

Overview of Environmental Transport Models Contained in the Risk Analysis, Communication, Evaluation, and Reduction (RACER) Software Tools at Los Alamos National Laboratory - 9070

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ABSTRACT

The objective of the Risk Analysis, Communication, Evaluation, and Reduction (RACER) project is to provide more relevant and timely access to information related to chemicals and radionuclides in the environment around Los Alamos National Laboratory (LANL), and to develop tools to support an effective and logical evaluation and reduction of human health risks and ecological impacts associated with exposures to these materials. The guiding principle of RACER is an open and transparent process that considers community input as an integral part of making decisions about how to most effectively reduce risks related to LANL operations. Tools and resources include a database of geo-referenced environmental data, mapping software to display spatial data, environmental transport models, a risk assessment module, and various options to assist with interpreting the results. Human health risk assessment is performed for a user-defined exposure scenario using current environmental measurements, environmental transfer functions to estimate contaminant concentrations in environmental media that do not have measurements, and environmental transport models to estimate contaminant concentrations in the future. Environmental transport and transfer models address transport in air, vadose zone, groundwater, and the food chain. Recognizing that environmental transport models are generally developed on a site-specific basis, the RACER software tools incorporate methodology to distill complex site-specific model behavior into simple functional forms that are stored within the RACER database tables and are executed either by external dynamic-linked libraries or within Visual Basic code. Groundwater model computer run times can be excessively long and construction and operation of the model require specialized expertise. Instead of incorporating a complex groundwater model directly into the tool, a response surface model was developed that abstracts the behavior of an external groundwater model into simple response functions that can be stored within the RACER database. The convolution of the contaminant flux to the aquifer with the response function yields contaminant concentrations in the aquifer. Likewise, atmospheric transport models can involve detailed analysis and specialized expertise. RACER incorporates site-specific and radionuclide-specific dispersion factors for each potential emission point that are calculated with an external atmospheric transport model. The product of the contaminant emission rate and the site-specific dispersion factor yields the concentration of the contaminant in ambient air. Generic models are also incorporated to address situations where detailed modeling is not warranted or site-specific data necessary for complex models are lacking. RACER is currently being instituted at Los Alamos National Laboratory. The three-dimensional MODFLOW/MT3D groundwater flow and transport model was used to develop response functions for over 800 potential release points and over

8000 potential receptors in the aquifer modeling domain. The CALPUFF complex terrain atmospheric transport model was used to develop site-specific dispersion factors for eleven release points and over 600 receptors. The RACER environmental database is currently being implemented on the web and contains nearly six million records dating back to the early 1950's.

INTRODUCTION

The Los Alamos National Laboratory (LANL) began as Project Y of the Manhattan Project during World War II. Its primary mission in 1943 was to develop the world's first nuclear weapon. This undertaking drove the Laboratory's operations from its inception in 1943 to August of 1945 when that goal was fulfilled. The Laboratory was renamed Los Alamos Scientific Laboratory in 1947, which in turn became Los Alamos National Laboratory in 1981. Today, the Laboratory's core mission is national security research; ensuring the safety and reliability of the nation's nuclear deterrent; and addressing national energy, infrastructure, and health security. As research continued at the Laboratory, concerns about the impact of facility operations on the environment increased.

The Laboratory encompasses about 110 km² (27,500 acres) in northern New Mexico and is situated on the Pajarito Plateau, a series of finger-like mesas separated by deep east-to-west oriented canyons cut by intermittent stream flows. The mesas range in elevation from approximately 2,400 m (7,800 ft) on the eastern flanks of the Jemez Mountains to about 1,900 m (6,200 ft) just west of the Rio Grande Canyon. During its history, chemicals and radionuclides have been released to the air, soil, and surface water, and indirectly, to groundwater as a result of routine operations, accidents, and waste disposal practices. Although the Laboratory has substantially reduced radionuclide and chemical releases, the impact of and risk associated with current and historical releases of chemical and radioactive waste continue to concern individuals in nearby communities. The cleanup, removal, and treatment of historical releases of chemicals and radionuclides, referred to as legacy waste, are being addressed under the Los Alamos Environmental Programs (EP), formerly called the Environmental Restoration (ER) Project.

In 2003, Colorado State University (CSU) initiated an independent and comprehensive risk assessment for public health and the environment to evaluate the relative importance of various sources of chemicals and radionuclides released into the environment because of LANL operations. Risk Assessment Corporation (RAC) of Neeses, South Carolina, was selected to conduct the technical work as the primary, independent sub-contractor. CSU is supported by the University of California (UC) to conduct this work and to manage the project through a contract designed to ensure the independence of the work. The project is called Risk Analysis, Communication, Evaluation, and Reduction at LANL, abbreviated as the RACER project.

