(i)	REAL/*	---	Milk ingestion modification factor
	ingwm(i)	REAL/*	---	Wild game ingestion modification factor
	cindoor(i)	REAL/*	---	Ratio of indoor to outdoor air
	esf(i)	REAL/*	---	Ratio of indoor exposure to soil to outdoor
	ssf(i)	REAL/*	---	Ratio of indoor submersion to outdoor
48	nsim	INT/*	---	Number of Monte Carlo simulations. Set to zero for deterministic run
	srand	INT/*	---	Random number seed for Monte Carlo sampling
49	fileusrc	CHAR*80/*	---	Uncertainty distribution file for source, dispersion, deposition, meteorology, and resuspension
50	fileudcf	CHAR*80/*	---	Uncertainty distribution file for dose coefficients

X/Q and ψ/Q Files

The X/Q and ψ/Q files are read in grid format beginning with the SW corner of the domain and moving to the east until the eastern boundary of the domain is reached. The NE corner of the domain is the last value read. The coordinates are not read in the file but are inferred from the grid definition parameters read in Record 3 of the parameter definition file. These parameters are *nx* (number of x nodes), *ny* (number of y nodes), *dx* (grid spacing), *xsw* (x-coordinate of SW corner), and *ysw* (y-coordinate of SW corner. Each line contains *nresol* values (see Record 5). Thus, if *nresol* is 1, then one value corresponding to an x,y coordinate is read per line. If *nresol* is 12, then 12 values on each line are read. The first line in this file is a header line that is read and discarded. The x-y coordinates can be placed following the last value read on the line. These values are not read but are useful for file documentation purposes. After the grid is read, discrete receptors are read. The number of discrete receptors is specified in Record 3 of the parameter definition file. The discrete receptors are read identically to the gridded data and referenced in the same numerical order in which they are read. The total number of values read in the X/Q and ψ/Q files are $nx \times ny \times nresol + ndiscrete \times nresol$. The units of the X/Q files are s m^{-3} and the units for the ψ/Q files are m^{-2}. Separate X/Q and ψ/Q are needed for each source in the model.

Grid Types, Variables, and Coordinate Transformations

DOSEMM allows the computational grid based on 1) geographic coordinates or latitude and longitude, 2) Cartesian coordinates based on UTM projection, and 3) Cartesian coordinates based on user or other defined coordinate system. Regardless of the coordinate type selected, the grid must have uniform grid spacing. For latitude and longitude coordinates, grid spacing is defined in termed of decimal degrees, and does not translate to equal grid spacing on a Cartesian system. Thus, Surfer grid files when using latitude and longitude are only output in terms of latitude and longitude. Latitude and longitude coordinates for receptors are converted to UTM coordinates for reference purposes and printed in the output file. Coordinate conversion is performed using the methods described in Karney (2011).

Distance between the source and receptors are used in conjunction with the average wind speed to decay-correct concentrations for short-lived radionuclides and calculate ingrowth of radon progeny. When using Cartesian coordinates, the distance calculation is straight forward.

$$d = \left(\left(x_s - x_r \right)^2 + \left(y_s - y_r \right)^2 \right) \tag{36}$$

where

d = distance between source and receptor (m),
x_s, x_r = x coordinate for source and receptor respectively (m),
y_s, y_r = y coordinate for source and receptor respectively (m).

When latitude and longitude coordinates are used, then the distance between points is estimated using the methodology described in Ramsdell et al. (1994). The distance Δx and Δy between two points is given by

$$\Delta x = r_e \cos(\phi_1)(\lambda_o - \lambda_1)$$
$$\Delta y = r_e (\phi_o - \phi_1) \quad (37)$$

where

ϕ_o, ϕ_1 = latitude between source and receptor respectively (decimal degrees),
λ_o, λ_1 = longitude between source and receptor respectively (decimal degrees),
re = radius of the earth (~6370 km)

Equation 36 is then used to compute the distance between the two points. Latitude and longitude are entered in decimal degrees with negative longitude values for points west of the Greenwich meridian and negative latitude values for points in the southern hemisphere.

Source Release Files

Source release files are provided in Record 12. A separate file is required for each source. The source release file must begin at a year greater than or equal to the begin time of the calculation. Once releases start, every year and period must be included if the release is positive. Missing years default to a zero release. A release rate for each radionuclide in the order presented in the parameter definition file must be provided. The number of periods must be a multiple of 12 (i.e., 1, 2, 3, 4, 6, and 12). Table 5 shows the file structure for a source file and Figure 3 shows an example source file. For area sources, release rates need to be integrated across the release area to yield release rates in Ci per second. No blank lines or comments are allowed in these files.

Table 5. File Structure for a Source Release[a]

Line 1	Header					
Line 2	Year 1	Period 1	Release, nuclide 1, (Ci s^{-1})	Release, nuclide 2, (Ci s^{-1})	…	Release, nuclide *n*, (Ci s^{-1})
	Year 1	Period 2	Release, nuclide 1, (Ci s^{-1})	Release, nuclide 2, (Ci s^{-1})	…	Release, nuclide *n*, (Ci s^{-1})
Line *m*+1	Year 1	Period *m*	Release, Nuclide 1, (Ci s^{-1})	Release, Nuclide 2, (Ci s^{-1})	…	Release, Nuclide *n*, (Ci s^{-1})
Line *m*+2	Year 2	Period 1	Release, Nuclide 1, (Ci s^{-1})	Release, Nuclide 2, (Ci s^{-1})	…	Release, Nuclide *n*, (Ci s^{-1})
Line *m*×*k*+1	Year *k*	Period *m*	Release, Nuclide 1, (Ci s^{-1})	Release, Nuclide 2, (Ci s^{-1})	…	Release, Nuclide *n*, (Ci s^{-1})

[a] In this file there are *k* years, containing *m* periods, and *n* radionuclides. The number of periods must be a multiple of 12 (i.e., 1, 2, 3, 4, 6, and 12).

```
Year Qrt  U-238      U-234      Th-230     Ra-226     Pb-210     Th-232     Ra-228     Th-228
1946 1    1.381e-13  1.381e-13  3.982e-13  2.083e-13  2.083e-13  7.718e-15  2.159e-15  6.554e-15
1946 2    1.372e-13  1.372e-13  3.955e-13  2.069e-13  2.069e-13  7.666e-15  2.145e-15  6.510e-15
1946 3    2.915e-14  2.915e-14  8.402e-14  4.395e-14  4.395e-14  1.629e-15  4.556e-16  1.383e-15
1946 4    1.617e-13  1.617e-13  4.661e-13  2.438e-13  2.438e-13  9.036e-15  2.528e-15  7.673e-15
1947 1    2.624e-13  2.624e-13  7.565e-13  3.957e-13  3.957e-13  1.466e-14  4.103e-15  1.245e-14
1947 2    2.380e-13  2.380e-13  6.860e-13  3.588e-13  3.588e-13  1.330e-14  3.720e-15  1.129e-14
1947 3    4.724e-14  4.724e-14  1.362e-13  7.123e-14  7.123e-14  2.640e-15  7.384e-16  2.242e-15
1947 4    2.486e-13  2.486e-13  7.166e-13  3.748e-13  3.748e-13  1.389e-14  3.886e-15  1.180e-14
```

Figure 3. Sample source release file for two years of releases and four periods (i.e., quarters) within the year (*nresol*=4).

