DOCUMENTATION FOR EPA'S IMPLEMENTATION OF THE JOHNSON AND ETTINGER MODEL TO EVALUATE SITE SPECIFIC VAPOR INTRUSION INTO BUILDINGS

Version 6.0

Prepared By

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF SUPERFUND REMEDIATION AND TECHNOLOGY INNOVATION
WILLIAM JEFFERSON CLINTON BUILDING, 5202G
1200 PENNSYLVANIA AVENUE, NW
WASHINGTON, D.C. 20460

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DISCLAIMER

This document provides technical instructions and recommendations of the U.S. Environmental Protection Agency (EPA) on the use of an EPA-developed excel based tool for supporting assessments of the vapor intrusion pathway. The excel workbook implements the one-dimensional model of soil vapor intrusion that was originally was developed by Paul Johnson and Robert Ettinger in 1991, and includes additional risk calculations as well as suggested default parameter values. This spreadsheet and the recommendations included in this guide are based on our current understanding of the phenomenon of soil vapor intrusion into indoor air. Users of this document are reminded that the science concerning vapor intrusion is complex and evolving.

This document does not impose any requirements or obligations on the EPA, the states or tribal governments, or the regulated community. Rather, the sources of authority and requirements for addressing subsurface vapor intrusion are the applicable and relevant statutes and regulations. Decisions regarding a particular situation should be made based upon statutory and regulatory authority.

This user's guide, and the accompanying spreadsheet tool, is not intended as guidance. The purpose of this document and the model are to provide an implementation of a widely used screening model, to support vapor intrusion risk assessment at Superfund sites. This tool is intended to assist Remedial Project Managers (RPMs), On Scene Coordinators (OSCs), risk assessors and others involved in decision-making concerning CERCLA hazardous waste sites and to determine whether levels of contamination found at the site may warrant further investigation or site cleanup, or whether no further investigation or action may be required. Users within and outside the CERCLA program should use the model results at their own discretion and they should take care to understand the assumptions incorporated in these results and to apply the results appropriately.

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1. Introduction

1.1 What is Vapor Intrusion?

Chemicals that are released into subsurface soil or groundwater may volatilize and form hazardous vapors that subsequently may diffuse or migrate through the vadose zone. These vapors may eventually enter buildings through cracks or perforations in basement floors and walls. Vapor intrusion is the general term given to the migration of chemical vapors from subsurface contaminant sources through the vadose zone and into indoor air. For hazardous chemicals, vapor intrusion constitutes a potential inhalation exposure pathway of concern, which may need to be evaluated when assessing contaminated sites and preparing risk assessments.

1.2 Johnson & Ettinger's Model

Johnson and Ettinger (1991) introduced a screening-level model (referred to as the J&E Model) that incorporates both convective and diffusive mechanisms for estimating the transport of contaminant vapors emanating from subsurface soil or groundwater into indoor spaces located directly above the source of contamination. The J&E Model is a one-dimensional analytical solution to convective and diffusive vapor transport into indoor spaces and provides an estimated attenuation coefficient that relates the vapor concentration in the indoor space to the vapor concentration at the source of contamination. Inputs to the model include chemical properties of the contaminant, saturated and unsaturated zone soil properties, and structural properties of the building. In their article, Johnson and Ettinger reported that the results of the model were in qualitative agreement with published experimental case histories and in good qualitative and quantitative agreement with detailed three-dimensional numerical modeling of radon transport into houses.

1.3 Document Scope

This manual provides the technical documentation for the J&E Model as implemented by EPA in the accompanying spreadsheets (Version 6.0). These spreadsheets employ the steady-state solution to vapor transport (infinite or non-diminishing source and steady state vapor concentrations) described by Johnson and Ettinger (1991). The spreadsheet tool allows the user to input a site-specific subsurface soil gas concentration and sampling depth or a groundwater concentration and depth to groundwater. The model provides default values of vadose zone characteristics, building characteristics, and exposure parameters, or allows the user to enter site-specific information. Model output includes both risk-based soil gas or groundwater concentrations below which associated health effects are considered unlikely, and estimates of the incremental risks associated with user-defined initial soil gas or groundwater concentrations. The model reverse-calculates an "acceptable" soil gas or groundwater concentration given a user-defined risk level (i.e., target risk level or target hazard quotient), and the model will also forward-calculate an incremental cancer risk or hazard quotient based on an initial soil or groundwater concentration.

1.4 Model overview

The EPA spreadsheet implementation of the J&E model provides users with a tool that takes measured chemical concentrations from groundwater or soil gas and predicts indoor air concentrations and the associated risks to human health. This tool builds upon the model put forth in Johnson and Ettinger (1991) and Johnson (2005) by building in the calculations for the inputs and adding risk calculations as a final step. Figure 1, below, shows how the different calculations relate to each other and how they are used together to estimate risks to human health.

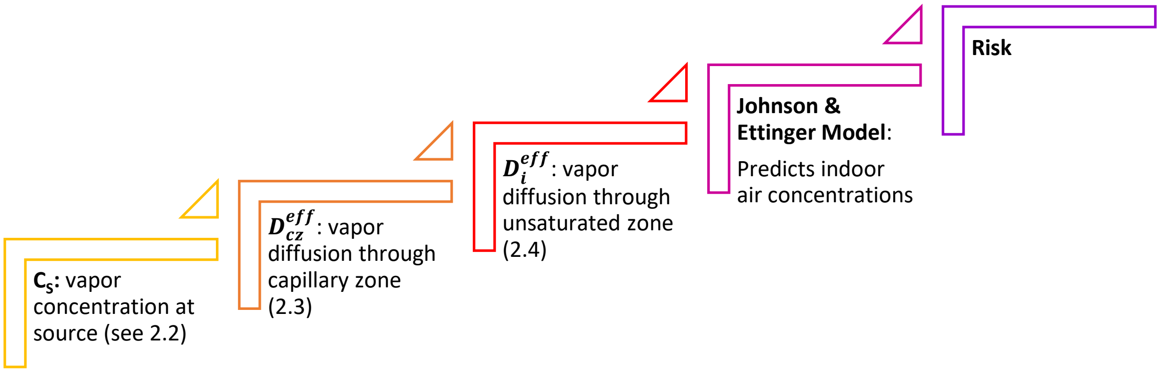

Figure 1: Theoretical Underpinnings of the EPA Vapor Intrusion Spreadsheet Tool

Note that the EPA's vapor intrusion model calculates diffusive transport differently than the original J&E model. The equations used in the EPA model have been selected because they have easily measured, quantifiable inputs and are flexible enough to take into account different soil types and temperatures. These equations are explained in section 2.

1.5 Other Models of Vapor Intrusion

A complete model of vapor intrusion describes the entry of volatile compounds into building located over contaminated media (typically groundwater or soil), and include two parts: vapor transport in the soil, and entry of vapor into a building. Broadly, models can be distinguished by:

- whether they incorporate advection (motion of particles along bulk flow) or diffusion (movement from high to low concentration)
- Model transport through the soil in 1 (vertical) , 2 (vertical and horizontal) or 3 (all directions) dimensions,

- If they use transient or steady state dynamics to describe the system, and
- If biodegradation is incorporated.

The J&E model is a 1 dimensional model that is governed by steady state diffusion through the unsaturated zone, and advection and diffusion through the building slab, with no biodegradation taken into account. The J&E model is widely used because it is fairly easy to implement, does not require intensive computational resources, and uses a limited number of site specific parameters. While it is generally believed to be a conservative model, it is widely considered to be appropriate for screening level purposes (Tillman and Weaver, 2005).

The purpose of this document is to provide users with information on how the EPA implemented the J&E model and risk based screening level calculations, and to explain to users how to use the spreadsheet tool. For a thorough review of other models of vapor intrusion, see:

- Strategic Environmental Research and Development Program (SERDP) Report "Vapor Intrusion from Entrapped NAPL Sources and Groundwater Plumes: Process Understanding and Improved Modeling Tools for Pathway Assessment" Project ER-1687, July 2014 (https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-1687/ER-1687, specifically section 2.3)
- Provoost et al. "Accuracy and Conservatism of Vapor Intrusion Algorithms for Contaminated Land Management." *Environment and Pollution* (2013). 2.2, p 71.
- Yao et al. "A Review of Vapor Intrusion Models". *Environmental Science & Technology* (2013) Vol 46, 2457-2470.
- Yao et al. "Comparison of the Johnson-Ettinger Vapor Intrusion Screening Model Predictions with Full Three-Dimensional Model Results" (2011). Vol 45, p 2227-2235.

1.6 Version Notes

This revised version of the User's Guide corresponds with the release of Version 6.0 of EPA's version of the Johnson and Ettinger (J&E) (1991) model for estimating subsurface vapor intrusion into buildings. Several changes have been made since the previous version (Version 3.1) was released in February 2004. The following represent the major changes in Version 6.0:

1. The model includes changes to streamline the model and improve ease of use:
    - The use of color and new fonts enhances readability and identifies key model parameters.
    - The groundwater and soil gas models have been combined into the same sheet, although only one model may be run at a time.
    - The DATAENTER, CHEMPROPS, INTERCALCS, and RESULTS worksheets in the previous version have been combined into the MODEL worksheet in Version 6.0.

- The model includes a blue-highlighted preview section at the top of the MODEL sheet which displays the indoor air attenuation factor (α)and the indoor air concentration due to vapor intrusion based on currently entered input values. This value will be automatically updated as the user modifies the model inputs.
- The screening and advanced models for groundwater and soil gas have been combined into a single model. The user may elect to use or to change default values for toxicity factors, building characteristics, vadose zone characteristics, and exposure time parameters.
- Chemicals, building characteristics, and soil types are selected by name via dropdown menus. The model automatically displays the relevant default values for chemical properties, building characteristics, and vadose zone characteristics once the user selects the appropriate inputs.

2. This version models vapor intrusion based on either groundwater or soil gas concentrations, which are the most well-supported approaches for modeling volatile chemicals. The soil model option has been removed to become consistent with U.S. EPA guidance (U.S. EPA, 2015c). The non-aqueous phase liquids (NAPL) models from Version 3.1 (U.S. EPA, 2004) have not been incorporated into Version 6.0.

3. The model has the capability to calculate output for multiple chemicals simultaneously for a given set of building, soil, and exposure inputs. See section 3.3 for more information.

4. The revised model calculates both the risk-based target screening levels (target indoor air concentration and target soil gas or groundwater concentration) and incremental risk estimates (hazard quotient and incremental cancer risk) for user input site-specific soil gas or groundwater concentrations. It displays the target indoor air concentration in both µg/m3and ppbv and notes whether the concentration was based on the inhalation unit risk (IUR; cancer risk) or the reference concentration (non-cancer toxicity).The model calculates the incremental cancer risk using a default exposure duration of 26 years for non-mutagenic chemicals and 76 years for mutagenic chemicals. Previous versions of the model used an exposure duration of 30 years for all chemicals.

5. The model includes options for three new foundation types: a basement with a dirt floor, a closed crawlspace with a dirt floor, and a closed crawlspace with slab. These options supplement the basement with slab and slab-on-grade options available in the previous model. The crawlspace options are only valid for closed, unvented crawlspaces and will not accurately model vapor intrusion in buildings with vented (open) crawlspaces.

6. The model output has been expanded. The output now includes a graph of the predicted soil gas concentration by depth to allow users to compare values calculated by the model to measured soil gas values. An interpretation section displays whether

advection or diffusion is the dominant mechanism of transport across the foundation of the building or whether both diffusion and advection contribute to this process. It also displays which mechanism is the rate-limiting process. This section lists which parameters are critical and non-critical for vapor intrusion into a building based on the input chemical, building, and soil characteristics.

7. The toxicological and chemical properties tables (CHEM_DATA) have been updated with values from the U.S. EPA regional screening level tables (US EPA, 2015a). The list of chemicals is now identical to chemicals listed as “sufficiently volatile and toxic to pose inhalation risk” from both soil and groundwater sources in the U.S. EPA Vapor Intrusion Screening Level (VISL) Calculator (US EPA, 2015b).

8. The error messages now indicate if values input by the user are outside of reasonable ranges. These warning messages appear next to the parameter entered as well as in the output section of the MODEL sheet.

9. An option for users to enter measured soil gas concentrations by depth has been added. These concentrations are plotted alongside soil gas concentrations by depth calculated by the model.

10. Version 6.0 has an English to metric units converter. When users enter distances and areas in feet into the converter, these measurements are converted to meters and inputted into the model.

11. The model spreadsheet reports coefficients of variation for default parameters, based on published literature.

12. The reset to defaults options have been expanded to include reset options for each section of the MODEL sheet, as well as for the entire workbook at once.

13. The model now outputs a range for the predicted attenuation factors, indoor air concentration, and human health risk, based on the range of values for $Q_{soil}/Q_{building}$ reported in the literature.

2. Technical Documentation

This section provides the derivations for the formulas used in the EPA workbooks. The estimated indoor air concentration is based on a series of processes: the presence of a vapor forming contaminant in groundwater or soil below, or near, a building; vapor diffusion from the contaminated source through the soil; entry into a building; and then risk calculations based on predicted indoor air concentrations.

2.1 Equations for Diffusion from the Contaminated Source through Soil

Chemical fate and transport within the vadose zone, and vapor transport into enclosed spaces, is determined by a number of physical and chemical processes. This section presents the theoretical framework behind the inputs into the EPA implementation of the J&E Model, taking into account the most significant processes. In addition, this section also presents the theoretical basis for estimating values for model parameters when empirical field data are lacking.

2.1.1 Conceptual Overview

Consider a contaminant vapor source (C_{medium}) located some distance below the floor of an enclosed residential building constructed with a basement, crawl space, or slab-on-grade foundation.[1] The source of contamination is either a volatile contaminant in soil or a volatile contaminant dissolved in groundwater at or below the top of the water table.