The objective of the RACER project is to provide more relevant and timely access to information related to chemicals and radionuclides in the environment around LANL, and to develop tools to support an effective and logical evaluation and reduction of human health and ecological impacts associated with exposures to these materials. The guiding principle of RACER is an open and transparent process that considers community input as an integral part of making decisions about how to most effectively reduce human health impacts related to LANL operations.

Two primary tools have been developed as part of RACER. They are the Data Analysis Tool (DAT) and the Ranking Tool (RT). The DAT is a web-enabled database containing nearly six million records of environmental monitoring data. These data form the basis of the exposure area characterizations needed to perform risk assessments for legacy waste on LANL property. The RT is a tool for computing representative exposure-point concentrations from measured data, evaluating transport and transfer of contaminants in environmental media (air, soil, groundwater, biota), and estimating human health risk

from exposure to contaminants in the environment media. A consistent approach combined with sound science and careful data management produce a relative ranking of the significance of contaminants, media, and sources in the environment based on their relative contribution to the overall human health risk. Other criteria related to confidence in the source characterization and importance of background are presented to assist with decision making.

This paper provides an overview of the environmental transport models embedded in the RACER RT tool. The overall site conceptual exposure model which illustrates the assumptions and the physical processes included in the environmental transport models is presented first followed by the specific models incorporated in the RT.

Site Conceptual Exposure Model

The conceptual model defines the model assumptions and physical processes of the system being modeled in terms of addressing the assessment question. The assessment question in this case is twofold. The first question is what are the human health impacts posed by a contaminant source for the current time frame and how might that change in the future? The second question is, given the human health impacts for multiple sources, how do these sources compare (i.e., rank) to one another? In this paper, only the first assessment question is addressed.

A source in this context is defined as a geographically bounded volume in the surface soil or vadose zone that currently contains radionuclides and chemicals from past operations at LANL. Contaminants are assumed to be homogeneously mixed within this volume. The potential human health impacts for a surface soil source and a vadose zone source are time-dependent and include different transport pathways and exposures. For this reason four separate conceptual models are presented: surface soil source current time, surface soil source in the future, vadose zone (or subsurface) source current time, and vadose zone source in the future.

Figure 1 shows the conceptual model for the surface soil source for current exposures. Processes acting on the surface soil source include particulate suspension, volatilization and diffusion of volatile organic compounds (VOCs), and leaching. Radioactive decay and ingrowth are implied although not explicitly shown. The leachate does not reach the regional aquifer during the current time frame and therefore there are no groundwater exposure pathways to consider. Direct exposure pathways (exposure pathways that involve no transport) include soil ingestion, dermal contact, and external exposure to gamma-emitting radionuclides. Indirect exposure pathways include inhalation of suspended soil or volatilized VOCs and ingestion of impacted food products. It is assumed that any crops and animal feed are grown directly on the surface soil source and that the radionuclides and chemicals in the soil are transferred to milk, meat, and vegetables that are consumed by the person.

The conceptual model for the surface soil source for future exposure pathways assumes all the exposure pathways in the current time frame are included, and groundwater is considered an exposure pathway because leachate may reach the regional aquifer. It is assumed that a groundwater well is located in the region where the leachate enters the regional aquifer and that the groundwater may be used for human consumption, livestock watering, and crop irrigation. Radionuclides and chemicals in groundwater are transferred to these food products. Radionuclide and chemical concentrations in the surface soils are reduced over time by leaching, radioactive decay, and chemical volatilization.