Dose Coefficient Files

The dose coefficient file provides inhalation, ingestion, and external dose coefficients. These file names are entered in Records 16–19 of the parameter definition file. Age-dependent dose coefficients are allowed for inhalation and ingestion. Inhalation dose coefficients include specification of solubility class and aerodynamic median particle size (AMAD). External dose coefficients include separate files for submersion in air, ground surface, and ground volume. The first line in each file is a header that is read and discarded. The header is useful for documenting the data types and units. For external dose coefficients, all progeny that will be included in the parent dose coefficient need to be present in the file. The radionuclide data file identifies the decay chains and adds the progeny to the parent. No blank lines or comments are allowed in these files. Each dose coefficient is presented, one value per line. Nuclide names must match those in

the parameter definition file and, along with organ names and solubility class, should be placed in single quotes. This file can contain more radionuclides than are in any given simulation. Organ names should not include spaces and must match those identified in the parameter definition file. The dose coefficient file structure is described in Table 6.

Table 6. Dose Coefficient (DC) File Structure

Position	Inhalation	Ingestion	Submersion	Ground	Soil volume
1	Nuclide name	Nuclide name	Nuclide name	Nuclide name	Nuclide name
2	Organ	Organ	Organ	Organ	Organ
3	solubility class	f1	DC (rem-m^3 Ci^{-1} s^{-1})	DC (rem-m^2 Ci^{-1} s^{-1})	DC (rem-m^3 Ci^{-1} s^{-1})
4	f1	DC (rem Ci^{-1})			
5	AMAD (μm)	Age (years)			
6	DC (rem Ci^{-1})				
7	Age (years)				

[a] Units of the DC are in parenthesis. The f1 value for inhalation and ingestion is not used but is included for documentation and completeness. Position refers to the order in which the values are placed on a line.

Element and Radionuclide Files

The element file is entered in Record 26 of the parameter definition file and contains element-specific data including soil sorption coefficients (*Kd*), soil-plant concentration ratios (*Biv*) and milk and beef transfer coefficient (*Fm* and *Fb*, respectively) values. The file structure allows for comments by placing a dollar sign ($) in the first column. This file can contain more elements than are in any given simulation. The first line in the file is a header that is useful for documentation but is discarded.

An element record contains six lines of data. Each element record begins with the element symbol on the first line followed, by the *Kd*, *Biv* for vegetables, *Biv* for forage, *Fm* and *Fb* on the remaining five lines. For Lines 2–6, six variables are read per line because this file also defines the uncertainty distribution that is assigned to the *Kd*, *Biv*, *Fm*, and *Fb* values. The deterministic value is read first, followed by the distribution type and four parameters that define the distribution. Table 7 illustrates the element file structure. Position refers to the order on the line that the variables are placed. The uncertainty variables are discussed in the section on uncertainty files.

Table 7. Structure of the Element File [a]

Line	Position	Description
1	1	Element symbol
2	1	Deterministic soil sorption coefficient (K_d, mL g^{-1})
2	2	Distribution type (NORM, LNORM, UNIF, TRI)
2	3	Parameter 1 (see Table 9 uncertainty file discussion)
2	4	Parameter 2 (see Table 9 uncertainty file discussion)
2	5	Parameter 3 (see Table 9 uncertainty file discussion)

Table 7. Structure of the Element File [a]

Line	Position	Description
2	6	Parameter 4 (see Table 9 uncertainty file discussion)
3	1	Deterministic concentration ratio (B_{iv}) for vegetables
3	2	Distribution type (NORM, LNORM, UNIF, TRI)
3	3	Parameter 1 (see Table 9 uncertainty file discussion)
3	4	Parameter 2 (see Table 9 uncertainty file discussion)
3	5	Parameter 3 (see Table 9 uncertainty file discussion)
3	6	Parameter 4 (see Table 9 uncertainty file discussion)
4	1	Deterministic concentration ratio (B_{iv}) for forage
4	2	Distribution type (NORM, LNORM, UNIF, TRI)
4	3	Parameter 1 (see Table 9 uncertainty file discussion)
4	4	Parameter 2 (see Table 9 uncertainty file discussion)
4	5	Parameter 3 (see Table 9 uncertainty file discussion)
4	6	Parameter 4 (see Table 9 uncertainty file discussion)
5	1	Deterministic milk transfer coefficient (Fm, d L^{-1})
5	2	Distribution type (NORM, LNORM, UNIF, TRI)
5	3	Parameter 1 (see Table 9 uncertainty file discussion)
5	4	Parameter 2 (see Table 9 uncertainty file discussion)
5	5	Parameter 3 (see Table 9 uncertainty file discussion)
5	6	Parameter 4 (see Table 9 uncertainty file discussion)
6	1	Deterministic beef transfer coefficient (Fb, d L^{-1})
6	2	distribution type (NORM, LNORM, UNIF, TRI)
6	3	Parameter 1 (see Table 9 uncertainty file discussion)
6	4	Parameter 2 (see Table 9 uncertainty file discussion)
6	5	Parameter 3 (see Table 9 uncertainty file discussion)
6	6	Parameter 4 (see Table 9 uncertainty file discussion)

[a] Lines 1–6 are repeated for each element and the order of the elements can be random.