Figure 2 illustrates the scenario where the source of contamination is below the top of the water table. The contaminant must diffuse through a capillary zone immediately above the water table and through the overlying unsaturated or vadose zone before convection transports the vapors into the structure. The rate of soil gas entry (Q_{soil}) or average vapor flow rate into the building is a function solely of convection; however, the vapor concentration entering the structure may be limited by either convection or diffusion through the vadose zone, depending upon the magnitude of the source-building separation. Our model uses the steady-state solution for vapor transport provided by Johnson and Ettinger (1991) because generally insufficient information exists to estimate the size and total mass of the source of emissions.

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[1] In this model, both basement and crawl space foundations may have a dirt floor or slab construction.

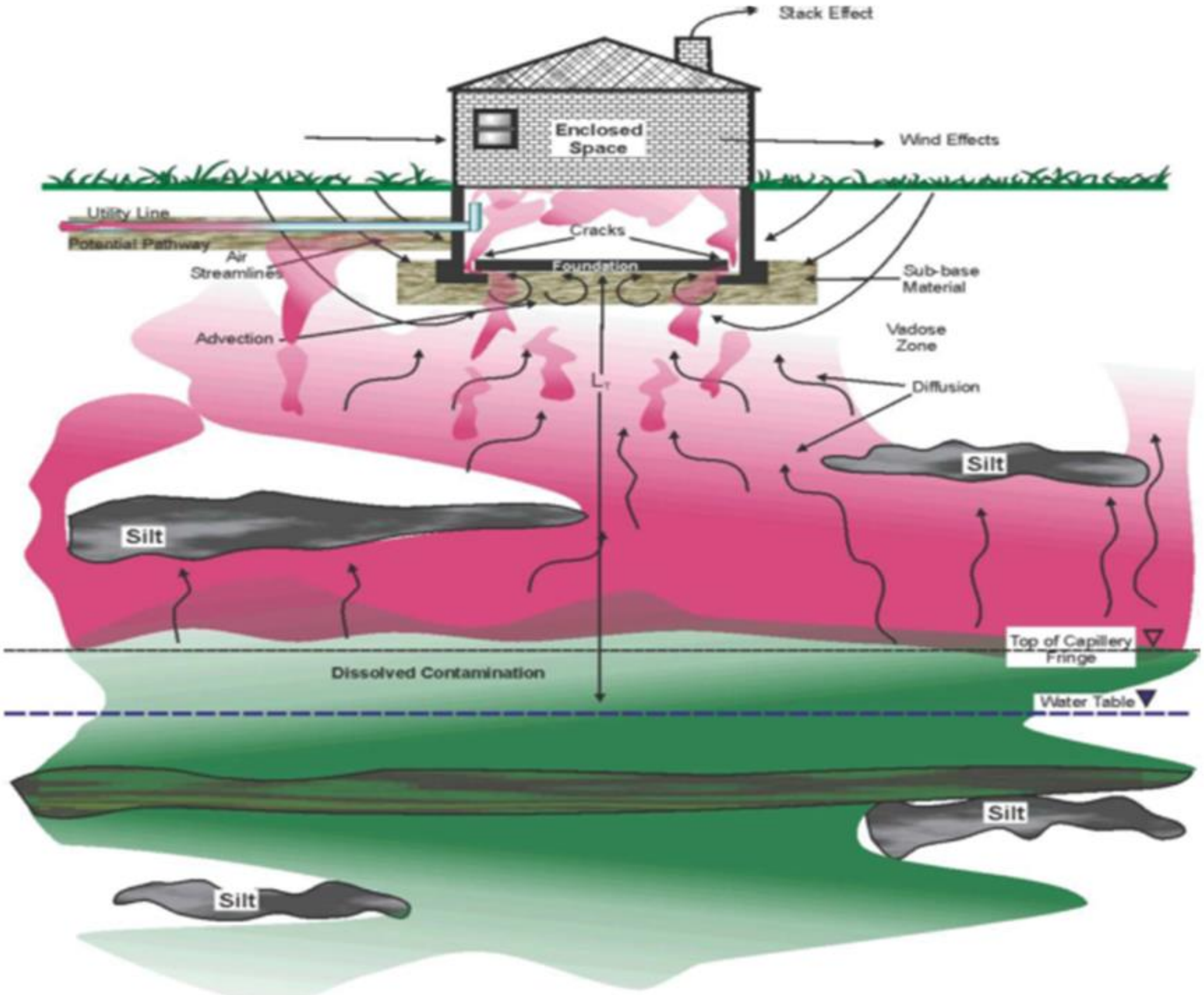


Figure 2: Vapor Intrusion Pathway into Buildings

The suggested minimum site characterization information for a first-tier evaluation of the vapor intrusion pathway includes: site conceptual model, nature and extent of contamination distribution, soil lithologic descriptions, depth to water and groundwater concentrations or near source soil vapor concentrations, and foundation type (basement or slab on grade). The number of samples and measurements needed to establish this information varies by site. The default building parameters assume a residential scenario.

Previous versions of the EPA implementation of the J&E Model included a bulk soil module, which relied on theoretical partitioning among the sorbed, aqueous, and vapor phases to calculate a soil vapor concentration. Considering the concerns expressed in EPA's 2015 vapor intrusion guidance, the bulk soil module has been removed from this version. Use of measured soil gas concentrations directly beneath the building floor instead of theoretical vapor concentrations helps to reduce the uncertainty in the indoor air concentration estimates made by the model.

2.1.2 Vapor Concentration at the Source of Contamination

With a general concept of the problem under consideration, the solution begins with an estimate of the vapor concentration at the source of contamination. For groundwater contamination, the source vapor concentration (C_S) is estimated assuming that the vapor and aqueous-phases are in local equilibrium according to Henry's law such that:

$$C_S = H_s \times C_{medium} \times 1000 \qquad (1)$$

where C_S = Vapor concentration in equilibrium with dissolved concentration in groundwater at the source of contamination, µg/L

H_S = Henry's law constant at the system (groundwater) temperature, dimensionless

C_{medium} = Groundwater concentration, µg/L

For contamination within the vadose zone, C_S is ideally the soil vapor concentration measured near the contamination source, though in practice it may be the vapor concentration measured at any depth in the vadose zone.

The dimensionless form of the Henry's law constant at the system temperature (i.e., at the average soil/groundwater temperature for the site) may be estimated using the Clausius-Clapeyron relationship:

$$H_S = \frac{exp\left[-\frac{\Delta H_{v,S}}{R_c}\left(\frac{1}{T_S} - \frac{1}{T_R}\right)\right] H_R}{RT_S} \qquad (2)$$

where H_S = Henry's law constant at the system temperature, dimensionless

$\Delta H_{v,S}$ = Enthalpy of vaporization at the system temperature, cal/mol

T_S = System temperature, K

T_R = Henry's law constant reference temperature, K

H_R = Henry's law constant at the reference temperature, atm-m^3/mol

R_C = Gas constant (= 1.9872 cal/mol - K)

R = Gas constant (= 8.205 E-05 atm-m^3/mol-K).

The enthalpy of vaporization at the system temperature can be calculated from Lyman et al. (1990) as:

$$\Delta H_{v,S} = \Delta H_{v,b} \left[\frac{\left(1 - {}^{T_s}\!/_{T_c}\right)}{\left(1 - {}^{T_B}\!/_{T_c}\right)} \right]^n \tag{3}$$

where $\Delta H_{v,S}$ = Enthalpy of vaporization at the system temperature, cal/mol

$\Delta H_{v,b}$ = Enthalpy of vaporization at the normal boiling point, cal/mol

T_S = System temperature, K

T_C = Critical temperature, K

T_B = Normal boiling point, K

n = Constant, unitless

Table 1 gives the value of n as a function of the ratio T_B/T_C, from the US EPA 2001 Fact Sheet, “Correcting for Henry’s Law Constant for Soil Temperature”.

Table 1: Values of n (exponent) as a function of T_B/T_C

T_B/T_C	*n*
< 0.57	0.30
0.57 to 0.71	$0.74 (T_B/T_C) - 0.116$
> 0.71	0.41

2.1.3 Diffusion through the Capillary Zone

Directly above the water table, a saturated capillary zone exists where groundwater is held within the soil pores at less than atmospheric pressure (Freeze and Cherry, 1979). Once the concentration at the source has been calculated, one can calculate the rate of diffusion across the capillary zone. In order to calculate the rate of mass transfer, the porosity and height of the capillary zone, as well as the diffusion coefficient across it, must be calculated.

Water Filled Porosity in the Capillary Zone

Between drainage and wetting conditions, the saturated water content in the capillary zone varies but is always less than the fully saturated water content, which is equal to the soil total porosity. This is the result of air entrapment in the pores during the wetting process (Gillham, 1984). Upon rewetting, the air content of the capillary zone will be higher than after main drainage. Therefore, the air content will vary as a function of groundwater recharge and discharge. At the saturated water content, Freijer (1994) found that the relative vapor-phase diffusion coefficient was almost zero. This implies that all remaining air-filled soil pores are disconnected and thus blocked for gas diffusion. As the air-filled porosity increased, however, the relative diffusion coefficient indicated the presence of connected air-filled pores that corresponded to the air-entry pressure head. The air-entry pressure head corresponds with the top of the saturated capillary zone. The effective diffusion coefficient for the capillary zone is calculated by considering the gas-phase and aqueous-phase together. The water-filled soil porosity in the capillary zone ($\theta_{w,cz}$) is calculated at the air-entry pressure head (h) according to the procedures of Waitz et al. (1996) and the van Genuchten equation (van Genuchten, 1980) for the water retention curve:

$$\theta_{w,cz} = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha_1 h)^N]^M} \tag{4a}$$

where $\theta_{w,cz}$ = Water-filled porosity in the capillary zone, cm^3/cm^3

θ_r = Residual soil water content, cm^3/cm^3

θ_s = Saturated soil water content, cm^3/cm^3

α_1 = Point of inflection in the water retention curve where d θ_w/dh is maximal, cm^{-1}

h = Air-entry pressure head, cm (= $1/\alpha_1$ and assumed to be positive)

N = van Genuchten curve shape parameter, dimensionless

M = 1/ (1-N).

Assuming θ_s=N, equation 4a reduces to:

$$\eta_{w,cz} = \theta_r + \frac{N - \theta_r}{2^M} \tag{4b}$$

where $\eta_{w,cz}$= total soil porosity (Saturated soil water content) cm^3/cm^3

The air-filled porosity within the capillary zone ($\theta_{a,cz}$) corresponds to the minimum value at which gas diffusion is relevant, and is calculated as the total porosity (η - $\theta_{w,cz}$). (Note: Version 6.0 of the model uses variable name n_{wcz} instead of $\theta_{w,cz}$.)

Hers (2002) computed the USDA Soil Conservation Service (SCS) class average values of the water filled porosity and the height of the capillary zone SCS soil textural classifications. Table 2 provides the class average values for each of the SCS soil types. These data replace the mean values developed by Schaap and Leij (1998) included in the previous U.S. Environmental Protection Agency (EPA) version of the J&E Model. With the class average values presented in Table 2, a general estimate can be made of the values of water and air filled porosities for each soil textural classification.

Table 2: Class Average Values of the van Genuchten Soil Water Retention Parameters for the 12 SCS Soil Textural Classifications

Soil texture (USDA)	Saturated water content, θ_s	Residual water Content, θ_r	van Genuchten parameters		
			α_1 (1/cm)	N	M
Clay	0.459	0.098	0.01496	1.253	0.2019
Clay loam	0.442	0.079	0.01581	1.416	0.2938
Loam	0.399	0.061	0.01112	1.472	0.3207
Loamy sand	0.390	0.049	0.03475	1.746	0.4273
Silt	0.489	0.050	0.00658	1.679	0.4044
Silty loam	0.439	0.065	0.00506	1.663	0.3987
Silty clay	0.481	0.111	0.01622	1.321	0.2430
Silty clay loam	0.482	0.090	0.00839	1.521	0.3425
Sand	0.375	0.053	0.03524	3.177	0.6852

Sandy clay	0.385	0.117	0.03342	1.208	0.1722
Sandy clay loam	0.384	0.063	0.02109	1.330	0.2481
Sandy loam	0.387	0.039	0.02667	1.449	0.3099

Effective Diffusion Coefficient Across the Capillary Zone

One the soil porosity is known, the total effective diffusion coefficient across the capillary zone (D_{cz}^{eff}) may then be calculated using the Millington and Quirk (1961) model as:

$$D_{cz}^{eff} = D_a\left(\theta_{a,cz}^{3.33}/n_{cz}^2\right) + (D_w/H_S)(\theta_{w,cz}^{3.33}/n_{cz}^2) \quad (5a)$$

where D_{cz}^{eff} = Effective diffusion coefficient across the capillary zone, cm^2/s

D_a = Diffusivity in air, cm^2/s

$\theta_{a,cz}$ = Soil air-filled porosity in the capillary zone, (η - n_{wcz}), cm^3/cm^3

n_{cz} = Soil total porosity in the capillary zone, cm^3/cm^3

D_w = Diffusivity in water, cm^2/s

H_S = Henry's law constant at the system temperature, dimensionless

$\theta_{w,cz}$ = Soil water-filled porosity in the capillary zone, cm^3/cm^3.