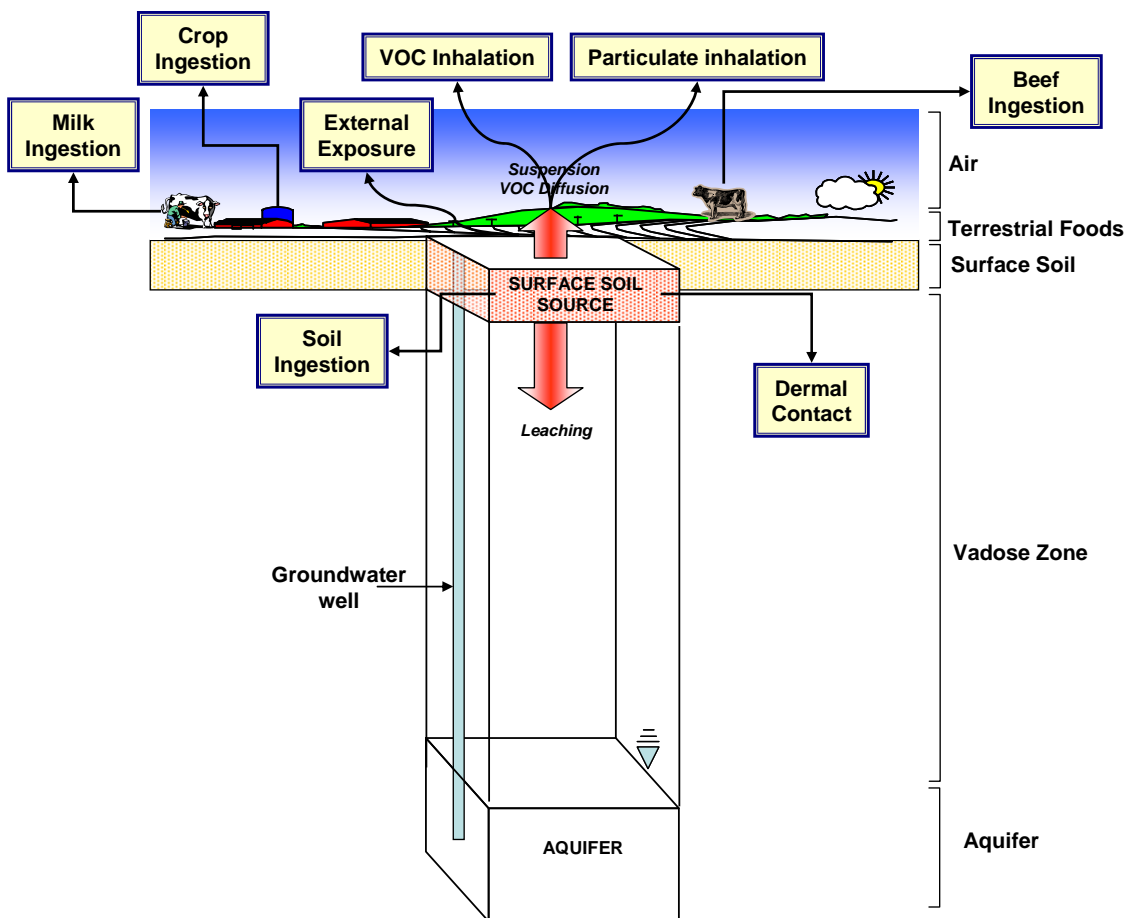


Figure 1. Conceptual model of the surface soil source for the current time frame.

There are no potential exposure pathways for the vadose zone source for the current time frame. This is because the source is isolated from direct human contact and transport of VOCs to the surface is considered to be negligible. Furthermore, leachate from the source has not reached the regional aquifer so there are no exposures associated with this transport pathway.

Figure 2 shows the conceptual model for the vadose zone source for the future time frame. A groundwater well is assumed to be located in the region where the leachate enters the regional aquifer. The groundwater may be used for human consumption or bathing, livestock watering, and crop irrigation. Radionuclides and chemicals in groundwater are transferred to these food products.