A sample element file for the uranium decay series for important radionuclides considered is shown below. Note that transport of short-lived progeny in DOSEMM are not explicitly modeled, but instead are assumed to be in secular equilibrium with their parent. Thus, transport parameters for short-lived members like isotopes of polonium and bismuth are not included.

```
Sample Element file for DOSEMM
U                                                    Element
195.0  NORM   195.0   39.   1.17e2 2.73e2          Kd
0.001  LNORM  0.001   2.0   8.0e-5 1.4e-2          CRveg (wet wt)
0.02   LNORM  0.02    2.0   2.0e-3 2.0e-1          CRforg (dry wt)
0.0003 LNORM  0.0003  1.8   1.0e-8 1.0e6           TCmilk (d/L)
0.0008 LNORM  0.0008  1.8   1.0e-6 1.0e6           TCmeat (d/kg)
Th                                                   Element
115.0  NORM   115.0    23.0 6.9e+1 1.58e2          Kd
0.0006 LNORM  0.0006   2.0  5.0e-7 4.0e-2          CRveg (wet wt)
0.01   LNORM  0.01     2.0  1.0e-3 1.0e-1          CRforg (dry wt)
5.0e-6 LNORM  5.0e-6   1.8  1.0e-8 1.0e6           TCmilk (d/L)
1.0e-4 LNORM  1.0e-4   1.8  1.0e-6 1.0e6           TCmeat (d/kg)
Ra                                                   Element
110.0  NORM   110.0   22.   8.0e+1 1.54e2          Kd
0.0016 LNORM  0.0016  2.0   2.0e-5 1.0e-1          CRveg (wet wt)
0.08   LNORM  0.08    2.0   1.0e-2 4.0e-1          CRforg (dry wt)
```

```
0.001  LNORM  0.001   1.8   1.0e-8 1.0e6          TCmilk (d/L)
0.001  LNORM  0.001   1.8   1.0e-6 1.0e6          TCmeat (d/kg)
Pb                                               Element
110.0  NORM   110.0   22.   8.0e+1 1.54e2         Kd
0.0014 LNORM  0.0014   2.0  1.0e-5 2.0e-2         CRveg (wet wt)
0.001  LNORM  0.001    2.0  1.0e-4 1.0e0          CRforg (dry wt)
3.0e-4 LNORM  3.0e-4   1.8  1.0e-8 1.0e6          TCmilk (d/L)
8.0e-4 LNORM  8.0e-4   1.8  1.0e-6 1.0e6          TCmeat (d/kg)
```

The radionuclide file is entered in Record 25 of the parameter definition file. This file contains radionuclide half-lives, progeny, decay fractions (branching ratio). This file can contain more radionuclides than are in any given simulation. The structure of the file is presented in Table 8. The first line in the code is a header and is read and discarded by the code. The remaining lines contain radionuclide data. Each line contains the data for one radionuclide. Nuclide names must match those in the dose coefficient files and parameter definition file.

Table 8. Structure of the Radionuclide File[a]

Position	Description
1	Nuclide name
2	Element symbol
3	Half-life (years)
4	Progeny name
5	Decay (branching) fraction

[a] Each radionuclide represents one line in the file. The first line is the header that is used for documentation but not used in the code.

A sample radionuclide file for the uranium decay series showing important radionuclides considered in the calculation is shown below. The first line of the file is a header that is useful for documentation but is discarded in the code.

```
Nuclide      Element   T1/2(years)  Progeny    DecayFrac
U-238        U         4.469e9      Th-234     1.0
Th-234       Th        6.57e-2      Pa-234m    1.0
Pa-234m      Pa        2.226E-07    U-234      0.9984
U-234        U         2.455e5      Th-230     1.0
Th-230       Th        7.538e4      Ra-226     1.0
Ra-226       Ra        1.6e3        Rn-222     1.0
Rn-222       Rn        1.0465e-2    Po-218     1.0
Po-218       Po        5.898e-6     Pb-214     0.998
Pb-214       Pb        5.098e-5     Bi-214     1.0
Bi-214       Bi        3.786e-5     Po-214     0.99979
Po-214       Po        5.2e-12      Pb-210     1.0
Pb-210       Pb        22.3         Bi-210     1.0
Bi-210       Bi        1.373e-2     Po-210     1.0
Po-210       Po        3.791e-1     STABLE     1.0
```

Media Intake File

The media intake file is specified in record 43 of the parameter definition file. This file is ASCII free-format and contains the age-specific media (i.e., air, soil, and food) intake rates. The age specification needs to be in ascending order and should start at birth (0 year). When performing the calculation, DOSEMM will linearly interpolate between ages to get the intake rate for the receptor at their current age. This file is only read if dose calculations are specified. The format of the file is provided in Table 9.

Uncertainty Files

Two additional files are needed to define distributions for the uncertain parameters considered in the model. The first file defines uncertainty in the dispersion, deposition, meteorology, source term, and resuspension factors (dispersion/deposition file). The second file defines the uncertainty for the dose coefficients. Uncertainty for soil and food-chain transport parameters are defined in the element file as discussed earlier.

Parameter distributions in all cases are limited to normal, lognormal, triangular, and uniform. Four parameters are read that describe the distribution as given in Table 10

Table 9. Structure of the Media Intake File[a]

Position	Description
1	Age (years)
2	Inhalation rate (m^3 hr^{-1})
3	Soil ingestion rate (m^3 hr^{-1})
4	Leafy vegetable ingestion (kg yr^{-1})
5	Other produce ingestion (kg yr^{-1})
6	Milk ingestion (L yr^{-1})
7	Meat ingestion (kg yr^{-1})
8	Wild game ingestion (kg yr^{-1})

[a] Each age represents one line in the file. The first line is the header that is used for documentation but not used in the code.

Table 10. Distribution Types and Parameters for Variables Considered in the Uncertainty Analysis[a]

Distribution	Identifier	Parameter 1 (P1)	Parameter 2 (P2)	Parameter 3 (P3)	Parameter 4 (P4)
Normal	NORM	Mean	Standard deviation	Minimum value	Maximum value
Lognormal	LNORM	Geometric mean	Geometric standard deviation	Minimum value	Maximum value
Triangular	TRI	Mode	Ignored	Minimum value	Maximum value
Uniform	UNIF	Ignored	Ignored	Minimum value	Maximum value

[a] Four parameter values must follow each distribution, but some of the parameters are ignored for the triangular and uniform distributions.

The file structure for the dispersion/deposition uncertainty file is fundamentally different from the parameter definition file or other files. The file uses keywords to identify variables that are to be considered in the uncertainty assessment. Comments are inserted by placing a dollar sign ($) in the first column of a line. Uncertainty factors for meteorology, dispersion, deposition, and short-term and long-term resuspension are identified by the keywords MET, DISP, DEP, RESS, and RESL, respectively. The distribution type as given in Table 10 follows the keyword. The next line contains parameters (in order) P1 through P4. Thus, the file should look as follows:

```
MET  LNORM
1.0   1.7   .05   50
DISP  TRI
1.0   0.0    0.1  10.0
DEP   UNIF
0.0   0.0   0.1   10.0
RESS  LNORM
1.0   2.2   0.01   100
RESL  LNORM
1.0   1.8   0.01  100
```

In the above example, the meteorological and resuspension uncertainty factors are assigned lognormal distributions, the dispersion uncertainty factor is assigned a triangular distribution, and deposition is assigned a uniform distribution. Parameter values that are ignored as set to zero in the example, but they can be any valid real number.