The spreadsheet calculates the effective diffusion coefficient in the same manner, using the following equation:

$$D_{cz}^{eff} = \frac{D_{air}((n_{cz} - n_{wcz})^{3.33}) + (D_{water} \times n_{wcz}^{3.33}/H_s)}{n_{cz}^2} \quad (5b)$$

where D_{cz}^{eff} = Effective diffusion coefficient across the capillary zone, cm^2/s

D_{air} = Diffusivity in air, cm^2/s

D_{water} = Diffusivity in water, cm^2/s

H_S = Henry's law constant at the system temperature, dimensionless

n_{cz} = Capillary zone total porosity, unitless

n_{wcz} = Capillary zone water-filled porosity, unitless

Rate of Mass Transfer Across the Capillary Zone

According to Fick's law of diffusion, the rate of mass transfer across the capillary zone can be approximated by the expression:

$$E = \frac{A(C_s - C_{g0})D_{cz}^{eff}}{h_{cz}} \tag{6}$$

where E = Rate of mass transfer, g/s

A = Cross-sectional area through which vapors pass, cm^2 (assumed to be 1 cm^2)

C_S = Vapor concentration within the capillary zone, g/cm^3 (calculated using Equation 1)

C_{g0} = A known vapor concentration at the top of the capillary zone, g/cm^3 (C_{g0} is assumed to be zero as diffusion proceeds upward)

D_{cz}^{eff} = Effective diffusion coefficient across the capillary zone, cm^2/s (calculated by Equation 5b)

h_{cz} = Height of capillary zone, cm

Calculating the Height of the Capillary Zone

In order to calculate the rate of mass transfer, the height of the capillary zone must be known. Lohman (1972) and Fetter (1994) estimated the rise of the capillary zone above the water table using the phenomenon of capillary action, where water molecules are subject to an upward attractive force due to surface tension at the air-water interface and the molecular attraction of the liquid and solid phases. The rise of the capillary zone can thus be estimated using the equation for the height of capillary rise in a bundle of tubes of various diameters equivalent to the diameters between varying soil grain sizes. Fetter (1994) estimated the mean rise of the capillary zone as:

$$h_{cz} = \frac{2\,\alpha_2 \cos\lambda}{\rho_w g\, R} \tag{7a}$$

where h_{cz} = Mean rise of the capillary zone, cm; model defines h_{cz} in meters

α_2 = Surface tension of water, dyne/cm (= 73)

λ = Angle of the water meniscus with the capillary tube, degrees (assumed to be zero)

ρ_w = Density of water, g/cm^3 (= 0.999)

g = Acceleration due to gravity, cm/s^2 (= 980)

R = Mean interparticle pore radius, cm (=0.2D)

D = Mean grain diameter in cm

Assuming that the default values of the parameters given in Equation 7a are for groundwater between 5° and 25°C, Equation 7a reduces to:

$$h_{cz} = \frac{0.15}{0.2 \times D} \tag{7b}$$

Nielson and Rogers (1990) estimated the arithmetic mean particle diameter for each of the 12 SCS soil textural classifications at the mathematical centroid calculated from its classification area

(Figure 2). Table 3 shows the centroid compositions and mean particle sizes of the 12 SCS soil textural classes.

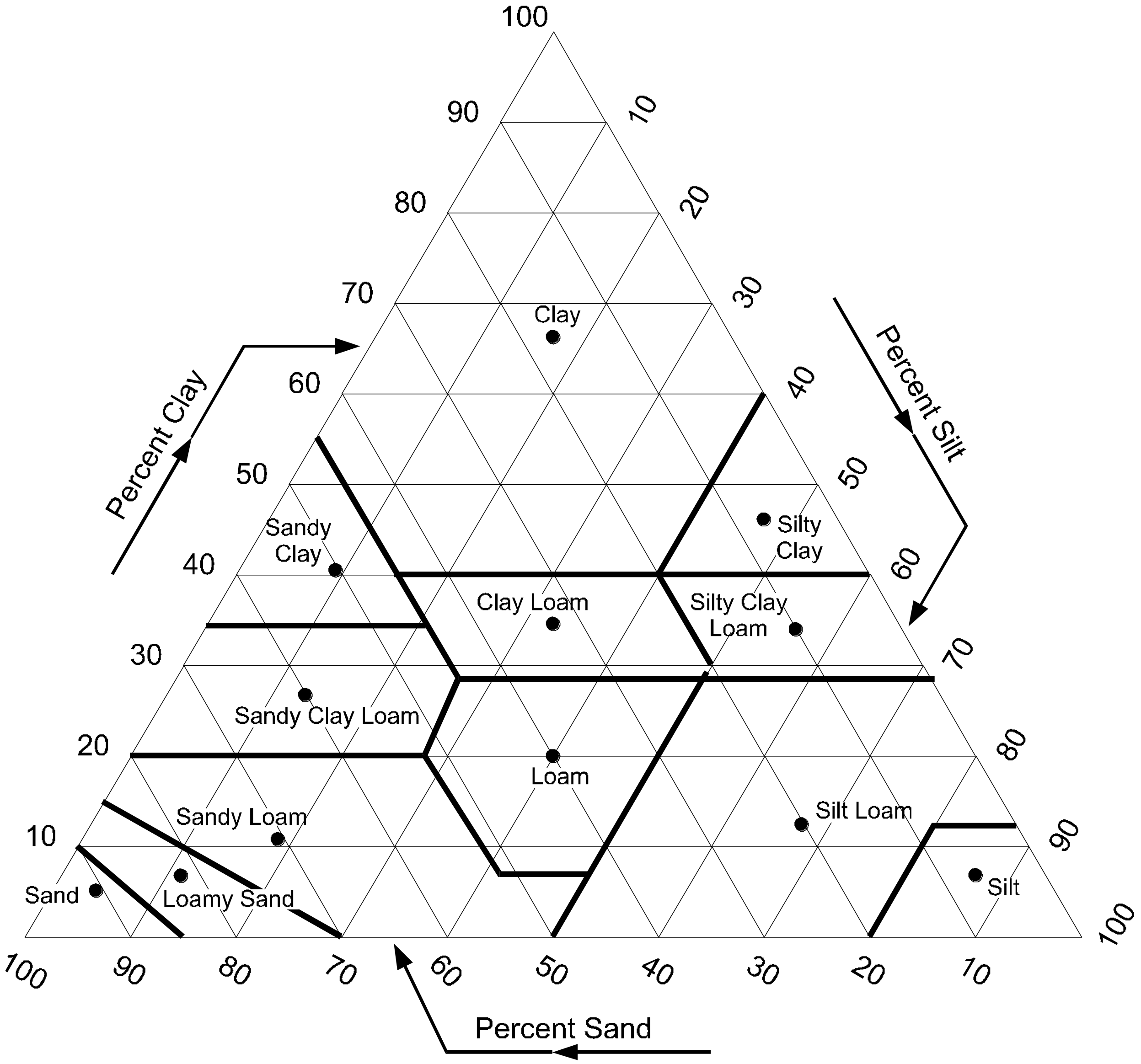


Figure 3: U.S. Soil Conservation Service Classification Chart Showing Centroid Compositions (Solid Circles)

Table 3: Centroid Compositions, Mean Particle Diameters, and Dry Bulk Density of the 12 SCS Soil Textural Classifications

Textural class	**% clay**	**% silt**	**% sand**	**Arithmetic mean particle diameter, cm**	**Dry Bulk Density g/cm^3**
Sand	3.33	5.00	91.67	0.044	1.66
Loamy sand	6.25	11.25	82.50	0.040	1.62
Sandy loam	10.81	27.22	61.97	0.030	1.62
Sandy clay loam	26.73	12.56	60.71	0.029	1.63
Sandy clay	41.67	6.67	51.66	0.025	1.63
Loam	18.83	41.01	40.16	0.020	1.59
Clay loam	33.50	34.00	32.50	0.016	1.48
Silt loam	12.57	65.69	21.74	0.011	1.49
Clay	64.83	16.55	18.62	0.0092	1.43
Silty clay loam	33.50	56.50	10.00	0.0056	1.37
Silt	6.00	87.00	7.00	0.0046	1.35
Silty clay	46.67	46.67	6.66	0.0039	1.38

Given the mean particle diameter data in Table 3, the mean thickness of the capillary zone may then be estimated using Equation 7b.

Assumptions About Capillary Zone Rise and Diffusion

Estimation of the rise of the capillary zone is based on the equation for the rise of a liquid in a capillary tube. The procedure assumes that the interstitial space between the soil particles is equivalent to the capillary tube diameter and that the resulting rise of water occurs under steady-state soil column drainage conditions. In actuality, the height of the capillary zone is uneven or fingered due to the variation in the actual in situ particle size distribution. In addition, the groundwater model does not account for the episodic rise and fall of the water table or the capillary zone due to aquifer recharge and discharge. As constructed, the groundwater model does not allow the top of the capillary zone to be above the bottom of the building floor in contact with the soil. The user should be aware, however, that in reality the top of the capillary zone may rise to levels above the floor in some cases.

Diffusion across the capillary zone is estimated based on combining vapor and aqueous-phase diffusion together within the calculation of the effective diffusion coefficient. To allow for vapor-phase diffusion within the capillary zone, the air-filled soil pores must be connected. In reality, the capillary zone may be comprised of a tension-saturated zone immediately above the water table and the deep portion of the vadose zone within which the soil water content is strongly dependent on the pressure head. Diffusion across the tension-saturated zone is dominated by liquid-phase diffusion, which is typically four orders of magnitude less than vapor-phase diffusion. Therefore, a large concentration gradient may exist between the top of the water table and the top of the tension-saturated zone (McCarthy and Johnson, 1993).

Combining vapor and aqueous-phase diffusion together is a less-intensive, although less-rigorous, method for estimating the effective diffusion coefficient. The result is typically a higher effective diffusion coefficient relative to separate solutions for aqueous diffusion across the tension-saturated zone and both vapor and aqueous diffusion across the unsaturated portion of the vadose zone.

To minimize the possible overestimation of the effective diffusion coefficient, the soil air-filled porosity within the capillary zone is estimated based on the air-entry pressure head, which corresponds with the water-filled porosity at which the interstitial air-filled pores first become connected. The user should be aware that this procedure is inherently conservative if a significant concentration gradient exists across the tension-saturated zone. This conservatism may be somewhat offset in that the model does not consider any episodic rise in the level of the water table. During such events, water that had previously been part of the saturated zone (and hence contains higher contaminant concentrations) is redistributed in the vadose zone resulting in temporary elevations in soil gas concentrations.

2.1.4 Diffusion through the Unsaturated Zone

Using many of the same equations as presented in section 2.1.3, the effective diffusion coefficient within the unsaturated zone may also be estimated using the same form as Equation 5a:

$$D_i^{eff} = D_a\left(\theta_{a,i}^{3.33}/n_i^2\right) + (D_w/H_S)(\theta_{w,i}^{3.33}/n_i^2) \tag{8}$$

where D_T^{eff} = Effective diffusion coefficient across soil layer i, cm^2/s

D_a = Diffusivity in air, cm^2/s

$\theta_{a,i}$ = Soil air-filled porosity of layer i, cm^3/cm^3

n_i = Soil total porosity in layer i, cm^3/cm^3

D_w = Diffusivity in water, cm^2/s

H_S = Henry's law constant at the system temperature, dimensionless

$\theta_{w,i}$ = Soil water-filled porosity of layer i, cm^3/cm^3.

The overall effective diffusion coefficient for systems composed of n distinct soil layers between the source of contamination and the enclosed space floor is:

$$D_T^{eff} = \frac{L_T}{\sum_{i=0}^{n} L_i/D_i^{eff}} \tag{9}$$

where D_T^{eff} = Total overall effective diffusion coefficient, cm^2/s

L_T = Distance between the source of contamination and the bottom of the enclosed space floor, cm

L_i = Thickness of soil layer i, cm

D_i^{eff} = Effective diffusion coefficient across soil layer i, cm^2/s

Note that in the case of cracks in the floor of the enclosed space, the value of L_T does not include the thickness of the floor, nor does the denominator of Equation 9 include the thickness of the floor and the associated effective diffusion coefficient across the crack(s). An unlimited number of soil layers, including the capillary zone, may be included in Equation 9, but all layers must be located between the source of contamination and the enclosed space floor. In Version 6.0 of the model, users may input up to three soil layers (strata A, B, and C). The groundwater model automatically calculates the height of the capillary fringe based on the user input soil types. As the capillary zone is not relevant to the soil gas model, L_i includes only the height of the user input soil layer(s) and does not include a capillary zone height when calculating D_T^{eff}.

2.2 Johnson and Ettinger's One-Dimensional Model

The values calculated in section 2.1 (mass transfer rates, concentration at source, and soil porosity) are used as variables in the Johnson and Ettinger model to calculate attenuation coefficients. The J&E Model is a one-dimensional analytical solution to diffusive and convective transport of vapors into indoor spaces. The model is formulated as an attenuation factor that relates the vapor concentration in the indoor space to the vapor concentration at the source. It was developed for use as a screening level model and consequently is based on a number of simplifying assumptions regarding contaminant distribution and occurrence, subsurface characteristics, transport mechanisms, and building construction.

The J&E model assumes that (1) contaminant vapors enter structures primarily through cracks and openings in the walls and foundation, (2) convective transport is likely to be most significant in the region very close to the basement (or foundation) and vapor velocities decrease rapidly with increasing distance, (3) vapor phase diffusion is the dominant mechanism for transporting contaminant vapors from sources located away from the foundation to adjacent soils, and (4) all contaminant vapors emanating from directly below will enter the structure.

The J&E Model as implemented by EPA assumes homogeneous soil layers with isotropic properties that characterize the subsurface. The model allows up to three layers. Sources of contaminants that can be modeled include dissolved, or vapor sources where the concentrations are below the aqueous solubility limit, and/or the pure component vapor concentration. The contaminants are assumed to be homogeneously distributed at the source. Vapor from the source is assumed to diffuse directly upward (one-dimensional transport) through uncontaminated soil (including an uncontaminated capillary fringe if groundwater is the vapor source) to the base of a building foundation, where convection carries the vapor through cracks and openings in the foundation into the building. Both diffusive and convective transport processes are assumed to be at steady state.