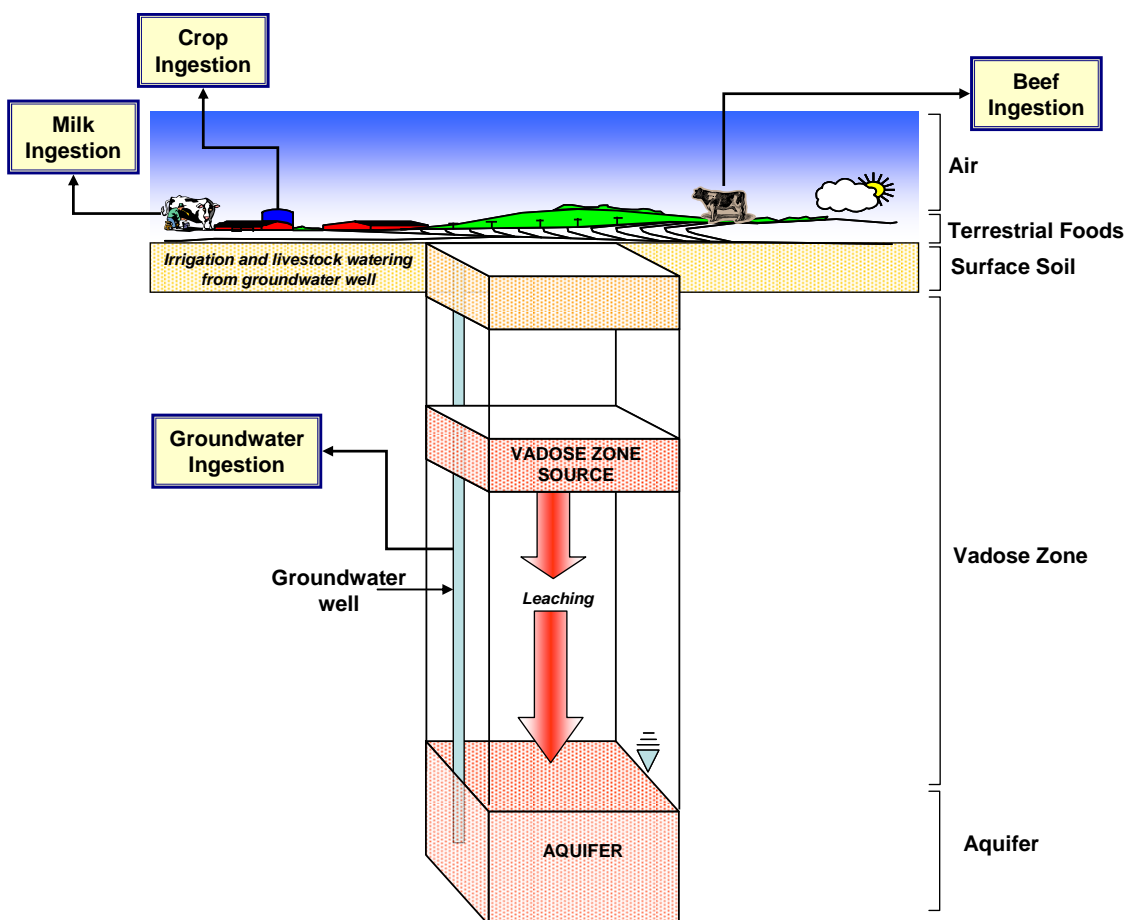


Figure 2. Conceptual model of the vadose zone source for the future time frame.

SOURCE DEFINITION

Measurement data provide the basis for estimating the representative concentration and inventory that lies within a surface source compartment. Inventories must be input manually for subsurface or vadose zone sources. A source is defined by delimiting a geographic region and thickness. The source can be thought of as a compartment where contaminants are uniformly mixed and can be transported out of transferred to other compartments, and is referred to as a compartment.

The representative concentration is used to evaluate direct exposure to soil, the transfer from the soil to other environmental media, or the inventory available for transport to groundwater. Various methods are used to derive a representative concentration from measurements ranging from a simple arithmetic average of all the samples contained within the source boundaries, to spatial interpolation followed by numerical integration. In the RT, simple methods include the arithmetic and geometric mean. The user may also use EPA's ProUCL software (Singh et al. 2004), which defines the upper 95th percentile of the mean value based on the best fit of the sample population to a distribution. More complex methods may be devised by the user and used in lieu of the simple methods or those included in ProUCL.

The inventory is computed from the representative concentration by multiplying the concentration by the mass of the source compartment. The mass of the source compartment is computed by the product of the assumed source concentration, the source compartment volume, and a representative bulk density. The

user also has the option to compute the inventory independently and use that inventory in the computations.

The surface soil sources are defined for present-day concentrations of radionuclides or chemicals that lie between the soil surface to a depth of 3.9 m (12.8 ft) below the soil surface. The subsurface vadose zone sources are defined for present day concentrations of radionuclides or chemicals that exist from 3.9 m below the soil surface to the vadose-zone-regional-aquifer interface. These are the default source thicknesses, but other thicknesses can be entered by the user. Subsurface vadose zone sources include concentrations of radionuclides or chemicals in perched water bodies that lie above the regional aquifer.

TRANSPORT AND TRANSFER PROCESSES

A conceptual model of transport and transfer processes (i.e., movement of radionuclides or chemicals in the environment) considered in the RT is illustrated in Figure 3. The transfer processes are those between environmental media (e.g., soil-to-water partitioning or food product uptake of radionuclides or chemicals). The transport processes are those where there is movement of the radionuclides or chemicals with the bulk movement of an environmental medium (e.g., advection and dispersion of groundwater). The environmental media are those discrete portions of the total environment that may be sampled or measured directly, such as soil, groundwater, or air. As noted above, environmental sources are defined in the surface soil and vadose zone (blue ovals in Figure 3) by assigning an initial radionuclide or chemical concentration or inventory. These compartments are subject to transport processes over time. Transport pathways are indicated by heavy dashed lines in Figure 3 and include transport from the surface soil to the subsurface vadose zone and regional aquifer, transport from the vadose zone to the regional aquifer, and transport within the regional aquifer. Other processes that are accounted for include radioactive decay and ingrowth.