Source uncertainty is defined for each source and year where it is applied. The order of sources must be the same as presented in the parameter definition file, and all sources should be read as a block. In all cases, the first year must equal the begin year of the simulation. The last year entered should be the end year of the simulation. Source uncertainty is indicated by the SRC keyword. Following the SRC keyword, the distribution type is entered. The next lines provide the start year and the parameters P1 through P4 for each year or block of years. The END keyword terminates input for that source. For example, if four sources are included in the simulation, and the begin and end years of the simulation are 1990 and 2000, respectively, then file would look like:

```
$ --- Source 1
SRC   LNORM
1990  1.0       1.5     0.1  10
2001  1.0       1.5     0.1  10
END
$ --- Source 2
SRC   NORM
1990  1.0       0.5     0.5  5
2001  1.0       0.5     0.5  5
END
$ --- Source 3
SRC   TRI
1990  1.0       0.0     0.1  10
2001  1.0       0.0     0.1  10
```

```
END
$ --- Source 4
SRC   UNIF
1990  0.0       0.0     0.5  2
2001  0.0       0.0     0.5  2
END
```

Note that the end year is set to 2001, so the distribution is sampled once for each source during a model realization and applied to all years of the simulation. If a different distribution is applied to a different sequence of years, then the input for Source 1 would look like:

```
$ --- Source 1
SRC   LNORM
1990  1.0       1.5     0.1  10
1995  1.0       2.5    0.01  100
1996  1.0       1.7    0.02  50
2001  1.0       1.7    0.02  50
END
```

In the above example, three independent uncertainty factors are sampled for each model realization and applied to Source 1. The first is applied from 1990 to 1994, the second is applied to 1995, and the third is applied from 1996 to 2001. Note that the distribution type cannot change; only the parameters that define the distribution can change.

If the keyword for a variable is missing from the file, then uncertainty will not be considered for that variable. The END keyword at the end of the file terminates input and closes the file.

Code Execution and Output

Execution of DOSEMM is performed from the command line in a terminal window by entering:

[*Path*]DOSEMM [*parameter definition file*] [*list file*]

If the parameter definition file is not provided, then the code will check for the file dosemm.par in the working directory. If this file is found, then the code will execute writing output to the file dosemm.lst. If a parameter definition file name is provided, then the name of the list file must also be provided. The list file contains the deterministic results for a deterministic run and a Monte Carlo simulation. Model input is echoed back in the list file. Concentrations and doses are reported by media, radionuclide, source, and receptor. Concentrations and doses are summed across sources at each receptor to provide totals. Surfer® grid files are produced if requested for source/radionuclide combinations. The naming convention for these files is the radionuclide name followed by –cnc for air concentration or –dep for deposition with a .grd file extension.

If Monte Carlo simulation is requested, then numerous other files are generated. The files have hardwired names and each one is described below.

udep.dat: This file contains the total deposition by radionuclide and receptor for each model realization. A summary of the output distribution in terms of percentiles is provided at the end of the file.

udose.dat: This file contains the total dose summed across all radionuclides and receptor locations by model realization and organ. The total inhalation dose is also broken out separately. A summary of the output distribution in terms of percentiles is provided at the end of the file.

uidep.dat: This file contains the integrated deposition across the model domain by radionuclide and model realization. If the wild game pathway is invoked (which requires integrated deposition), this file will be populated; otherwise, all values will be zero.

ures.dat: This file contains the time-integrated concentration from resuspension by radionuclide and receptor, and the total across all receptors for each model realization.

utic.dat: This file contains the time-integrated concentration from direct emissions and resuspension by radionuclide and receptor, and the total across all receptors for each model realization. A summary of the output distribution in terms of percentiles is provided at the end of the file.

udoseall.dat: This file contains a detailed output by realization of dose summed across all receptor locations. Output includes radionuclide, year, pathway, and organ for each model realization.

Gridded Dose Output: If gridded dose output is invoked by setting *nrecept* equal to zero, then grid files compatible with the Surfer® software are produced along with a data file that contains the dose at each grid node and discrete receptor summed across all radionuclides and tabulated for inhalation, ingestion, and external pathways along with the total dose. A separate file is produced for each organ and is given the name [*organ*].dat for the data file and [*organ*].grd for the grid file.

Conclusions

DOSEMM provides a flexible framework to calculate radionuclide concentrations in environmental media (air, soil, vegetation, and animal products) from radionuclide emissions to the air. Using the calculated media concentrations and an accompanying exposure scenario and dose coefficients, DOSEMM calculates doses as a function of time over the operational time period of the facility.

Uncertainty may be assessed by assigning distributions to parameters considered uncertain in the code. Multiplicative uncertainty factors are used to address uncertainty in atmospheric transport, deposition, meteorology, source term, and dose coefficients. Parameter distributions can be assigned to element-specific parameters (such as concentrations ratios, transfer coefficients, and sorption coefficients), and resuspension parameters.

Model output includes radionuclide concentrations in environmental media, and doses for a user-provided exposure scenario. Concentrations and doses are presented by radionuclide, source, and receptor location. Output also includes grid files that are compatible Surfer® software program.

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Appendix A: Software Design Description and Configuration Management Plan

The software design description depicts how the software is structured to satisfy the requirements of the software and the components and subcomponents of the software. The software requirements are stated in the main body of this report. Specifically, the software is required to implement the conceptual model using the equations in the methodology section of the report. The DOSEMM software is written in Fortran 95 with Fortran77 modules (Routines from Numerical Recipes) and was developed on a Mac workstation running Mac OS X Version 10.10.5. It was compiled using the gfortran compiler. Each subroutine and function is described in Table A-11.

Table A-11. Description of Each Subroutine and Function in DOSEMM

Type	Name	Purpose
Program	dosemm	Main program unit
Subroutine	dosemmf	Man subroutine to read input files and call computations
Subroutine	radonWL	Calculate radon working levels
Subroutine	printdcf	Print dose coefficients
Subroutine	radonc	Print radon concentrations
Subroutine	rdk	Compute decay and ingrowth
Subroutine	mkplot	Write grid plot file for time-integrated concentration and deposition
Subroutine	ctic	Calculate time-integrated concentration for grid plotting
Subroutine	mkgrid	Calculates grid coordinates from user provided grid dimensions
Subroutine	readrel	Reads source term release files
Subroutine	readchiq	Reads X/Q and Psi/Q values from files
Subroutine	dtcalc	Calculate computational time steps
Subroutine	readline	File reading utility: read a line of input from a parameter definition file
Subroutine	numvaline	File reading utility: counts number of valid values on a line
Subroutine	checkfile	File reading utility: checks for existence of a file
Subroutine	filcase	File reading utility: checks the case of a file
Subroutine	ingrowth	Main program unit to calculate ingrowth factors
Subroutine	difcalone	Subroutine to set up matrix of ingrowth factor results
Subroutine	difcalc	Calculate ingrowth factor
Subroutine	printconc	Print concentrations to output file
Subroutine	printdose	Prints doses to output file
Subroutine	printsum	Print sums of concentrations to output file
Subroutine	printWL	Print working levels to output file
Subroutine	find	Finds the nearest node number for a receptor coordinate
Subroutine	initializeconcdose	Initializes and allocates space for concentration and dose arrays
Subroutine	initialize	Initial other variables and arrays at the start of the simulation
Subroutine	readsrcmc	Reads uncertainty parameters for source releases
Subroutine	sample	Calls the sampling routines for monte carlo uncertainty analysis
Subroutine	getsamp	Gets a sample from a user provided distribution
Subroutine	openufiles	Opens output file for monte carlo output
Subroutine	printmc	Prints monte carlo uncertainty results
Subroutine	initializemc	Initialize monte carlo uncertainty output arrays
Subroutine	percentiles	Calculate percentiles of uncertainty output distribution
Subroutine	printef	Print exposure factors to output file
Subroutine	writecontamdata	Print contaminant data to output file
Subroutine	sfood	Calculate radionuclide concentrations in agriculture products