2.2.1 Equations to Calculate the Attenuation Coefficient

Mass transfer is assumed to be at steady state; this is because no evaluation has been made regarding the size and total mass of the source of emissions. The source of emissions, therefore, cannot be depleted over time. Under this assumption, Johnson and Ettinger (1991) gave the solution for the attenuation coefficient (α) as:

$$\alpha = \frac{\left[\left(\frac{D_T^{eff} A_{bf}}{Q_{building}\, L_T}\right) \times \exp\left(\frac{Q_{soil} L_{crack}}{D_{crack}\, A_{crack}}\right)\right]}{\left[exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) + \left(\frac{D_T^{eff} A_{bf}}{Q_{building} L_T}\right) + \left(\frac{D_T^{eff} A_{bf}}{Q_{soil} L_T}\right)\left[\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) - 1\right]\right]} \tag{10}$$

where α = Steady-state attenuation coefficient, unitless

D_T^{eff} = Total overall effective diffusion coefficient, cm^2/s

A_{bf} = Area of the enclosed space below grade, cm^2

Q_b = Building ventilation rate, cm^3/s

L_T = Source-building separation, cm

Q_{soil} = Volumetric flow rate of soil gas into the enclosed space, cm^3/s

L_{crack} = Enclosed space foundation or slab thickness, cm

A_{crack} = Area of total cracks, cm^2

D_{crack} = Effective diffusion coefficient through the cracks, cm^2/s (assumed equivalent to D_i^{eff} of soil layer i in contact with the floor).

In equation 10, the exponent term is $\frac{Q_{soil} L_{crack}}{D_{crack}\, A_{crack}}$. This term represents the equivalent Peclet number for transport through the building foundation, or the ratio of the rate of advection to the rate of diffusion. As the value of B approaches infinity, the value of α approaches:

$$\frac{\left(\frac{D_T^{eff} A_{bf}}{Q_{building} L_T}\right)}{\left(\frac{D_T^{eff} A_{bf}}{Q_{soil} L_T}\right) + 1} \tag{12}$$

In the accompanying spreadsheets, if B is too great to be calculated, the value of α is set equal to Equation 12.

2.2.2 Critical Inputs for the J&E Model

To simplify the use of the model, Johnson (2005) proposed rewriting equation 10:

$$\alpha = \frac{[A] \cdot \exp(B)}{\exp(B) + [A] + \left[\frac{A}{C}\right] \cdot (\exp(B) - 1)}$$

Where A, B, and C are parameterized independently as follows:

$$A_{param} = \frac{D_T^{eff} \times \left(A_{bf} + 4 \times L_b \times \sqrt{A_{bf}}\right) \times 0.36}{Q_b \times (L_s - L_b)} \tag{13}$$

$$B_{param} = \frac{\left(\frac{Q_{soil}}{\mathrm{Q_b}}\right) \times Q_b \times L_f}{D_A^{eff} \times \eta \times \left(\mathrm{A_{bf}} + 4 \times L_b \times \sqrt{A_{bf}}\right) \times 0.36} \tag{14}$$

$$C_{param} = \frac{Q_{soil}}{Q_b} \tag{15}$$

where

D_T^{eff} = Total overall effective diffusion coefficient, cm^2/s

A_{bf} = Area of enclosed space below grade, m^2

L_b = Depth below grade to base of foundation, m

L_s = Depth below grade to water table, m

Q_{soil} = Pressure driven soil-gas flow rate from the subsurface into the enclosed space, cm^2/s

Q_b = Building ventilation rate m^3/s

Q_{soil}/Q_b = Ratio of average vapor flow rate into building and building ventilation rate

L_f = Foundation thickness, m

D_A^{eff} = Effective diffusion through stratum A, cm^2/s

η = Fraction of foundation area with cracks, equal to A_{crack}/A_B

A_{param} can be interpreted as the coefficient of diffusive transport for basement with dirt floor. While A is generally similar to the formula used in Johnson(2005) the EPA spreadsheet explicitly calculates the surface area of the space (basement, crawlspace, etc) subject to vapor intrustion with the term $4 \times L_b \times \sqrt{A_{bf}}$ – this calculates the area of the walls, which is added to the floor (A_{bf}). The 0.36 used in both A_{param} and B_{param} is a conversion factor, for seconds/cm to hours/meter.

B_{param} represents the equivalent Peclet number for transport through the building foundation. The model uses the Peclet number to determine whether advection or diffusion is the dominant mechanism of transport across the foundation. For values less than 0.1, diffusion is the dominant mechanism of transport and for values greater the 3.0, advection is the dominant mechanism. For values between 0.1 and 3.0, both processes contribute to transport across the foundation.

In equation 14, as opposed to 10, B is formulated in terms of explicit parameters (Q_{soil}/Q_b, Q_B, A_B, η, L_{crack}, L_T, D_T^{eff}, D_{crack}^{eff}) instead of the simplified version in equation 10. This modification was proposed by Johnson (2005) for several reasons:

1. reasonable values for V_B/A_B and E_B are constrained to a fairly narrow range,
2. using the explicit ratio of V_B/A_B eliminates the possibility of a user assigning inconsistent values,
3. Use of the ratio Q_{Soil}/Q_Bavoids inconsistent assignment of Q_{soil} and Q_B, and
4. the literature provides more information for selecting reasonable values for the ratios than the individual values.

C_{param} represents convective transport from subslab to building; Johnson (2005) uses the ratio of the average vapor flow rate into a building and the building ventilation rate (Q_{soil}/Q_b) as the sub-slab soil gas to indoor air attenuation coefficient. Because this parameter value is intended to be derived from the literature or site data, it is represented henceforth as a single variable, "$Q_{soil}\_Q_B$."

2.2.3 Special Cases

The model calculates the exterior soil gas and groundwater indoor air attenuation coefficients depending on the foundation type. The simplifying assumptions presented below are taken from Johnson (2005), which identified critical parameters for varying scenarios depending on which processes were dominant and rate-limiting.

Basements or Crawl Spaces with Dirt Floors

For either basement or crawl space with dirt floor construction the model calculates the attenuation coefficient as:

$$\alpha = \frac{A_{Param}}{1 + A_{Param}} \tag{16a}$$

This is because, with dirt floors, diffusion is the dominant mechanism and the overall rate limiting process.

Slab Construction

For slab-on-grade, basement with slab, or crawl space with slab construction, the model calculates the attenuation coefficient as:

$$\alpha = \frac{A_{Param}}{(1 + A_{Param} \times e^{-B_{Param}}) + \frac{A_{Param}}{C_{Param}} \times (1 - e^{-B_{Param}})} \tag{16b}$$

where α = attenuation coefficient

A_{Param} = Coefficient of diffusive transport for basement with dirt floor

B_{Param} = Peclet number for transport through the foundation

C_{param} = Coefficient of convective transport from subslab to building

2.2.4 Supplemental Equations

Several formulas for default values, derived from the literature, are used in the EPA Vapor Intrustion modelling tool. This section explains how these values are used, and how user-specified values are incorporated.

Ratio of Vapor Flow Rate to Building Ventilation Rate

The model uses a default value of 0.003 for the ratio of the average vapor flow rate into a building to the building ventilation rate ($Q_{soil}\_Q_B$), based on the median values reported in "Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings" (US EPA, 2012). This average is close the calculated approximation of 0.003, based on default values for air exchange rate (0.45 air changes per hour) and residential building volume (395 m^3) from the 2011 Exposure Factors Handbook (U.S. EPA 2011) and a central value for Q_{soil} (5 L/min) (U.S. EPA 2012).

In default mode (where a ratio for $Q_{soil}\_Q_B$) is used, if the user elects to enter a site-specific air exchange rate, the model adjusts $Q_{soil}\_Q_B$ by the ratio of the default air exchange rate to the user defined air exchanged rate. The ratio of the average vapor flow rate into the building and the building ventilation rate (Q_{soil}/Q_b) may be calculated as:

$$\left[\frac{Q_{soil}}{Q_b}\right]_{adj} = 0.003 \times \frac{0.45}{ach} \tag{17}$$

where $\left[\frac{Q_{soil}}{Q_b}\right]_{adj}$ = adjusted ratio of the average vapor flow rate into the building and the building ventilation rate, unitless

ach = Indoor air exchange rate, entered by user, 1/h

The model calculates the building ventilation rate (Q_b) using the following equation:

$$Q_b = A_{bf} \times H_b \times ach \tag{18}$$

where Q_b = Building ventilation rate, m^3/hr

A_{bf} =Enclosed space floor area, m^2

H_b =enclosed space mixing height, m

ach = Indoor air exchange rate entered by user,1/h

The building dimensions in Equation 18 are those dimensions representing the total "living" space of the building; this assumes that the total air volume within the structure is well mixed and that any vapor contaminant entering the structure is instantaneously and homogeneously distributed.

Note that if a user enters site specific data for Q_{soil} and $Q_{building}$, the ratio ($Q_{soil}\_Q_B$) will be calculated from those values instead.

Rate of Soil Gas Entering the Building

The volumetric flow rate of soil gas entering the building (Q_{soil}) is calculated by the following equation:

$$Q_{soil} = \frac{Q_{soil}}{Q_b} * Q_b \qquad (19)$$

This equation is used because, in default mode, the model handles $\frac{Q_{soil}}{Q_B}$ as a single variable (not two independent terms); using this formula allows the flow rate of soil gas to be back calculated using the default (or calculated) value for the ratio and the input building ventilation rate. This equation **does not apply** to basements or closed crawl spaces with dirt floor construction. If the user selects this option, the model will display “NA” for this parameter. Alternatively, if a site specific value is used for Q_{soil}, then $Q_{soil}\_Q_{building}$ will be calculated from these values.

2.3 Formulas for Predicting Indoor Air Concentrations

Using the attenuation rates calculated by the J&E model (described in section 2.3, above), the spreadsheet tool predicts steady-state vapor-phase concentration of the contaminant in the building ($C_{building}$) in either µg/m^3 or parts per billion volume (ppbv), respectively using the following equations:

$$C_{building_{\mu g/m^3}} = \alpha C_s \tag{20a}$$

where $C_{building}$= concentration of contaminant in building, µg/m^3

α = Steady-state attenuation coefficient, unitless

C_S = Vapor concentration at the source of contamination, µg/m^3

And

$$C_{building_{ppbv}} = \alpha C_s \left[\frac{24.46}{MW}\right] \tag{20b}$$

where *MW* = Molecular weight of compound, g/mol

24.46 = Molar volume of gas at 1atm and 25°C

2.4 Limitations of the J&E Model

Care must be taken to ensure reasonably conservative and self-consistent model parameters are used as input to the model. Considering the limited site data typically available in preliminary site assessments, the J&E Model can be expected to predict *only* whether or not a risk-based exposure level is likely to be exceeded at the site. Precise prediction of concentration levels is not possible with this screening level model. In the EPA model, both the building ventilation rate and the difference in dynamic pressure between the interior of the structure and the soil surface are constant values.

Based on the conceptual site model (CSM), the user can select the appropriate medium corresponding to the vapor source at the site and determine which of the site-specific inputs to enter into the model. Because most of the inputs to the J&E Model are not collected during a typical site characterization, conservative inputs have to be estimated or inferred from available data and other non-site-specific sources of information. Unless otherwise specified, Version 6.0 of the model uses central estimates as defaults for key parameters, including the air exchange rate, but it allows users to modify the default values within the bounds of the reported variation in estimates in order to address site-specific issues or conduct uncertainty analyses.

Use of the J&E Model as a first-tier screening tool to identify sites needing further assessment requires careful evaluation of the model assumptions to determine whether any conditions exist that would render the J&E Model inappropriate for the site.

2.4.1 Major Assumptions

The model assumes that all vapors from underlying soils will enter the building through gaps and openings in the walls, floor, and foundation. This implies that a constant pressure field is generated between the interior spaces and the soil surface and that the vapors are intercepted within the pressure field and transported into the building. This assumption is inherently conservative in that it neglects periods of near zero pressure differentials (e.g., during mild weather when windows are left open).

The model assumes isotropic soils in the horizontal direction; vertical anisotropy is accounted for by a series of isotropic soil strata above the top of contamination. Soil properties within the zone of soil contamination are assumed to be identical to those of the soil stratum directly above the contamination and extend downward to an infinite depth. Solute transports by convection (e.g., water infiltration) and by mechanical dispersion are neglected. Transformation processes (e.g., biodegradation, hydrolysis, etc.) are also neglected.

An empirical field study (Fitzpatrick and Fitzgerald, 1997) indicated that the model may be overly conservative for nonchlorinated species (e.g., benzene, toluene, ethylbenzene and xylene) but in some cases, may underpredict indoor concentrations for chlorinated species. The authors contribute the likely cause for this discrepancy to the significant biodegradation of the nonchlorinated compounds.

The J&E Model treats the entire building as a single chamber with instantaneous and homogeneous vapor dispersion. It therefore neglects contaminant sinks and the room-to-room variation in vapor concentration due to unbalanced mechanical and/or natural ventilation.

Finally, convective vapor flow from the soil matrix into the building is represented as an idealized cylinder buried below grade. This cylinder represents the total area of the structure below the soil surface (walls and floor). The total crack or gap area is assumed to be a fixed fraction of this area. Because of the presence of basement walls, the actual vapor entry rate is expected to be 50 to 100 percent of that provided by the idealized geometry (Johnson and Ettinger, 1991).

Table 4, below, lists the relevant assumptions of the EPA spreadsheet tool, along with the implications and field interpretation of each one.