The green boxes represent transfer compartments. Transfer compartments are assumed to be in equilibrium with the donor compartment from which radionuclides or chemicals are transferred. Thus, changes in concentration and inventory of the donor source compartment are mirrored in the transfer compartment, which has no explicit time component (the time component is only in the media that they mirror). Transfer losses from a donor compartment to a transfer compartment are not accounted for because this quantity is relatively small compared to the overall inventory in the source compartment. Inputs to a transfer compartment are the radionuclide or chemical concentration in the donor compartment. Transfer compartments include terrestrial vegetation (produce and animal forage) and animal products (meat and milk). Transfer pathways are indicated in Figure 1 by solid lines.

Transport compartments (blue ovals) consider the temporal, and in some cases, the spatial distribution of radionuclides and chemicals within their domain. Input to a transport compartment is the time-dependent flux from the donor compartment and the initial quantity of radionuclides or chemicals in the compartment at the start of the simulation. Transport compartments include the two source compartments (surface soil and vadose zone), the regional aquifer, and air. Transport within and out of transport compartments to other transport compartments accounts for mass lost and gained over time. That is, transport compartments are mass balanced. However, there are several exceptions. These include the radionuclide or chemical mass lost from the surface soils via particulate suspension, and the loss of volatile organic compounds (VOC) to groundwater from the VOC flux to the surface. The mass lost by these processes are relatively small and are ignored.

Transport, Transfer, and Exposure Pathways Conceptual Model

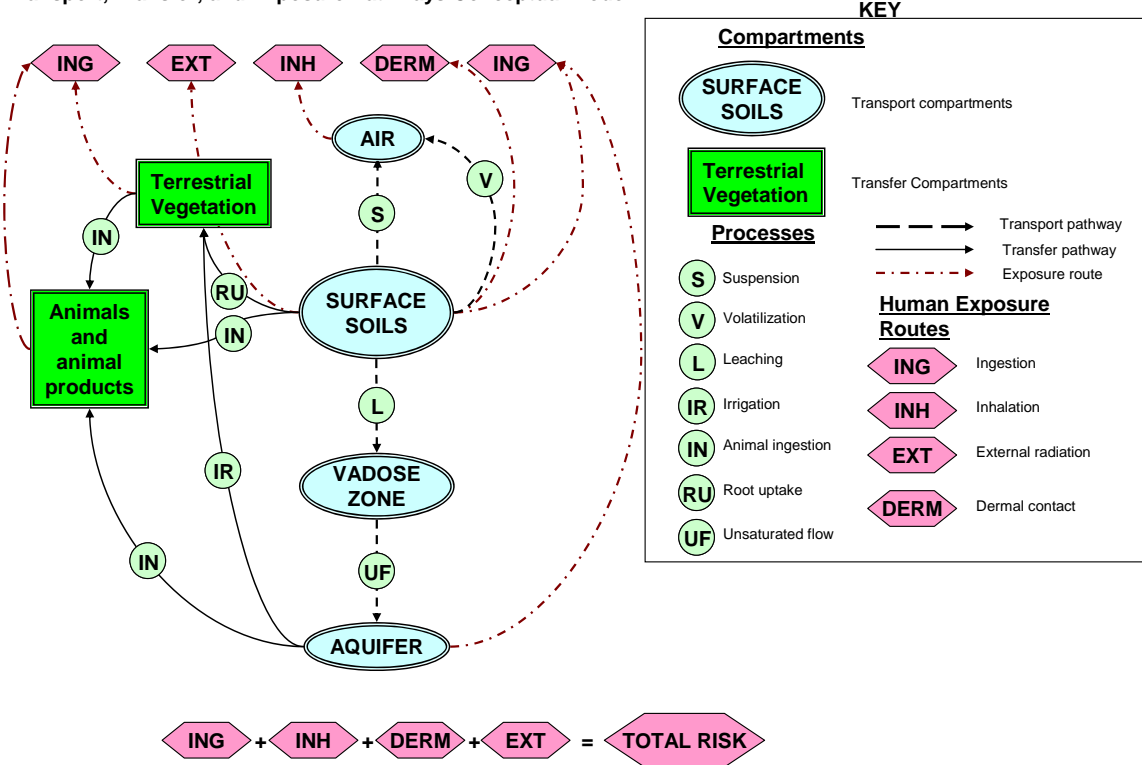


Figure 3. Conceptual model of the transport and transfer processes from source compartments to other environmental media and complete exposure pathways.

Environmental transport mechanisms considered for radionuclides and chemicals are aqueous-phase leaching through surface soil and vadose zone sources, aqueous-phase transport in the vadose zone and the regional aquifer, VOC diffusion from the surface soil to air at the ground surface, and particulate suspension from the surface soil to ambient air. Transfer processes considered for radionuclides and chemicals in the models include the transfer of radionuclides and chemicals in soil and irrigation water to edible crops and animal products (milk and meat).