Table A-11. Description of Each Subroutine and Function in DOSEMM

Type	Name	Purpose
Subroutine	wfoodparms	Prints food chain parameters to output file
Subroutine	dosecalc	Perform dose calculations
Subroutine	expconc	Calculate concentrations in environmental media
Subroutine	printgridheader	Print header in output grid files
Subroutine	printgriddose	Print grid dose data to data and grid files
Function (real kind 8)	logdev	Random sample from a lognormal distribution
Function (real kind 8)	triangular	Random sample from a triangular distribution
Function (real kind 8)	normdev	Random sample from a normal distribution
Function (real kind 8)	uniform	Random sample from a uniform distribution
Function (real kind 8)	GetAGE	Retrieve age index of a receptor
Function (real kind 8)	GetINH	Retrieve the inhalation dose coefficient
Function (real kind 8)	GetING	Retrieve the ingestion dose coefficient
Function (real kind 8)	GetEXT	Retrieve the ground surface external dose coefficient
Function (real kind 8)	GetGRD	Retrieve the ground soil volume dose coefficient
Function (real kind 8)	GetSUB	Retrieve the submersion in air dose coefficient
Function (character len 2)	GetELEMENT	Retrieve the element symbol for a radionuclide
Function (real kind 8)	GetTHALF	Retrieve the radionuclide half-life
Function (character len 8)	GetPROG	Retrieve the radioactive progeny
Function (real kind 8)	GetFRACT	Retrieves decay fraction of progeny
Function (real kind 8)	GetLAM	Retrieves radioactive decay fraction for progeny
Function (real kind 8)	GetKD	Retrieve soil sorption coefficient (Kd)
Function (real kind 8)	GetCRVEG	Retrieve concentration ratio for leafy vegetables and produce
Function (real kind 8)	GetCRFORG	Retrieve concentration ratio for animal forage
Function (real kind 8)	GetTCMILK	Retrieve milk transfer coefficient
Function (real kind 8)	GetTCMEAT	Retrieve meat transfer coefficient
Function (real kind 8)	getrad	Converts degrees to radians
Function (real kind 8)	fssoil	Calculates surface soil concentration (without ingrowth) for a time step
Function (real kind 8)	fsbsoil	Calculates subsurface soil concentration (without ingrowth) for a time step
Subroutine	resusint	Calculates resuspension function for a unit psi/Q value
Subroutine	GetKDparms	Retrieve uncertainty parameters for the Kd
Subroutine	GetCRparms	Retrieve uncertainty parameters for CR
Subroutine	GetCRForgeparms	Retrieve uncertainty parameters for CR in forage
Subroutine	GetTCMparms	Retrieve uncertainty parameters for TC in milk
Subroutine	GetTCBparms	Retrieve uncertainty parameters for TC in beef
Subroutine	readinhdcf	Read inhalation dose coefficients from file
Subroutine	readingdcf	Read ingestion dose coefficients from file
Subroutine	readextdcf	Read external dose coefficients from file
Subroutine	readgrddcf	Read soil volume external dose coefficients from file
Subroutine	readsubdcf	Read submersion in air dose coefficients form file
Subroutine	readnucdata	Read radionuclide data from file
Subroutine	readelementdata	Real element-specific data from file
Subroutine	readdcfu	Read uncertainty parameters for dose coefficients
Subroutine	GetDCUNCERT	Retrieve dose coefficient uncertainty parameters
Subroutine	GetSampleValue	Retrieve a sampled value for a given parameter
Subroutine	latlonutm	Converts latitude and longitude in decimal degrees to UTM coordinates
Subroutine	distancell	Computes distance from points represented by latitude and longitude coordinates
Routine Copyright from Numerical Recipes Routines		
Subroutine	lint	Linear interpolation routine
Function (real kind 8)	deviates(idum)	Get a standard normal deviate
Function (real kind 8)	ran2(idum)	Retrieve a random number

Configuration Management Plan

Software configuration management provides the mechanism to identify, document, and control changes to the software. Software configuration management for DOSEMM is addressed within the module headers and the version date. Each module in the DOSEMM code contains a header that documents (1) the name and purpose of the module, (2) the code author, (3) the date it was written, (4) a change history to the module, (5) arguments and returned values, and (6) calls to and from the module. The module header forms the basis for most of the code documentation. An example module header is provided in Figure A-1.

```
      subroutine GetKDparms(element,srand,x)
!! ================================================
!! Modual Name: GetKDparams
!! Author:  A. S. Rood
!! Date Created: 06/07/13
!! Last Modified:
!! Modifications:
!!
!! Purpose:  Retrieves the distribution type and parameters and returns a sampled value
!!
!! Arguments:
!!       element => element symbol
!!       srand => random number seed
!! Return
!!       x => sampled value

!! Variables
!!       dtype => distribution type
!!       p1 => parameter 1
!!       p2 => parameter 2
!!       p3 => parameter 3
!!       p4 => parameter 4



!! Called By: MAIN
!! Calls To: GetSampleValue
!! ================================================
```

Figure A-1. Module header for subroutine GetKdparms in DOSEMM.

Version control is primarily handled in DOSEMM through the version date instead of a version number. The version date can be thought of as essentially a version number and is stored in the variable vdate in the main program unit. The version date is a six-digit number, where the first two digits represent the year, the second two digits the month, and the last two digits the day. The version date is in the header of the general output file generated by DOSEMM and in all ancillary output files generated by the code. The version date is identified as the “Version” in the ancillary output files. In this way, results from an old version of the code can be identified.

The code custodian has the responsibility of maintaining and updating the code, identifying and archiving code versions, verifying new versions of the code operate correctly, and distributing the software to end users.