Table 4: Assumptions and Limitations of the EPA Vapor Intrusion Model

Assumption	**Implication**	**Field Evaluation**
Contaminant		
No contaminant free-liquid/precipitate phase present	J&E Model not representative of NAPL partitioning from source	NAPL or not at site–easier to evaluate for floating product or soil contamination sites. Most DNAPL sites with DNAPL below the water table defy easy characterization.
Contaminant is homogeneously distributed within the zone of contamination		
The areal extent of contamination is greater than that of the building floor in contact with the soil.		
No contaminant sources or sinks in the building.	Indoor sources of contaminants and/or sorption of vapors on materials may confound interpretation of results.	Survey building for sources, assessment of sinks unlikely
Equilibrium partitioning at contaminant source.	Groundwater flow rates are low enough so that there are no mass transfer limitations at the source.	Not likely
Chemical or biological transformations are not significant (model will predict more intrusion)	Tendency to over predict vapor intrusion for degradable compounds	From literature
Subsurface Characteristics		

Assumption	Implication	Field Evaluation
Soil is homogeneous within any horizontal plane	Stratigraphy can be described by horizontal layers (not tilted layers)	Observe pattern of layers and nonconformities
The soil layer in contact with the structure floor and walls is isotropic with respect to permeability.		
All soil properties in any horizontal plane are homogeneous		
The top of the capillary fringe must be below the bottom of the building floor in contact with the soil.		
EPA version of JE Model assumes the capillary fringe is uncontaminated.		
Transport Mechanisms		
One-dimensional transport	Source is directly below building, stratigraphy does not influence flow direction, no effect of two- or three-dimensional flow patterns.	Observe location of source, observe stratigraphy, pipeline conduits, not likely to assess two- and three-dimensional pattern.
Two separate flow zones, one diffusive one convective.	No diffusion (dispersion) in the convective flow zone. Plug flow in convective zone	Not likely
Vapor-phase diffusion is the dominant mechanism for transporting contaminant vapors from contaminant sources located away from the foundation to the soil region near the foundation	Neglects atmospheric pressure variation effects	Not likely
Straight-line gradient in diffusive flow zone.	Inaccuracy in flux estimate at match point between diffusive and convective sections of the model.	Not likely
Diffusion through soil moisture will be insignificant (except for compounds with very low Henry's Law Constant	Transport through air phase only. Good for volatiles. Only low volatility compounds would fail this and they are probably not the compounds of concern for vapor intrusion	From literature value of Henry's Law Constant.

Assumption	Implication	Field Evaluation
Convective transport is likely to be most significant in the region very close to a basement, or a foundation, and vapor velocities decrease rapidly with increasing distance from a structure		Not likely
Vapor flow described by Darcy's law	Porous media flow assumption.	If observations of fractured rock, fractured clay, karst, macropores, or preferential flow channels is made this model cannot be used
Steady State convection	Flow not affected by barometric pressure, infiltration, etc.	Not likely
Uniform convective flow near the foundation	Flow rate does not vary by location	Not likely
Uniform convective velocity through crack or porous medium	No variation within cracks and openings and constant pressure field between interior spaces and the soil surface	Not likely
Significant convective transport only occurs in the vapor phase	Movement of soil water not included in vapor impact	Not likely
Vapor transport occurs in the absence of convective water movement within the soil column (i.e., evaporation or infiltration), and in the absence of mechanical dispersion.		
Both the building ventilation rate and the difference in dynamic pressure between the interior of the structure and the soil surface are constant values.		
All contaminant vapors originating from directly below the basement will enter the basement, unless the floor and walls are perfect vapor barriers. (Makes model over est. vapors as none can flow around the building)	Model does not allow vapors to flow around the structure and not enter the building	Not likely

Assumption	**Implication**	**Field Evaluation**
Contaminant vapors enter structures primarily through cracks and openings in the walls and foundation	Flow through the wall and foundation material itself neglected except for the basement with a dirt floor scenario	Observe numbers of cracks and openings. Assessment of contribution from construction materials themselves not likely

The assumptions described above and in Table 4 suggest a number of conditions that preclude the use of the models as implemented by EPA. These conditions include:

- The presence or suspected presence of residual or free-product non-aqueous phase liquids (LNAPL, DNAPL, fuels, solvents, etc.) in the subsurface.
- The presence of heterogeneous geologic materials (other than the three layers allowed in the advanced spreadsheets) between the vapor source and building. The J&E Model does not apply to geologic materials that are fractured, contain macropores or other preferential pathways, or are composed of karst.
- Sites where significant lateral flow of vapors occurs. These can include geologic layers that deflect contaminants from a strictly upward motion and buried pipelines or conduits that form preferential paths. Significantly different permeability contrasts between layers are likely to cause lateral flow of vapors. The model assumes the source of contaminants is directly below the potential receptors.
- Very shallow groundwater where the building foundation is wetted by the groundwater as the model assumes that the capillary fringe is not contaminated.
- Very small building air exchange rates (e.g., < 0.25/h)
- Contaminated groundwater sites with large fluctuations in the water table elevation. In these cases, the capillary fringe is likely to be contaminated; whereas in the groundwater source spreadsheets, the capillary fringe is assumed to be uncontaminated.

In theory the above limitations are readily conceptualized, but in practice the presence of these limiting conditions may be difficult to verify even when extensive site characterization data are available. Conditions that are particularly difficult to verify in the field include the presence of residual non-aqueous phase liquids (NAPLs) in the unsaturated zone and the presence and influence of macropores, fractures and other preferential pathways in the subsurface. Additionally, in the initial stages of evaluation, especially at the screening level, information about building construction and water table fluctuations may not be available. Even the conceptually simple assumptions (e.g., one-dimensional flow, lack of preferential pathways) may be difficult to assess when there are little site data available.

In the case of contaminated groundwater, the vapor equilibrium model operates under the assumption that the contaminant is present at levels below the water solubility limit. If the user-defined groundwater concentration is greater than the solubility limit (S), an error message will appear stating that the value of the contaminant concentration exceeds the aqueous solubility limit.

The user is reminded that when estimating a risk-based groundwater concentration, the model will compare the calculated risk-based groundwater concentration to the aqueous solubility limit of the compound. If the risk-based groundwater concentration is greater than the solubility limit, the contaminant is not of concern for the vapor intrusion pathway.

Finally, it should be recognized that the procedures used to estimate the aqueous solubility limit do not consider the effects of multiple contaminants when using the multiple chemical model. The estimated values, therefore, may be artificially high such that a residual phase may actually exist at somewhat lower concentrations.

2.4.2 Assumptions and Limitations of the Soil Gas Model

The soil gas model operates under the assumption of steady-state conditions. This means that enough time has passed for the vapor plume to have reached the building of interest directly above the source of contamination and that the vapor concentrations have reached their maximum values. Depending on the depth at which the soil gas is sampled, diffusion of the soil gas toward the building is a function of the soil properties between the building floor in contact with the soil and the sampling depth. Convection of the soil gas into the structure is a function of the building properties and the effective soil vapor permeability. Assumptions and limitations of the soil gas models are the same as those in Section 2.4.1 with the exception of the source vapor concentration that is determined empirically through soil gas sampling.

The user should also recognize the inherent limitations of soil gas sampling. First, the geologic variability of the subsurface may be considerable. This may be especially problematic for shallow soil gas sampling because soil moisture content can vary widely as a function of precipitation events and surface runoff. The soil moisture content has an exponential effect on the rate of vapor diffusion. Transformation processes such as biodegradation can also occur in shallow subsurface soils. In some cases, only a relatively thin stratum of bioactive soil can greatly reduce the emission flux toward the soil surface. Finally, subsurface phase equilibrium is a dynamic process resulting in varying vapor-phase concentrations over time at the same sampling location and depth. These factors can result in significant differences in measured soil gas concentrations over relatively small spatial and temporal scales.

For these reasons, the planning phase of the soil gas-sampling program should carefully consider the inherent uncertainties in site-specific sampling and analytical data. In the final analysis, the extent of soil gas sampling is a trade-off between sampling costs and the degree of certainty required in the soil gas concentration data.

2.4.3 Model Sensitivity and Parameter Uncertainty

The uncertainty in determining key model parameters and sensitivity of the J&E Model to those key model parameters is qualitatively described in Table 5. As shown in the table, building-related parameters with moderate to high uncertainty and model sensitivity include: building crack ratio (η), building air-exchange rate (ach), and building mixing height (H_b). Building-related parameters with low uncertainty and sensitivity include foundation area (A_{bf}) and foundation thickness (L_F). Of the soil-dependent properties, the soil moisture parameters clearly are of critical importance for the attenuation value calculations. These soil-dependent properties are stored in the SOIL_DATA sheet and cannot be changed by the user.

Table 5: Uncertainty and Sensitivity of Key Parameters for the Vapor Intrusion Model

Input Parameter	Parameter Uncertainty Or Variability	Building Underpressurized		Building Not Underpressurized	
		Shallower Contamination	Deeper Contamination	Shallower Contamination	Deeper Contamination
Crack Ratio (η)	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Capillary Zone Water-filled Porosity (nwcz)	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Thickness of Capillary Zone (h_{cz})	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Soil to Building Pressure Differential (ΔP)	Moderate	Moderate	Low to Moderate	N/A	N/A
Henry's Law Constant (for single chemical) (H)	Low	Low	Low	Low	Low
Diffusivity in Air (D_{air})	Low	Low	Low	Low	Low
Indoor Air Exchange Rate (ach)	Moderate	Moderate	Moderate	Moderate	Moderate

Enclosed Space Mixing Height (H_b)	Moderate	Moderate	Moderate	Moderate	Moderate
Area of Enclosed Space Floor Area (A_{bf})	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Foundation Thickness (L_F)	Low	Low	Low	Low	Low
Enclosed Space Floor Thickness (L_f)	Low	Low	Low	Low	Low

For additional discussion of the assumptions and uncertainties regarding VI models, please see:

- US EPA (2012) "Conceptual Model Scenarios for the Vapor Intrusion Pathway". Office of Land and Emergency Management, EPA 530-R-10-003
- Hers et al (2003) "Evaluation of the Johnson and Ettinger model for prediction of indoor air quality." *Groundwater Monitoring and Remediation.* Vol 23.2, p 119-133.

2.5 Calculation of Risk

The unique contribution of the EPA spreadsheet tool is to combine the calculations used to predict indoor air concentrations with risk calculations. The infinite source model estimate of the steady-state building concentration represents the exposure point concentration used to assess potential risks. The model calculates a risk-based indoor air concentration in µg/m^3 in the same manner as EPA's Vapor Intrusion Screening Level (VISL) Calculator (U.S. EPA 2015b). Risk calculations are taken from US EPA's Risk Assessment Guidance for Superfund (RAGS) Part F, Supplemental Guidance for Inhalation Risk Assessment (US EPA, 2009).

Exposure factors and toxicity values are supplied within the spreadsheet tool. Exposure factors are taken from the exposure factors handbook (US EPA, 2011 and 2014) and toxicity data (IURs, RfCs) are taken from the RSLs (US EPA 2015a).

2.5.1 Cancer Based Indoor Air Screening Levels

The J&E spreadsheet tool calculates screening levels risk based concentrations for contaminants using the formulas in RAGS B (US EPA, 1991). For carcinogenic contaminants, this calculation takes the form:

$$C_{ca} = \frac{TCR \cdot ATc \cdot 365\ (days/year) \cdot 24 (hours/day)}{EF \cdot ED \cdot ET \cdot IUR} \tag{21a}$$

where C_{Ca} = Risk-based media concentration for carcinogens, µg/m^3

Target_CR = Target risk level for carcinogens, unitless

AT_C = Averaging time for carcinogens, yr

IUR = Incremental Unit Risk, (ug/m3)-1

ED = Exposure duration, yr

EF = Exposure frequency, days/yr

ET = Exposure time, hrs/day

For mutagenic compounds generally, the risk-based indoor air concentration in μg/m^3 is calculated as:

$$C_{ca} = \frac{Target_{CR} \times AT_C \times 365\ days/yr \times 24\ hrs/day}{EF\ \times ED_{MMOA} \times ET\ \times IUR} \qquad (21b)$$

where C_{Ca} = Risk-based media concentration for carcinogens, μg/m^3

Target_CR = Target risk level for carcinogens, unitless

AT_C = Averaging time for carcinogens, yr

IUR = Incremental Unit Risk, (μg/m^3)$^{-1}$

MMOAF = Mutagenic mode of action factor, yr

EF = Exposure frequency, days/yr

ET = Exposure time, hrs/day

And ED_{MMOA} is calculated as $ED_{MMOA} = (ED_{0-2} \times AF_{0-2}) + (ED_{2-6} \times AF_{2-6}) + (ED_{6-16} \times AF_{6-16}) + (ED_{16-30} \times AF_{16-30})$, where ED_{x-y} = exposure duration for age cohort from age x to y, and AF_{x-y}=age dependent adjustment factor (10 for ages 0-2, 3 for ages 2 – 6 and ages 6-16, and 1 for ages 16 to 30)

However, for vinyl chloride (chloroethene), this concentration is calculated as:

$$C_{ca} = \frac{Target\_CR}{IUR + \frac{(IUR \times MMOAF \times EF \times ET/24hrs)}{(AT_C \times 365\ \ days/yr)}} \qquad (21c)$$

where C_{Ca} = Risk-based media concentration for carcinogens, $\mu g/m^3$
$Target\_CR$ = Target risk level for carcinogens, unitless
IUR = Incremental Unit Risk, $(\mu g/m^3)^{-1}$
$MMOAF$ = Mutagenic mode of action factor, yr
EF = Exposure frequency, days/yr
ET = Exposure time, hrs/day
AT_C = Averaging time for carcinogens, yr

2.5.2 Non-Cancer Screening Levles

For the case of a non-carcinogenic contaminant, the risk-based indoor air concentration in $\mu g/m^3$is calculated by:

$$C_{NCa} = \frac{Target\_HQ \cdot RfC \cdot ATnc \cdot 365 \cdot 24 \cdot 1000(ug/mg)}{EF \cdot ED \cdot ET} \tag{21d}$$

where C_{NCa} = Risk-based media concentration for noncarcinogens,$\mu g/m^3$
$Target\_HQ$ = Target hazard quotient, unitless
RfC = Reference concentration, mg/m^3
AT_{NC} = Averaging time for noncarcinogens, yr
ED = Exposure duration, yr
EF = Exposure frequency, days/yr
ET = Exposure time, hrs/day

For trichloroethylene specifically, the model calculates a combined risk-based indoor air concentration in $\mu g/m^3$ using the following equation from EPA's Vapor Intrusion Screening Level (VISL) Calculator (U.S. EPA 2015a):

$$C = \frac{1}{\frac{1}{\frac{Target\_CR \times AT_c \times 365\,days/yr}{IUR \times ED \times EF \times ET/24hrs}} + \frac{1}{\frac{Target\_HQ \times RfC \times AT_{NC} \times 365\ days/yr}{ED \times EF \times ET/24hrs}}} \tag{21e}$$

2.5.3 Conversions

Equations 21a through 21e calculate the risk-based indoor air concentration in µg/m^3. The model also displays this concentration in parts per billion by volume (ppbv). The calculation to convert this value from µg/m^3 to ppbv assumes conditions are at 1 atm and 25°C.

$$C_{ppbv} = C \times \left(\frac{24.46}{MW}\right) \tag{21f}$$

where C = Risk-based media concentration as calculated by model, µg/m^3

C_{ppbv} =Risk-based media concentration as calculated by model, ppbv

MW = Molecular weight of compound, g/mol

24.46 = Molar volume of gas at 1atm and 25°C

Calculation of risk-based media concentration takes the form:

$$C_{groundwater} = \frac{C_{Ca}}{H_S \times 1000 \times \propto} \tag{22a}$$

$$C_{soil\ gas} = \frac{C_{Ca}}{\propto} \tag{22b}$$

where $C_{groundwater}$ = Risk-based groundwater concentration for carcinogens, µg/L

$C_{soil\ gas}$ = Risk-based soil gas concentration for carcinogens, µg/m^3

H_S = Henry's law constant at the system temperature, dimensionless

α = Steady-state attenuation coefficient, unitless

The model calculates risk-based media concentrations based on a unity initial concentration. That is, groundwater risk-based concentrations are calculated with an initial hypothetical concentration of 1 µg/L-water.