In general, relatively simple models are implemented in the ranking tool for leaching and vadose zone transport, which can be classified as assessment models rather than predictive models. That is, the models account for the major transport processes that govern the transport of material, but lack the temporal or spatial resolution to allow comparisons with measured data over more refined timescales and spatial dimensions than those modeled. While more complex models include refined spatial and temporal resolution and additional processes, often, the data necessary to characterize the model domain are lacking. Furthermore, these more complex models require specialized expertise, detailed analysis of characterization data, and often, model calibration, which is beyond the scope of the ranking tool. The ranking tool methodology is designed to be flexible so that output from detailed modeling work can be substituted for the existing ranking tool models when appropriate. Each transport process is discussed below.

Suspension

Suspension is the process of the lifting of small particles (usually <50 μm) from the ground surface into the air stream by wind forces. Once suspended in the air stream, and if the particles are sufficiently small,

they can move considerable distances by wind and ultimately be redeposited on soil and vegetation or inhaled by a person.

The suspension model used in the ranking tool is derived from the Particulate Emission Factor (PEF) developed by Cowherd et al. (1985) and implemented in EPA's soil screening guidance (EPA 1996). The PEF is given by

$$PEF = \left[\frac{0.036(1 - f_V)(U_m/U_t)^3 F(x)}{3,600 \text{ s h}^{-1}} \right] \quad (1)$$

where

- PEF = particulate emission factor (g of PM_{10} $m^{-2} s^{-1}$)
- f_V = fraction of vegetative cover (unitless)
- U_m = mean annual wind speed ($m s^{-1}$)
- U_t = equivalent threshold wind speed at 7 m ($m s^{-1}$)
- $F(x)$ = function dependent on U_t/U_m in Cowherd et al. (1985) (unitless);
- x = $0.886 U_t/U_m$ (EPA 1996).

This model provides a mass flux to the air stream of radionuclides or chemicals attached to particles less than 10 μm . The estimated mass flux is then used with a site-specific dispersion factor to yield the radionuclide or chemical concentration in air above the source.

Volatilization and Diffusion

Transport via volatilization and diffusion applies to chemicals defined as volatile organic compounds (VOC). VOCs are defined as chemicals having Henry's Law constant greater than $1 \times 10^{-5} \text{ atm}\cdot\text{m}^3 \text{ mol}^{-1}$ and a molecular weight less than 200 g mol^{-1} (EPA 1996). VOCs that are present in the surface soil diffuse to the soil surface where they are released to the atmosphere. Once in the atmosphere, a person can inhale them.

The model used for estimating VOC flux from soil was obtained from the model given in EPA (1996), which is based on the model of Jury et al. (1990). This model applies to both VOCs present in pore water and soil because partitioning between the gas and liquid phase is accounted for in the model. The model was expanded to provide the integrated flux to the soil surface and the integrated flux to groundwater and, thereby, achieves mass balance between the two transport pathways. The VOC transport model provides the mass flux of VOC at the soil surface. The estimated mass flux is then used with a site-specific dispersion factor to yield the VOC concentration in air above the source.

The VOC model has the following assumptions and limitations

- Uniform soil properties
- Instantaneous linear equilibrium sorption
- Linear equilibrium liquid-vapor partitioning
- Uniform initial contaminant concentration in the source
- Soil VOC concentrations below the saturated limit
- No boundary-layer thickness at ground level ($C=0$ at ground level)
- No water evaporation or leaching
- No contaminant degradation

The flux at any point z in a one-dimensional model domain where the land surface is defined at $z = 0$ and the aquifer is at $z = Z$, and for the initial conditions $C = C_0$ at $t = 0$ and $L \leq z > 0$, and boundary conditions $C = 0$ at $z = 0$, and $C = 0$ at $z = \infty$ is

$$J(z,t) = \frac{D_e C_0}{2} \left[\frac{2e^{-\left(\frac{z}{2\sqrt{D_e t}}\right)^2}}{\sqrt{\pi D_e t}} - \frac{2e^{-\left(\frac{z-L}{2\sqrt{D_e t}}\right)^2}}{\sqrt{\pi D_e t}} - \frac{2e^{-\left(\frac{z+L}{2\sqrt{D_e t}}\right)^2}}{\sqrt{\pi D_e t}} \right] \quad (2)$$

where D_e = the effective diffusion coefficient given in EPA 1996.

Equation 2 gives the flux at depth in the vadose zone down to the aquifer and also at the ground surface. The integrated flux at the surface from the start of the simulation to the time when the flux at $z = Z$ is maximized is subtracted from the total initial mass used for groundwater leaching and transport calculations, and thereby accounts for the mass lost to the surface via vapor-phase diffusion.