Appendix B: Verification Benchmark Problem

Verification of DOSEMM involved comparison of radionuclide concentrations in environmental media and doses with a spreadsheet application that has been used at the Idaho National Laboratory (INL) to produce the Annual Site Environmental Report (ASER) (INL 2016). Releases from the INTEC facility were evaluated and include particulate radionuclides (transuranics and fission and activation products), noble gases, iodine isotopes, and tritium (as tritiated water) and ^{14}C. Environmental media concentrations and doses were calculated at a single receptor location where the maximum off-site dose was reported. In general, DOSEMM uses the same equations for calculating radionuclide transfer through the food chain, except for tritium and ^{14}C. The ASER model uses factors derived from CAP88 (Moore et al. 1979) modeling, where DOSEMM uses the specific activity models as described in NCRP (1996). Model parameters including concentration ratios, soil parameters, and dose coefficients were mostly taken from the ASER model. For tritium and ^{14}C, parameters from Moore et al. (1979) and NCRP (1996) were used.

Radionuclide concentrations in environmental media for the two models are provided in Table B-1, and effective doses are provided in Table B-2. Air concentrations were generally the same between the two models for all particulate radionuclides and iodine. DOSEMM concentrations for tritium, ^{14}C, and the noble gases were slightly higher because X/Q values used for these radionuclides did not include deposition. The ASER spreadsheet only allows for a single X/Q value representing a non-depositing radionuclide. Deposition is calculated in ASER by entering a deposition velocity for particles and iodine. Plume depletion is calculated outside the spreadsheet and only iodine is accounted for. To provide consistent X and ψ input to benchmark DOSEMM, the spreadsheet was modified to use a separate X/Q value for particles, tritium and ^{14}C, and noble gases, and another for iodine. The X/Q values used in DOSEMM and the ASER spreadsheet were derived from the CALPUFF model simulations described in Rood and Sondrup (2014). In DOSEMM, X/Q values for particles were based on a 1-µm particle, and for iodine on a 15-µm particle. Tritium, ^{14}C, and noble gases did not include deposition; thus, ψ/Q values were zero at all nodes, and X/Q values reflect no depletion. Because little depletion occurs for small particles, the X/Q values for particles from DOSEMM were used in the ASER spreadsheet for tritium, ^{14}C, and noble gases. The slightly higher predicted DOSEMM air concentration compared to ASER for tritium, ^{14}C, and noble gases reflects no plume depletion in DOSEMM. The X/Q value for iodine in DOSEMM was used in the ASER spreadsheet. Deposition velocities used in the ASER spreadsheets were calculated by taking the ratio of the ψ/Q to X/Q values used in DOSEMM.

Another difference was noted in the ground external exposure dose. For consistency with DOSEMM, the ground exposure dose in ASER was calculated assuming one year of deposition. However, DOSEMM accounts for decay, ingrowth, and leaching during the year while ASER does not. Thus, radionuclides that had any significant decay or leaching during the year as calculated by DOSEMM had lower doses compared to ASER. DOSEMM also accounts for ingrowth of radioactive progeny; ^{241}Am ingrowth from ^{241}Pu makes a substantial difference in the ground external exposure dose, which results in the DOSEMM dose being a factor of 2 higher than the ASER dose.

Finally, notable differences were observed for the tritium and ^{14}C doses. Tritium and ^{14}C doses calculated in DOSEMM are a function of only a few parameters, and model results were

checked with hand calculations to assure that they were done correctly. These differences can be attributed to differences in the implementation of the specific activity model in DOSEMM and ASER spreadsheets.

The DOSEMM input and output files are provided as an attachment to this appendix. Model runs were separated into four files: particulates, noble gases, iodine, and tritium and ^{14}C. Model parameters are printed to the output files except for the source term, which is provided also in four separate files.

Table B-12. Radionuclide Concentrations in Environmental Media for the DOSEMM Verification Problem

DOSEMM	Air concentration (pCi m^{-3})	Deposition (pCi m^{-2})	Leafy vegetable (pCi kg^{-1})	Produce (pCi kg^{-1})	Milk (pCi L^{-1})	Beef (pCi kg^{-1})
Pu-241	5.04E-06	3.25E-02	1.79E-04	1.79E-04	3.53E-08	3.52E-06
Am-241	7.65E-09	4.94E-05	2.88E-07	2.88E-07	1.09E-10	2.72E-09
Cs-137	2.59E-05	1.67E-01	2.12E-03	2.12E-03	1.61E-03	6.02E-03
Pu-238	1.66E-07	1.07E-03	6.13E-06	6.13E-06	1.17E-09	1.17E-07
Pu-239	3.12E-07	2.01E-03	1.18E-05	1.18E-05	2.22E-09	2.22E-07
Pu-240	1.64E-07	1.06E-03	6.23E-06	6.23E-06	1.17E-09	1.17E-07
Sr-90	1.98E-05	1.28E-01	7.43E-03	7.43E-03	4.88E-04	1.95E-03
Co-60	4.14E-08	2.67E-04	2.19E-06	2.19E-06	5.91E-07	5.87E-06
I-129	5.87E-06	2.26E+00	3.33E-02	3.33E-02	2.81E-02	1.97E-02
I-131	2.71E-02	1.05E+04	7.68E+00	7.68E+00	8.39E+00	1.24E+00
H-3	2.23E-01	a	3.75E+01	3.75E+01	4.56E+01	2.84E+01
C-14	1.48E-08	a	2.79E-05	2.79E-05	1.39E-05	1.89E-05
Kr-85	1.14E+00	a	b	b	b	b
Ar-41	4.58E-01	a	b	b	b	b
ASER spreadsheet	Air conc (pCi m^{-3})	Depostion (pCi m^{-2})	Leafy vegetable (pCi kg^{-1})	Produce (pCi kg^{-1})	Milk (pCi L^{-1})	Beef (pCi kg^{-1})
Pu-241	5.02E-06	3.23E-02	1.77E-04	1.77E-04	3.49E-08	3.49E-06
Am-241	7.64E-09	4.92E-05	2.87E-07	2.87E-07	1.08E-10	2.71E-09
Cs-137	2.58E-05	1.66E-01	2.10E-03	2.10E-03	1.60E-03	5.99E-03
Pu-238	1.65E-07	1.06E-03	6.09E-06	6.09E-06	1.17E-09	1.17E-07
Pu-239	3.11E-07	2.00E-03	1.18E-05	1.18E-05	2.21E-09	2.21E-07
Pu-240	1.64E-07	1.05E-03	6.19E-06	6.19E-06	1.16E-09	1.16E-07
Sr-90	1.98E-05	1.27E-01	7.19E-03	7.19E-03	4.79E-04	1.92E-03
Co-60	4.13E-08	2.66E-04	2.17E-06	2.17E-06	5.87E-07	5.87E-06
I-129	5.86E-06	2.29E+00	3.37E-02	3.37E-02	2.84E-02	1.99E-02
I-131	2.71E-14	1.06E+04	7.81E+00	7.81E+00	8.52E+00	1.27E+00
H-3	2.10E-01	a	c	c	c	c
C-14	1.40E-08	a	c	c	c	c
Kr-85	1.08E+00	a	b	b	b	b
Ar-41	4.29E-01	a	b	b	b	b
Ratios DOSEMM/ASER	Air	Deposition	Leafy vegetable	Produce	Milk	Beef
Pu-241	1.00	1.01	1.01	1.01	1.01	1.01