2.5.4 Calculation of Incremental Risks

Forward-calculation of incremental risks begins with a site-specific initial media concentration (µg/m^3), and determines the incremental risk posed to a receptor. For carcinogenic contaminants, the risk level is calculated as:

$$Risk = \frac{IUR \times EF \times ED \times ET \times C_{ia}}{AT_c \times (365\ \ days/yr) \times (24hrs/day)} \tag{23a}$$

where *Risk* = Incremental risk, unitless

IUR = Incremental Unit Risk, (µg/m^3)$^{-1}$

EF = Exposure frequency, days/yr

ED = Exposure duration, yr

ET = Exposure time, hrs/day

C_{ia} = Indoor air concentration due to vapor intrusion, µg/m^3

AT_C = Averaging time for carcinogens, yr

For mutagens, including trichloroethylene, the risk level is calculated as:

$$Risk = \frac{IUR \times EF \times MMOAF \times ET/24hrs \times C_{ia}}{ATc \times 365\ \ days/yr} \tag{23b}$$

Where *Risk* = Incremental risk, unitless

IUR = Incremental Unit Risk, (µg/m^3)$^{-1}$

EF = Exposure frequency, days/yr

MMOAF = Mutagenic mode of action factor, yr

ET = Exposure time, hrs/day

C_{ia} = Indoor air concentration due to vapor intrusion, μg/m^3

AT_C = Averaging time for carcinogens, yr

For vinyl chloride (chloroethene), the risk level is calculated as:

$$Risk = C_{ia}\left[IUR + \frac{EF \times ED \times ET \times IUR}{AT_c \times (365\,days/yr) \times (24\,hrs/day)}\right] \tag{23c}$$

where $Risk$ = Incremental risk, unitless

C_{ia} = Indoor air concentration due to vapor intrusion, μg/m^3

IUR = Incremental Unit Risk, (μg/m^3)$^{-1}$

EF = Exposure frequency, days/yr

ED = Exposure duration, yr

ET = Exposure time, hrs/day

AT_C = Averaging time for carcinogens, yr

For noncarcinogenic contaminants, the hazard quotient (HQ) is calculated as:

$$HQ = \frac{EF \times ED \times ET/24hrs \times C_{ia}}{RfC\ \times AT_{NC} \times 365\ \ days/yr} \tag{24}$$

where HQ = Hazard quotient, unitless

EF = Exposure frequency, days/yr

ED = Exposure duration, yr

ET = Exposure time, hrs/day

C_{ia} = Indoor air concentration due to vapor intrusion, μg/m^3

RfC = Reference concentration, mg/m^3

AT_{NC} = Averaging time for noncarcinogens, yr

3. How to use the spreadsheet tool

This section provides a description of EPA's workbook and step-by-step instructions on how to implement the spreadsheets for the soil gas and groundwater contamination J&E Models. The model is implemented in an excel workbook, which can be downloaded from https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion . Version 6.0 of EPA's workbook calculates both a risk-based concentration and the incremental risk from a site-specific concentration for soil gas or groundwater. Up to three individual soil strata may be considered, for which soil properties may be varied. The user may enter data for a subset of model parameters or all of the model parameters.

3.1 Workbook Overview

The spreadsheet provides multi-contaminant modules that allow users to enter the concentrations of up to 118 chemicals for a site.

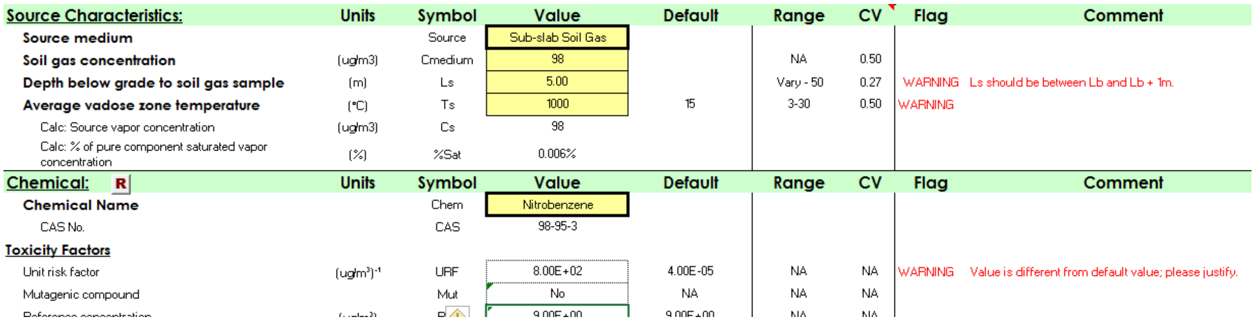
The model consists of the following worksheets:

1. README
2. MODEL (main data entry and model output sheet)
3. MEASURED_SOIL_GAS_CONC (data entry for site-specific soil gas concentrations)
4. MULTI_CHEM_INPUT (data entry for concentrations of multiple chemicals sheet)
5. MULTI_CHEM_OUTPUT (outputs from multiple chemical model sheet)
6. SOIL_DATA (table of soil properties)
7. CHEM_DATA (table of chemical properties)
8. BLDG_DATA (table of building properties)
9. SOIL_CV_DATA (table of coefficients of variation for soil properties)
10. CHEM_CV_DATA (table of coefficients of variation for chemical properties)
11. Exposure data (default values for exposure parameters)
12. Reference Sources (reference list for default values, ranges, and cv values)
13. Converter (data entry for conversion from english to metric distance measurements)
14. Parameters Summary (generic RSL chemical properties table from EPA)
15. ToxSummary (screening level tables from EPA RSLs)
16. Pick_lists (populates pick lists on data entry pages – hidden by default)
17. Version Notes (listing of updates to model)

To run the models, open the file within Microsoft Excel 2013 or later. The following sections will walk through analyzing a single chemical (section 3.2) and multiple chemicals (3.3).

3.1.1 Error and Warning Messages

Error messages will appear in red type next the appropriate cell if required data are missing, or if entered values exceed reasonable values. Examples of the latter include a groundwater concentration greater than the aqueous solubility limit for a given chemical or a foundation thickness other than zero is entered for a basement with a dirt floor scenario. Warning messages will appear in the same manner if default values are changed, if data are out of range or if they do not conform to model conventions. Because the model does not account for biodegradation, a warning message will appear if the model may be overestimating outputs such as the indoor air attenuation coefficient, the indoor air concentration, or the incremental risk estimates. The message will tell the user what kind of error or warning has occurred. The model will still function and display output when error and/or warning messages appear.

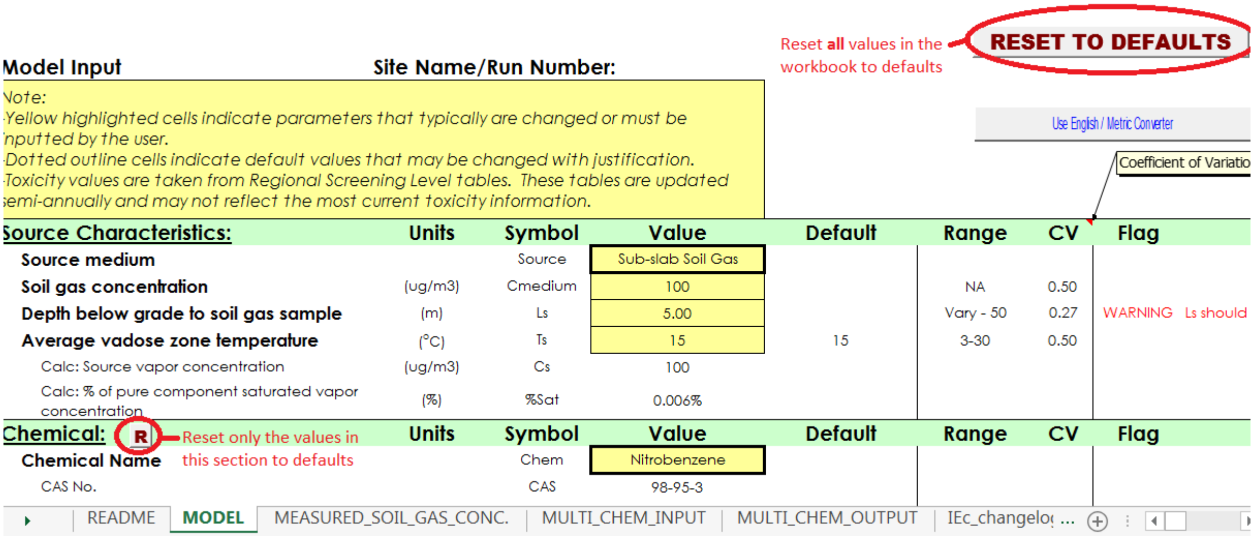


Source Characteristics:	**Units**	**Symbol**	**Value**	**Default**	**Range**	**CV**	**Flag**	**Comment**
Source medium		Source	Sub-slab Soil Gas					
Soil gas concentration	(ug/m3)	Cmedium	98		NA	0.50		
Depth below grade to soil gas sample	(m)	Ls	5.00		Vary - 50	0.27	WARNING	Ls should be between Lb and Lb + 1m.
Average vadose zone temperature	(°C)	Ts	1000	15	3-30	0.50	WARNING	
Calc: Source vapor concentration	(ug/m3)	Cs	98					
Calc: % of pure component saturated vapor concentration	(%)	%Sat	0.006%					
Chemical: R	**Units**	**Symbol**	**Value**	**Default**	**Range**	**CV**	**Flag**	**Comment**
Chemical Name		Chem	Nitrobenzene					
CAS No.		CAS	98-95-3					
Toxicity Factors								
Unit risk factor	$(ug/m^3)^{-1}$	URF	8.00E+02	4.00E-05	NA	NA	WARNING	Value is different from default value; please justify.
Mutagenic compound		Mut	No	NA	NA	NA		

Figure 4: Examples of warning messages

3.1.2 Reset to Defaults

The user may elect to restore default input values for the entire sheet at any point by clicking on the RESET TO DEFAULTS button on the top right of the MODEL sheet. To restore default values for only a specific set of inputs to the model, click on the R button to the right of a section heading (Chemical/Toxicity Factors, Chemical Properties, Building Characteristics, Vadose Zone Characteristics, and Exposure Parameters). A dialogue box will appear with the message “Do you want to reset values of the [entire model or section name] to defaults? All unsaved inputs will be lost.” Click *Yes* to proceed. **Resetting default values will erase any values input by the user for that section.**



Reset **all** values in the workbook to defaults

Model Input **Site Name/Run Number:**

Note:
Yellow highlighted cells indicate parameters that typically are changed or must be nputted by the user.
Dotted outline cells indicate default values that may be changed with justification.
Toxicity values are taken from Regional Screening Level tables. These tables are updated semi-annually and may not reflect the most current toxicity information.

Source Characteristics:	**Units**	**Symbol**	**Value**	**Default**	**Range**	**CV**	**Flag**
Source medium		Source	Sub-slab Soil Gas				
Soil gas concentration	(ug/m3)	Cmedium	100		NA	0.50	
Depth below grade to soil gas sample	(m)	Ls	5.00		Vary - 50	0.27	WARNING Ls should
Average vadose zone temperature	(°C)	Ts	15	15	3-30	0.50	
Calc: Source vapor concentration	(ug/m3)	Cs	100				
Calc: % of pure component saturated vapor concentration	(%)	%Sat	0.006%				

Chemical:	**Units**	**Symbol**	**Value**	**Default**	**Range**	**CV**	**Flag**
Chemical Name		Chem	Nitrobenzene				
CAS No.		CAS	98-95-3				

Reset only the values in this section to defaults

Figure 5: Reset options

3.1.3 Unlocking the spreadsheets

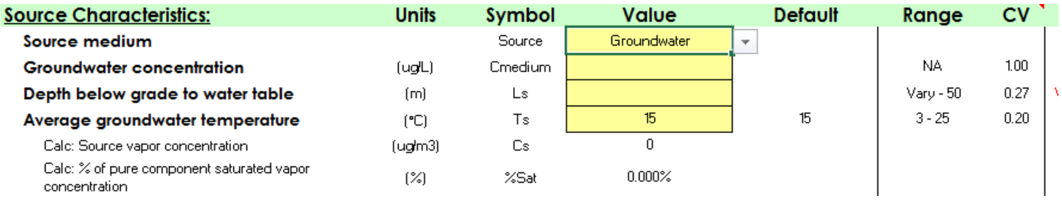
Most of the spreadsheets in the J&E Workbook are protected, to prevent users from inadvertently changing default values. Users may still enter site specific inputs, but are prevented from modifying many of the reference values, such as toxicity values or chemical properties like molecular weight. If a user needs to change locked values, sheets may be unlocked with the password “J&E.”