Transport in the Atmosphere

The concentration of either a VOC emitted from the ground surface or suspended contaminated particles is given by

$$C_{AIR} = J \frac{X}{Q} \quad (3)$$

where C_{AIR} = the air concentration on the source, J = the VOC or particulate flux from the ground surface, and X/Q is the site-specific dispersion factor. The site-specific dispersion factor was calculated using the complex terrain atmospheric dispersion model, CALPUFF (Scire et al. 2000a, 2000b). Because the air concentration from a diffuse source is dependent on the area of the source, air dispersion factors were calculated for various source areas and fitted to a function given by

$$\frac{X}{Q} = 0.129 L \quad (4)$$

where L is the length of one side of a square area source (m). The site-specific X/Q values can be compared to similar quantities estimated in EPA (1996). EPA's (1996) X/Q value for a 30-acre (121,406 m²) site in Albuquerque¹ was 23.1 s m⁻¹. Using the regression equation above and $L = (121,406 \text{ m}^2)^{1/2} = 348.43$ m, yields a X/Q value of 44.9 s m⁻¹, which is a factor of 1.9 higher than the value for Albuquerque. The difference is attributed to (1) the different meteorological conditions that exist at LANL and (2) the fact that EPA values are based on a receptor in the center of the source, whereas the CALPUFF modeling takes the maximum concentration across a grid of receptors overlaying the source. The site-specific CALPUFF X/Q values would yield a higher air concentration than the EPA generic X/Q value for Albuquerque.

¹ The value for Albuquerque in EPA (1996) is 43.31 and represents the inverse of the X/Q in units of g m⁻² s⁻¹ kg⁻¹ m⁻³ [1/(43.31 g m⁻² s⁻¹ kg⁻¹ m³ × (0.001 kg g⁻¹)) = 23.1 s m⁻¹].

Leaching, Vadose Zone, and Aquifer Transport

Radionuclides and chemicals present in the surface soil and vadose zone are subject to leaching and downward transport to the regional aquifer, and subsequent transport and dispersal in the aquifer. A separate computer code, the Response Surface Model (RSM) (Rood and Jacobs, 2008), was written to address the complete pathway. The RSM incorporates a first-order leaching model, a one-dimensional vadose zone transport model, and a response surface model to address aquifer transport.

The first-order leaching model and vadose zone transport model are based on the formulations given in Rood (1999). The mass flux from the source compartment (F_s) as a function of time is given by

$$F_s(t) = KM_o e^{-(\lambda+K)t} \quad (5)$$

where K = the leach rate constant (yr^{-1}), λ = decay rate constant (yr^{-1}), and M_o = the initial mass in the source (Ci, Bq or mg). The flux to the aquifer is computed using the convolution of the one-dimensional flux equation and $F_s(t)$. The one-dimensional flux equation is given by

$$F_{VZ}(t) = \frac{Z + \frac{vt}{\theta_V R_{dV}}}{4\sqrt{D_Z \pi t^3 / R_{dZ}}} \exp \left[\frac{-\left(Z - \frac{vt}{\theta_V R_{dV}} \right)^2}{4D_Z t / R_{dZ}} - \lambda t \right] \quad (6)$$

where

- D_Z = dispersion coefficient in the vadose zone = $\alpha_V v / \theta_V$ ($\text{m}^2 \text{yr}^{-1}$)
- Z = thickness of the vadose zone (m)
- $F_{VZ}(t)$ = mass flux per unit time entering aquifer for a unit mass release at base of the source compartment.

The convolution of equation 5 and 6 is given by

$$F_{VZA}(t) = \int_0^t F_{VZ}(t-\tau) F_s(\tau) d\tau \quad (7)$$

Aquifer concentrations are computed by the convolution of pre-calculated response functions and the radionuclide or chemical fluxes to the aquifer computed using the leaching and vadose zone transport model. The footprint of the source projected in the aquifer is assumed to be the same as the horizontal area of the region defined by the source at the surface or in the vadose zone.

Response functions (RF) were determined using the MODFLOW/MT3D numerical groundwater model for the regional aquifer underlying LANL. The RF is the concentration breakthrough curve at a given receptor that occurs in response to a unit mass input of a conservative tracer (i.e., non sorbing or decaying) in a given source region. To account for the decay and sorptive properties of different contaminants, several simplifying assumptions are made:

- Sorption is uniform throughout the aquifer
- Decay is constant throughout the aquifer

- Parent and progeny travel at the same rate in the aquifer (i.e., they have the same sorption coefficient).