Table B-12. Radionuclide Concentrations in Environmental Media for the DOSEMM Verification Problem

Am-241	1.00	1.00	1.00	1.00	1.00	1.00
Cs-137	1.00	1.01	1.01	1.01	1.01	1.01
Pu-238	1.00	1.01	1.01	1.01	1.01	1.01
Pu-239	1.00	1.01	1.01	1.01	1.01	1.01
Pu-240	1.00	1.01	1.01	1.01	1.01	1.01
Sr-90	1.00	1.01	1.03	1.03	1.02	1.02
Co-60	1.00	1.01	1.01	1.01	1.01	1.00
I-129	1.00	0.99	0.99	0.99	0.99	0.99
I-131	1.00	0.99	0.98	0.98	0.99	0.98
H-3	1.06	a	c	c	c	c
C-14	1.06	a	c	c	c	c
Kr-85	1.06	a	b	b	b	b
Ar-41	1.07	a	b	b	b	b

[a] No deposition calculated for these radionuclides
[b] These radionuclides do not accumulate in the food chain
[c] Concentrations in food products were not explicitly calculated in ASER.

Table B-13. Effective Doses by Exposure Pathway for the DOSEMM Verification Problem

DOSEMM	Inhalation (rem)	Vegetables (rem)	Meat (rem)	Milk (rem)	Ground (rem)	Submersion (rem)	Total (rem)
Pu-241	3.45E-07	6.09E-10	5.26E-12	6.95E-14	6.39E-15	3.73E-17	3.45E-07
Am-241	2.23E-08	4.23E-11	1.75E-13	9.20E-15	2.71E-13	6.06E-16	2.24E-08
Cs-137	3.21E-08	2.06E-08	2.57E-08	9.03E-09	1.06E-08	7.72E-11	9.81E-08
Pu-238	5.42E-07	1.00E-09	8.42E-12	1.11E-13	7.79E-14	6.79E-17	5.43E-07
Pu-239	1.12E-06	2.13E-09	1.75E-11	2.31E-13	6.67E-14	1.27E-16	1.13E-06
Pu-240	5.91E-07	1.12E-09	9.21E-12	1.21E-13	7.46E-14	6.58E-17	5.92E-07
Sr-90	9.67E-08	1.47E-07	1.69E-08	5.58E-09	1.64E-09	2.28E-13	2.68E-07
Co-60	4.06E-11	5.34E-12	6.28E-12	8.33E-13	6.74E-11	5.75E-13	1.21E-10
I-129	1.88E-08	2.53E-06	6.53E-07	1.23E-06	3.29E-09	1.94E-13	4.43E-06
I-131	2.10E-05	1.20E-04	8.49E-06	7.57E-05	1.59E-05	5.35E-08	2.41E-04
H-3	1.28E-07	5.15E-07	1.71E-07	3.62E-07			1.18E-06
C-14	2.70E-12	1.16E-11	3.45E-12	3.34E-12			2.11E-11
Kr-85						3.20E-08	3.20E-08
Ar-41						3.29E-06	3.29E-06
Total	2.39E-05	1.23E-04	9.36E-06	7.73E-05	1.59E-05	3.38E-06	2.53E-04
ASER	Inhalation (rem)	Vegetables (rem)	Meat (rem)	Milk (rem)	Ground (rem)	Submersion (rem)	Total (rem)
Pu-241	3.43E-07	6.04E-10	5.23E-12	6.89E-14	6.32E-15	3.72E-17	3.43E-07
Am-241	2.23E-08	4.21E-11	1.74E-13	9.16E-15	1.34E-13	6.04E-16	2.23E-08
Cs-137	3.20E-08	2.05E-08	2.55E-08	8.98E-09	1.07E-08	7.70E-11	9.77E-08
Pu-238	5.40E-07	9.97E-10	8.37E-12	1.10E-13	7.74E-14	6.77E-17	5.41E-07
Pu-239	1.12E-06	2.12E-09	1.74E-11	2.29E-13	6.65E-14	1.27E-16	1.12E-06
Pu-240	5.89E-07	1.11E-09	9.16E-12	1.21E-13	7.39E-14	6.57E-17	5.90E-07
Sr-90	9.63E-08	1.42E-07	1.66E-08	5.47E-09	1.65E-09	2.27E-13	2.62E-07

Table B-13. Effective Doses by Exposure Pathway for the DOSEMM Verification Problem

Co-60	4.05E-11	5.31E-12	6.29E-12	8.29E-13	6.70E-11	5.74E-13	1.21E-10
I-129	1.88E-08	2.56E-06	6.61E-07	1.24E-06	5.25E-09	1.94E-13	4.49E-06
I-131	2.10E-05	1.22E-04	8.66E-06	7.68E-05	1.43E-05	5.34E-08	2.43E-04
H-3	1.21E-07	5.61E-07	2.05E-07	3.44E-07			1.23E-06
C-14	2.55E-12	1.13E-11	1.43E-12	5.60E-12			2.08E-11
Kr-85						3.03E-08	3.03E-08
Ar-41						3.08E-06	3.08E-06
Total	2.39E-05	1.25E-04	9.57E-06	7.84E-05	1.44E-05	3.16E-06	2.55E-04
Ratios DOSEMM/ASER	Inhalation	Vegetables	Meat	Milk	Ground	Submersion	Total
Pu-241	1.00	1.01	1.01	1.01	0.98	1.00	1.00
Am-241	1.00	1.00	1.00	1.00	2.03	1.00	1.00
Cs-137	1.00	1.01	1.01	1.01	1.00	1.00	1.00
Pu-238	1.00	1.01	1.01	1.01	1.00	1.00	1.00
Pu-239	1.00	1.01	1.01	1.01	1.00	1.00	1.00
Pu-240	1.00	1.01	1.01	1.01	1.01	1.00	1.00
Sr-90	1.00	1.03	1.02	1.02	0.99	1.00	1.02
Co-60	1.00	1.01	1.00	1.01	1.01	1.00	1.00
I-129	1.00	0.99	0.99	0.99	0.63	1.00	0.99
	1.00	0.98	0.98	0.99	1.11	1.00	0.99
H-3	1.06	0.92	0.83	1.05			0.96
C-14	1.06	1.03	2.42	0.60			1.01
Kr-85						1.06	1.06
Ar-41						1.07	1.07
Total Dose	1.00	0.98	0.98	0.99			0.99