By default, the macros, which run the multiple chemical output page, reset a page to default values, and clear inputs, are also password protected. The password to modify the macros is “BETA,” but users are discouraged from modifying this portion of the workbook.

3.2 Evaluating a single chemical

The simplest way to run the Johnson and Ettinger spreadsheet is to analyze a single chemical and use default values. There are some values which users must enter, and this section will walk through that process.

1. Open the workbook and go to the “Model” Tab.
2. Enter the **source characteristics**:



Source Characteristics:	**Units**	**Symbol**	**Value**	**Default**	**Range**	**CV**
Source medium		Source	Groundwater			
Groundwater concentration	(ug/L)	Cmedium			NA	1.00
Depth below grade to water table	(m)	Ls			Vary - 50	0.27
Average groundwater temperature	(°C)	Ts	15	15	3 - 25	0.20
Calc: Source vapor concentration	(ug/m3)	Cs	0			
Calc: % of pure component saturated vapor concentration	(%)	%Sat	0.000%			

a. *Source Medium* (Source)
From the dropdown menu for source medium, choose either groundwater or soil gas. The names of the next three parameters will automatically fill depending on this selection.

b. *Groundwater, Exterior Soil Gas or Sub-Slab Soil Gas Concentration* (C_{medium})
Be sure to enter the concentration in units of µg/m^3 (soil gas) or µg/L (groundwater). The value of the groundwater or soil gas concentrations typically represents the average concentration within the zone of contamination. The user should select the sub-slab soil gas option if measurements were taken within one meter of the base of the foundation. Otherwise, the user should choose the exterior soil gas option. If descriptive statistics are not available to quantify the uncertainty in the average value, the maximum value may be used as an upper bound estimate.

c. *Depth Below Grade to Water Table or Soil Gas Sample* (L_s)
For groundwater, enter the depth to the top of the water table (i.e., where the pressure head is equal to zero and the pressure is atmospheric).

Note: The thickness of the capillary zone is calculated based on the SCS soil textural classification above the top of the water table. The depth below grade to the top of the water table minus the thickness of the capillary zone must be greater than the depth below grade to the bottom of the enclosed space floor. This means that the top of the capillary zone is always below the floor.

For soil gas, enter the depth to the top of soil contamination. The value of L_s should be at least one meter greater than the value of the depth below grade to the base of the foundation (L_b). Maps on water depth can be found at the United State Geological Survey site (http://water.usgs.gov/maps.html).

d. *Average Groundwater/Vadose Zone Temperature* (T_s)
The groundwater/vadose zone temperature is used to correct the Henry's law constant to the specified temperature. Figure 3 from U.S. EPA (1995) shows the average temperature of shallow groundwater in the continental United States.

Shallow groundwater temperatures may be used to approximate subsurface soil temperatures greater than 1 to 2 meters below the ground surface. Another source of information may be your State groundwater protection regulatory agency.

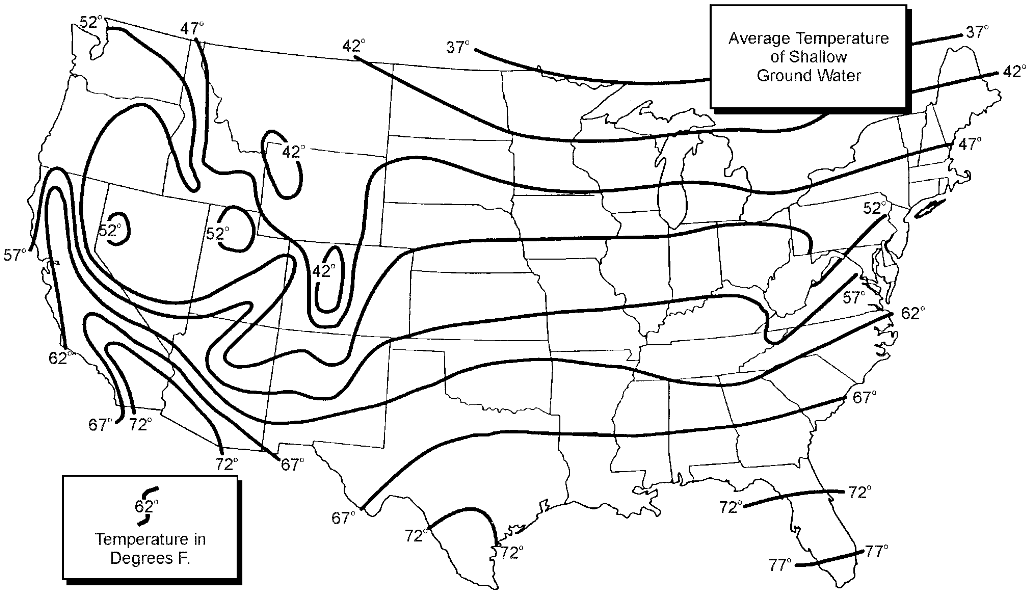
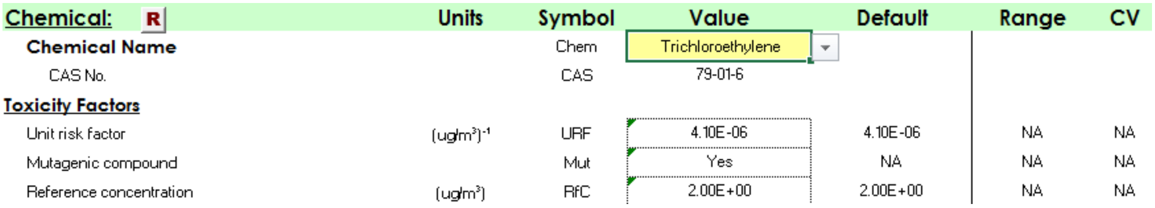


Figure 6: Average Groundwater Temperatures in the US (EPA, 1995)

3. **Select the chemical to analyze**: From the dropdown menu, select the chemical of interest. The dropdown menu lists chemicals by name rather than by CAS number. The CAS number, toxicity factors, and chemical properties will automatically appear in the appropriate cells after a chemical is selected.

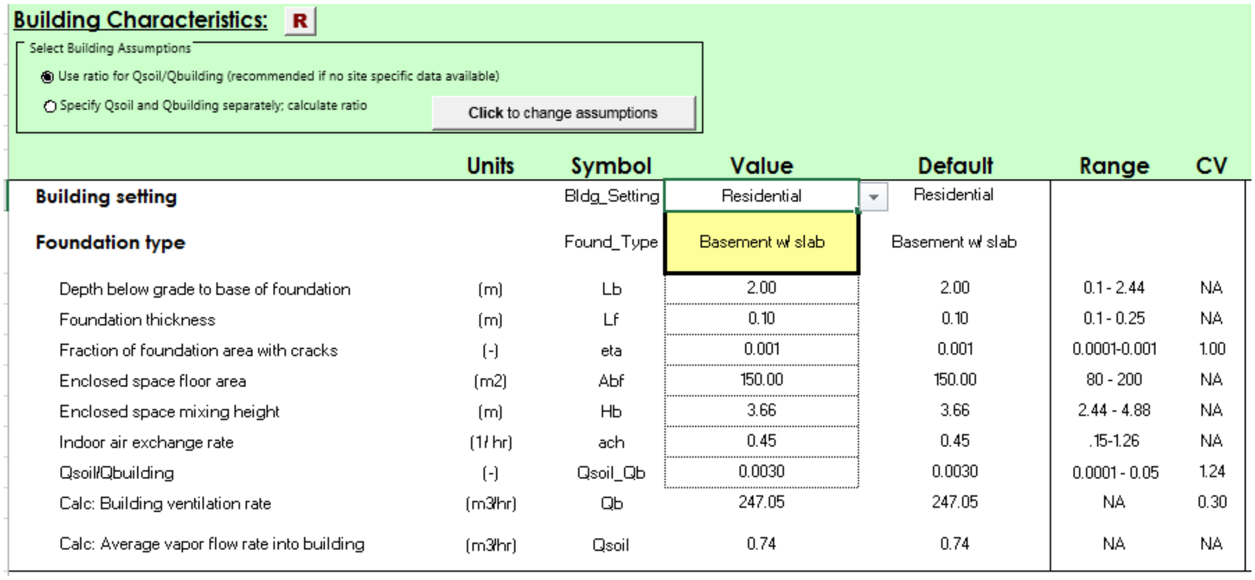


Chemical: R	Units	Symbol	Value	Default	Range	CV
Chemical Name		Chem	Trichloroethylene			
CAS No.		CAS	79-01-6			
Toxicity Factors						
Unit risk factor	$(ug/m^3)^{-1}$	URF	4.10E-06	4.10E-06	NA	NA
Mutagenic compound		Mut	Yes	NA	NA	NA
Reference concentration	(ug/m^3)	RfC	2.00E+00	2.00E+00	NA	NA

The user may elect to change the toxicity factors (inhalation unit risk and reference concentration) and certain chemical properties (pure component water solubility, Henry's Law constant at 25°C, diffusivity in air, and diffusivity in water) by entering these values in the MODEL sheet. If these values are altered by the user, the model will remind the user to document the rationale for the change, by presenting the following message: "WARNING: Value is different from default value: please justify."

4. Enter the **Building Characteristics**. Users should enter as many building specific parameters as they can, to get the best estimates of indoor air concentration and risk.

There are two modes that you can use for building data: using a ratio for Q_{soil}/Q_b, recommended if no site specific data are available, *or* using separate, measured values for Q_{soil} and Q_b, only recommended if you have actual measurements available. To switch between the two, select the appropriate mode and click the button to update the spreadsheet (it does not automatically update).



Building Characteristics:

Select Building Assumptions

● Use ratio for Qsoil/Qbuilding (recommended if no site specific data available)

○ Specify Qsoil and Qbuilding separately; calculate ratio

	Units	Symbol	Value	Default	Range	CV
Building setting		Bldg_Setting	Residential	Residential		
Foundation type		Found_Type	Basement w/ slab	Basement w/ slab		
Depth below grade to base of foundation	(m)	Lb	2.00	2.00	0.1 - 2.44	NA
Foundation thickness	(m)	Lf	0.10	0.10	0.1 - 0.25	NA
Fraction of foundation area with cracks	(-)	eta	0.001	0.001	0.0001-0.001	1.00
Enclosed space floor area	(m2)	Abf	150.00	150.00	80 - 200	NA
Enclosed space mixing height	(m)	Hb	3.66	3.66	2.44 - 4.88	NA
Indoor air exchange rate	(1/ hr)	ach	0.45	0.45	.15-1.26	NA
Qsoil/Qbuilding	(-)	Qsoil_Qb	0.0030	0.0030	0.0001 - 0.05	1.24
Calc: Building ventilation rate	(m3/hr)	Qb	247.05	247.05	NA	0.30
Calc: Average vapor flow rate into building	(m3/hr)	Qsoil	0.74	0.74	NA	NA

a. *Building Setting*: Currently, the only option is residential.

b. *Foundation Type*

The user can select one of five foundation types:

1. basement with slab,
2. basement with dirt floor,
3. slab-on-grade,
4. closed crawlspace with slab, and
5. closed crawlspace with dirt floor.

The default characteristics for each type of construction will automatically appear in the cells below. Please note that the crawlspace option is only valid for closed crawlspaces. The model will not return valid results for buildings with open (vented) crawlspaces.

c. *Depth below grade to base of foundation* (L_b)

Enter the depth to the <u>bottom</u> of the floor in contact with the soil. The default value for slab-on-grade and basement construction is 0.10 m and 2.00 m, respectively, with a range of 0.1 to 2.44 meters.

d. *Foundation Thickness* (L_f)
Enter the thickness of the floor slab. For both a basement with slab and slab-on grade construction, the model operates under the assumption that the floor in contact with the underlying soil is composed of impermeable concrete. The default value for slab-on-grade and basement with slab construction is 0.10 m, with a range of 0.10 to 0.15 m. For basement with dirt floor construction, the default value is 0 m.

e. *Fraction of Foundation Area with Cracks* (eta)
The default value is 0.001 for slab-on-grade and basement with dirt floor, with ranges 0.00019 to 0.0019 and 0.0001 to 0.001, respectively. The default value for basement with dirt floor is 1.00.

f. *Enclosed Space Floor Area* (A_{bf})
The default value is 150 m^2, with a range of 80 to 200 square m^2(U.S. EPA 2004).

g. *Enclosed Space Mixing Height* (H_b)
For a single story home, the variation in mixing height will be the greatest for houses with HVAC systems that result in significant air circulation (e.g., forced air heat pump). Mixing heights would be less for houses with electrical baseboard heaters. The mixing height is approximated by the room height. The default value is 2.44 meters with a range of 2.13 to 3.05 m for a single story house with slab-on-grade construction.

For a single story house with a basement, less mixing would be expected because of the cross-floor connections. The default values for a house with a basement (both slab and dirt floor construction) is 3.66 m, with a range of 2.44 to 4.88 m. This value represents a two-fold reduction in vapor concentrations between the floors.

h. *Indoor Air Exchange Rate* (ach)
The indoor air exchange rate is used along with the building dimensions to calculate the building ventilation rate. The default value of the indoor air exchange rate is 0.45/h. This value approximates the median air exchange rate recommended by the Exposure Factors Handbook (U.S. EPA, 2011, as reported in Koontz and Rector (1995)).

i. *Qsoil/Qbuilding* (Q_{soil}_Q_b)
The default value for all foundation types is 0.003, with a range of 0.0001 to 0.01. For further information, see Section 3.2: Justification of Default Building-Related Properties.