The contaminant concentration in the aquifer is then given by:

$$C_{i,j,k=1}(t) = \frac{1}{Rd_1} \int_0^t RF_{i,j} \left(\frac{t-\tau}{Rd_1} \right) S_i(\tau) e^{-\lambda_1(t-\tau)} d\tau \quad (8)$$

where

$C_{ij}(t)$ = aquifer concentration of a contaminant at time t for source i and receptor j (Bq m⁻³ or mg m⁻³)

$RF_{ij}(t-\tau)$ = response function for source i and receptor j at time $t - \tau$ (m⁻³)

$F_{VZA}(\tau)$ = radonucleide or chemical fluxes to the aquifer for source region i at time τ (Bq yr⁻¹ or mg yr⁻¹)

i = source region index

j = receptor index.

$C_{i,j,k=l}(t)$ = concentration of the first member of the decay chain at time t for source i and receptor j (Bq m⁻³ or mg m⁻³). The index k refers to the decay product where $k = 1$ is the parent or first member in a decay chain

Rd_1 = the retardation factor for the first member of the decay chain (unitless)

λ_1 = decay rate constant for the parent (yr⁻¹)

k = decay product index; $k = 1$ for parent.

The retardation factor is given by

$$Rd = 1 + \frac{K_d \rho}{\phi} \quad (9)$$

where

K_d = sorption coefficient in aquifer (mL g⁻¹)

ρ = bulk density of aquifer (g mL⁻¹)

ϕ = aquifer porosity.

The concentration of subsequent decay chain members (i.e., $k > 1$) is approximated by computing the amount of ingrowth that occurs from the start of the simulation and starting from an initially pure parent.

$$C_{i,j,k \neq 1}(t) = \frac{1}{Rd_k} \int_0^t RF_{i,j} \left(\frac{t-\tau}{Rd_1} \right) S_i(\tau) DIF_k(t) d\tau \quad (10)$$

where

$DIF_k(t)$ = decay-ingrowth factor for decay chain member k

The decay-ingrowth factor is the activity of decay product k present at time t relative to the original parent activity released at time $t = 0$. For the parent or first member in the decay chain, the decay-ingrowth factor is simply $\exp(-\lambda_1 t)$. For a decay product other than the parent, the decay-ingrowth factor is given by:

$$DIF_k(t) = \frac{\lambda_k}{\lambda_1} \left[\left(\prod_{i=1}^{k-1} \lambda_i \right) \sum_{i=1}^k \frac{e^{-\lambda_i t}}{\prod_{\substack{j \neq i \\ j=1}}^i (\lambda_j - \lambda_i)} \right] \quad (11)$$

where

λ_1 = decay constant for the parent (yr^{-1})

λ_k = decay constant for the k^{th} progeny (yr^{-1}).

The total contaminant concentration from all source regions is evaluated by superposition of each source-receptor pair. That is, the contaminant concentration at a given receptor location from multiple sources is the sum of the concentration from each individual source region as given by:

$$C_{j,k}(t) = \sum_{i=1}^n C_{i,j,k}(t) \quad (12)$$

where n is the number of source regions considered in the model domain.

Transfer to Food Products

Ingestion pathways include ingestion of homegrown cultivated food crops and home-raised animals and animal products. The food chain model implemented in the ranking tool is based on the National Council on Radiation Protection (NCRP) screening model for environmental releases of radionuclides (NCRP 1996). While the model has been developed for radionuclides, it is equally applicable to non-radioactive substances. Two sources of radionuclides and chemicals in crops and animals are considered: (1) radionuclide and chemicals in irrigation water and drinking water for animals and (2) radionuclide and chemicals in soil used for cultivation. For the ranking tool, the irrigation water and water for animals is assumed to be drawn from a well in the regional aquifer that is located in the region where leachate from the surface soil or vadose zone source enter the aquifer. The food chain model calculates concentrations of radionuclides and chemicals in milk, meat, and vegetables given a radionuclide or chemical concentration in soil or irrigation water.

CONCLUSIONS

The models used in the RACER risk ranking tool represent either simple conceptual models or abstractions from complex models. For example, the aquifer transport model and air dispersion model represent abstractions from complex models whereas the volatilizations model and vadose zone transport

model represent relatively simple models. One key principle in the employed in all the models is finite-mass initial mass. In this way, ranking is performed taking into consideration the total initial mass of contaminant in the system. Without this consideration, the ranking of sources may become distorted where sources with high contaminant concentrations but low total contaminant inventories would rank higher (i.e., greater importance) compared to sources that may have lower contaminant concentrations in soil but occupy a larger area. In general, the methodology attempts to take advantage of what is known wherever possible, and addressing the unknown with simplifying assumptions and flexible default values to address site-specific needs. The methodology also takes advantage of the abstracted complex modeling output to facilitate consistent and repeatable real-time assessments using up-to-date environmental measurement data. The ranking tool is due to be completed in June of 2009.

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