Verification and Benchmark of Resuspension Equation

The ASER spreadsheet does not include resuspension. Therefore, the formulation of the resuspension equation in DOSEMM was benchmarked with the resuspension equation published in Reg Guide 3.51 NRC (1982) for a constant deposition rate and using the ASER radionuclides and release rates (ignoring Am-241 because the NRC equation does not include progeny ingrowth). Assuming a constant deposition rate, the air concentration from resuspension (C_{arip}) is given in Reg Guide 3.51 as

$$C_{arip}(t) = 0.01 C_{adip} 10^{-5} \left[\begin{array}{l} \dfrac{1-\exp\left[-\left(\lambda R_i + \lambda\right)\left(t-a\right)\right]}{\left(\lambda R_i + \lambda\right)} + \\ 10^{-4}\,\delta\left(t\right)\dfrac{\exp\left[-\lambda R_i\left(t-a\right)\right]-\exp\left(\lambda R_i t\right)}{\lambda R_i} \end{array} \right] \qquad \text{(B-1)}$$

where

λr = short-term resuspension decay constant (5.06 yr^{-1})
λR_i = effective removal rate constant from soil (yr^{-1})
$\delta(t)$ = is zero if $t \leq 1.82$ and is unity
$0.01C_{adip}$ = air concentration times the deposition velocity (Ci m^{-2} yr^{-1})
a = is equal to $(t - 1.82)$ if $t > 1.82$, otherwise $a = 0$.

The short and long-term resuspension factors were 10^{-5} and 10^{-9} m^{-1} respectively and the short-term resuspension decay constant was 5.06 yr^{-1} (50 d half time). Equation B-1 provides the concentration at time *t*. The 1-year time-integrated concentration was approximated by numeric integration using a time step of 0.02 yr (7.3 d). This value was compared to the DOSEMM value at one year using *nresol*=1, *nresol*=12 and *iflag* equal to true or false. The *nresol* variable defines the number of periods in a year the release and X/Q and ψ/Q values are discretized with a year. For this case, the release rate was the same for all periods, but the concentration and deposition factors (X/Q and ψ/Q) values varied by period. For nresol=1, weighted average X/Q and ψ/Q values were used in DOSEMM (Table B-3). For use in the NRC equation, the total deposition rate over the year was used and was the same regardless of the setting of nresol. When *iflag* is set to true and *nresol*=12, then integration limits for short-term resuspension are set incrementally within the year. The first integration limit for the first period is from the beginning of the year end of the year. The second limit is from the beginning of the second period to the end of the year (~0.91 yr). And the third limit is from the beginning of the third period to the end of the year (~0.83 yr) and so forth.

Table B-14. X/Q (s m^{-3}) and ψ/Q (m^{-2}) Values

	Period											
	1	2	3	4	5	6	7	8	9	10	11	12
X/Q	5.42E-08	3.86E-08	5.14E-08	3.46E-08	3.38E-08	3.86E-08	4.47E-08	4.89E-08	3.99E-08	4.70E-08	5.23E-08	7.45E-08
ψ/Q	6.20E-12	3.59E-12	1.14E-11	1.09E-11	1.75E-11	2.44E-12	6.73E-12	1.45E-11	1.73E-11	9.99E-12	6.30E-12	7.16E-12

The DOSEMM solution closest to the integrated NRC equation was with *nresol*=12 and *iflag*=true (Table B-4). DOSEMM still slightly overestimated time-integrated concentrations. When *nresol*=12 or 1 and *iflag*=false, then DOSE overestimated the time-integrated concentration by about a factor of 1.24. This difference is not considered significant considering to overall uncertainty and variability in the resuspension model.

Table B-15 Parameters and Resuspension Benchmark Results

Parameter	Pu-241	Cs-137	Pu-238	Pu-239	Pu-240	Sr-90	Co-60
Radioactive decay (1/yr)	4.83E-02	2.31E-02	7.90E-03	2.88E-05	1.06E-04	2.41E-02	1.32E-01
Leach rate constant(1/yr)	1.19E-04	5.18E-05	1.19E-04	1.19E-04	1.19E-04	7.90E-03	2.38E-04
Effective removal (1/yr)	4.84E-02	2.31E-02	8.02E-03	1.48E-04	2.25E-04	3.20E-02	1.32E-01
C_{adip} (pCi m^{-2}-yr^{-1})	3.25E-02	1.67E-01	1.07E-03	2.01E-03	1.06E-03	1.28E-01	2.67E-04
NRC Conc (pCi m^{-3})	6.32E-08	3.27E-07	2.10E-09	3.95E-09	2.08E-09	2.50E-07	5.12E-10
NRC TIC (pCi-yr m^{-3})	5.12E-08	2.64E-07	1.70E-09	3.20E-09	1.68E-09	2.02E-07	4.16E-10
DOSEMM (pCi-yr m^{-3})a	5.43E-08	2.79E-07	1.79E-09	3.37E-09	1.77E-09	2.14E-07	4.45E-10
DOSEMM (pCi-yr/m^3)b	6.34E-08	3.26E-07	2.09E-09	3.94E-09	2.07E-09	2.50E-07	5.20E-10
DOSEMM (pCi-yr/m^3)c	6.24E-08	3.25E-07	2.09E-09	3.96E-09	2.08E-09	2.47E-07	4.92E-10

a. nresol=12 and iflag=true
b. nresol=12 and iflag=false
c. nresol=1

To test the long-term resuspension factor, the source was turned off after one year and the resuspension concentration at 10 years was computed with DOSEMM. Recall that after the sufficient time, short-term resuspension is negligible and resuspension is governed by the long-term factor. Thus, the 1-yr time-integrated concentration from resuspension long after deposition has ceased is the surface soil concentration (Ci m^{-2}) times the long-term resuspension factor (10^{-9} m^{-1}) times 1-yr. Table B-5 shows DOSEMM correctly predicts the time-integrated resuspension concentration 10-years after deposition has ceased.

Table B-16. Long-Term Resuspension Benchmark Results

Quantity	Pu-241	Cs-137	Pu-238	Pu-239	Pu-240	Sr-90	Co-60
TIC DOSEMM (pCi-yr/m^3)	1.96E-11	1.31E-10	9.82E-13	2.01E-12	1.06E-12	9.15E-11	6.71E-14
Soil Conc, 2025 (pCi/m^2)	1.96E-02	1.31E-01	9.82E-04	2.01E-03	1.06E-03	9.15E-02	6.71E-05

Appendix B References

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Attachment to Appendix B: DOSEMM Input and Output Files

Particulate Parameter Definition File (Input)

H-3 and C-14 Parameter Definition File (Input)

Iodine Parameter Definition File (Input)

Nobel Gas Parameter Definition File (Input)

Particulate Output File

H-3 and C-14 Output File

Iodine Output File

Nobel Gas Output File

Source Term Files

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