If you are using the default mode (using a ratio), Q_b and Q_{soil} will automatically be calculated.

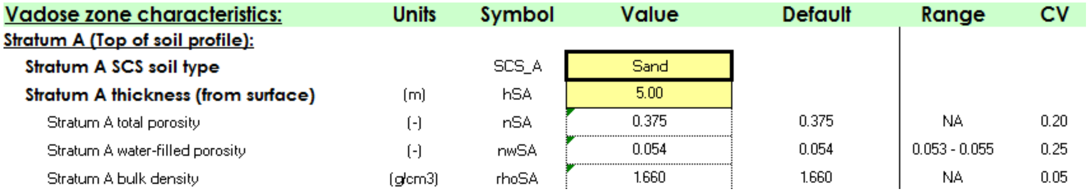
j. Calculated Building Ventilation Rate (Q_b)
In default mode, the model calculates the building ventilation rate as the product of the enclosed space floor area, enclosed space mixing height, and the indoor air exchange rate.

If you want to enter site specific data, change the radio button accordingly, and enter you Q_b value. The spreadsheet will automatically calculate Q_{soil}_Q_b from the values entered.

k. *Calculated Average Vapor Flow Rate into Building (Q_{soil})*
For foundations with slab construction, in default mode, the model calculates the average vapor flow rate as the Qsoil/Qbuilding value (default of 0.003) divided by the calculated building ventilation rate. The model uses the average vapor flow rate to calculate subslab vapor concentration (see Results section below).

If you want to enter site specific data, change the radio button accordingly, and enter you Q_{soil} value. The spreadsheet will automatically calculate Q_{soil}_Q_b from the values entered.

5. **Vadose Zone Characteristics**: The workbook allows up to three strata in the model. For each stratum, users should select the soil type and thickness. Additional parameters are automatically populated from defaults, but can be replaced with custom values as needed. Refer to section 4.3, tables 8 and 9, for more information about selecting custom values.



Vadose zone characteristics:	Units	Symbol	Value	Default	Range	CV
Stratum A (Top of soil profile):						
Stratum A SCS soil type		SCS_A	Sand			
Stratum A thickness (from surface)	(m)	hSA	5.00			
Stratum A total porosity	(-)	nSA	0.375	0.375	NA	0.20
Stratum A water-filled porosity	(-)	nwSA	0.054	0.054	0.053 - 0.055	0.25
Stratum A bulk density	(g/cm3)	rhoSA	1.660	1.660	NA	0.05

a. *Stratum SCS soil type* (SCS_X, X=A, B, or C)
For each soil stratum, choose one of the following SCS soil types from the drop-down menu for each stratum; clay, clay loam, loam, loamy sand, sand, sandy clay, sandy clay loam, sandy loam, silt, silt loam, silty clay, silty clay loam. The user may input up to three soil strata.

The SCS soil textural classification can be determined by using either the ATSM Standard Test Method for Particle-Size Analysis of Soils (D422-63) or by using the analytical procedures found in the U.S. Natural Resources Conservation Service (NRCS) Soil Survey Laboratory Methods Manual, Soil Survey Laboratory Investigations Report No. 42 (1993). After determining the particle size distribution of a soil sample, the SCS soil textural classification can be determined using the SCS classification chart in Figure 2.

b. *Stratum thickness (from surface)* (hSX, X=A, B, or C)
The user can define up to three soil strata between the soil surface and the top of contamination or to the soil gas sampling depth, as appropriate. These strata are listed as A, B, and C. Stratum A extends down from the soil surface, Stratum B is below Stratum A, and Stratum C is the deepest stratum. The thickness of Stratum A must be at least as thick as the depth below grade to the bottom of the enclosed space floor. The combined thickness of all strata must be equal to the depth to the top of the water table, or to the soil gas sampling depth, as appropriate. For strata B and C, the default setting is "not present" for SCS soil type and 0.00 for stratum thickness. Only change these entries if strata B and/or C are to be considered.

c. *Total Porosity* (ηSX, X=A, B, or C)

Total soil porosity (η) is determined as:

$$\eta = 1- (\rho_b/\rho_s)$$

where ρ_b is the soil dry bulk density (g/cm^3) and ρ_s is the soil particle density (usually 2.65 g/cm^3).

The model automatically displays the total porosity value for the soil type selected by the user. The user may elect to enter a total porosity value different from the default value. If the default value is changed, a message appears stating "WARNING: Value is different from default value; please justify."

d. *Water-filled Porosity* (nwSX, X=A, B, or C)

The default value for a given soil type appears once the user selects the SCS soil type for each stratum. If the user chooses to override this default value, a message appears stating "WARNING: Value is different from default value; please justify."

Enter the average long-term volumetric soil moisture content; this is typically a depth-averaged value for the appropriate soil stratum (see Figure 7 for examples of soil water content by depth). A long-term average value is typically not readily available. It is not advisable to use values based on episodic measurements unless they are representative of long-term conditions. Table 2 provides a soil-specific range of typical value for specified soils. The user must define soil type or input site-specific values.

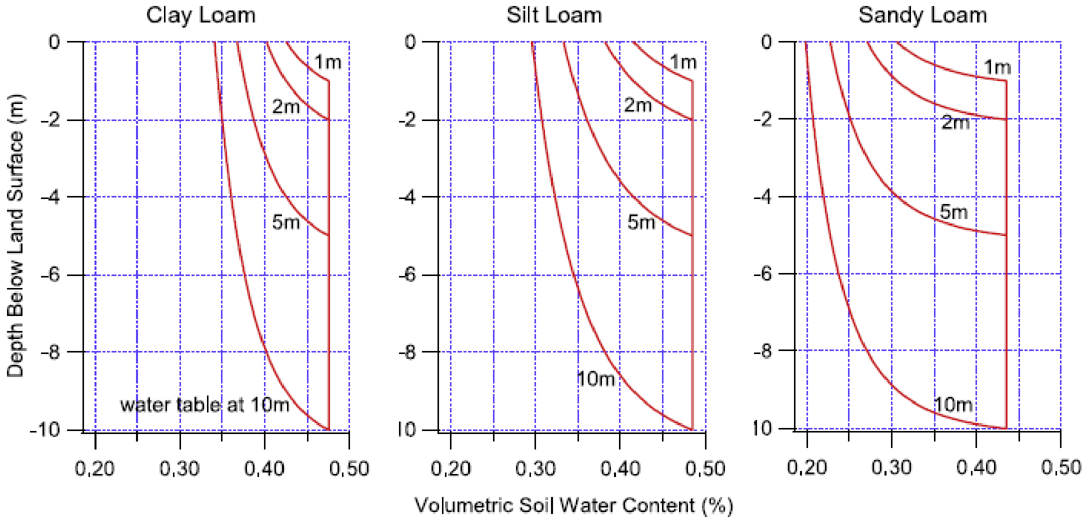
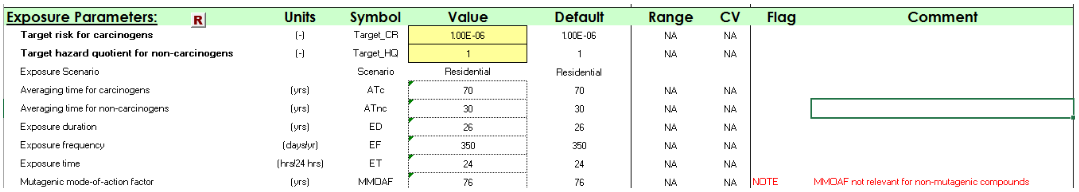


Figure 7: Soil Water Content by Depth for Clay Loam, Silt Loam, and Sandy Loam (from Fan et al., 2007)

One option is to use a model to estimate the long-term average soil water-filled porosities of each soil stratum between the enclosed space floor and the top of contamination. The HYDRUS model version 5.0 (Vogel et al., 1996) is a public domain code for simulating one-dimensional water flow, solute transport, and heat movement in variably-saturated soils. The water flow simulation module of HYDRUS will generate soil water content as a function of depth and time given actual daily precipitation data. Model input requirements include either the soil hydraulic properties of van Genuchten (1980) or those of Brooks and Corey (1966). The van Genuchten soil hydraulic properties required are the same as those given in Tables 2and 3(i.e., θ_s, θ_r, N, α_1, and K_s). The HYDRUS model is available from the U.S. Department of Agriculture (USDA) - Agricultural Research Service in Riverside, California via their website (http://www.ars.usda.gov/Services/docs.htm?docid=8921). Two- and three-dimensional commercial versions of HYDRUS (Windows versions) are available PC Progress (http://www.pc-progress.com/en/Default.aspx?hydrus-3d) or at the International Ground Water Modeling Center website (http://igwmc.mines.edu/software/hydrus.html), Schaap and Leij (1998) have recently developed a Windows program entitled ROSETTA for estimating the van Genuchten soil hydraulic properties based on a limited or more extended set of input data. The ROSETTA program can be found at the USDA website (http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/drainage/?cid=stelprdb1045315). The van Genuchten hydraulic properties can then be input into HYDRUS to estimate soil moisture content (USDA ARS, 2005).

e. *Bulk Density* (ρSX, X=A, B, or C)
Identify the soil type for each stratum and accept the default value or enter a site-specific value for the average soil dry bulk density in g/cm^3). Dry bulk density is used in a number of intermediate calculations and is normally determined by field measurements (ASTM D 2937 Method).

6. Exposure Parameters:
The main enhancement provided by the EPA spreadsheet tool, over the basic Johnson and Ettinger model, is the ability to calculate risk from predicted concentrations. This portion of the tool contains the parameters for these calculations. Default exposure parameters, from the Exposure Factors Handbook (US EPA, 2011 and 2014) are supplied, but may be changed for site specific analyses.



Exposure Parameters:	Units	Symbol	Value	Default	Range	CV	Flag	Comment
Target risk for carcinogens	(-)	Target_CR	1.00E-06	1.00E-06	NA	NA		
Target hazard quotient for non-carcinogens	(-)	Target_HQ	1	1	NA	NA		
Exposure Scenario		Scenario	Residential	Residential				
Averaging time for carcinogens	(yrs)	ATc	70	70	NA	NA		
Averaging time for non-carcinogens	(yrs)	ATnc	30	30	NA	NA		
Exposure duration	(yrs)	ED	26	26	NA	NA		
Exposure frequency	(days/yr)	EF	350	350	NA	NA		
Exposure time	(hrs/24 hrs)	ET	24	24	NA	NA		
Mutagenic mode-of-action factor	(yrs)	MMOAF	76	76	NA	NA	NOTE	MMOAF not relevant for non-mutagenic compounds

a. *Target Risk for Carcinogens* (Target_CR): Enter the target risk-level for a risk-based media concentration. The default value is 1 x 10-6.

b. *Target Hazard Quotient for Non-Carcinogens* (Target_HQ): Enter the target hazard quotient for a risk-based media concentration. The default value is 1.
c. *Exposure Scenario*: Commercial or residential.
d. *Averaging Time for Carcinogens* (ATc): Enter averaging time in units of years. The default value is 70 years.
e. *Averaging Time for Non-Carcinogens* (ATnc): Enter the averaging time in units of years. The averaging time for noncarcinogens is set equal to the exposure duration. The default value for residential exposure from U.S. EPA (2014) is 26 years.
f. *Exposure Duration* (ED): Enter the exposure duration in units of years. The default value for residential exposure is 26 years (see Section 1 for more information).
g. *Exposure Frequency* (EF): Enter the exposure frequency in units of days/yr. The default value for residential exposure from U.S. EPA (2011 and 2014) is 350 days/year.
h. *Exposure Time* (ET): Enter the exposure time in hours per 24 hours. The default value is 24 hours.
i. *Mutagenic mode-of-action factor* (MMOAF): Enter the mutagenic mode-of-action factor in years. The default value is 72 years. It is calculated by summing the products of the age-dependent adjustment factors by the exposure duration in each age class as shown in table 6, below. For mutagenic chemicals, the MMOAF is used as the exposure duration.

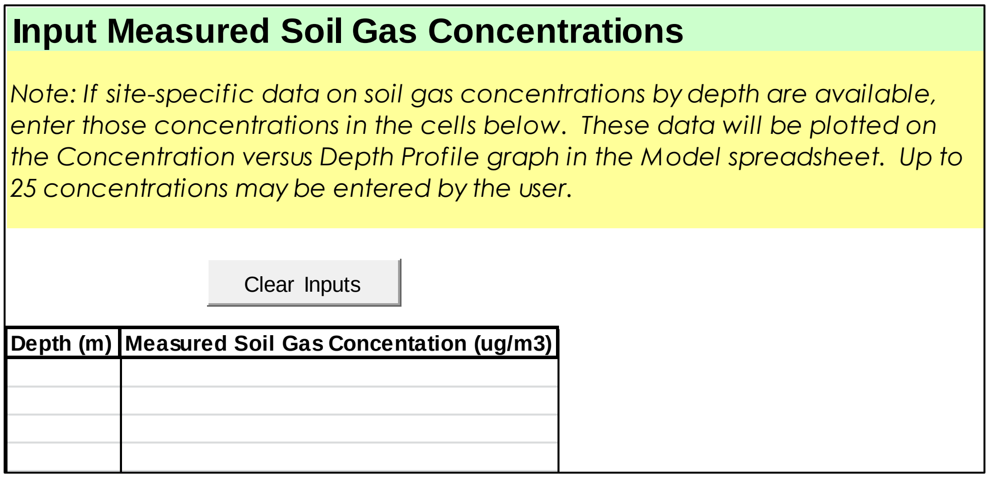
Table 6: Calculation of Mutagenic Mode of Action Factors

Input	**Abbrev.**	**Age Cohort (years)**			
		0 to 2	2 to 6	6 to 16	>16
Exposure Duration (years)	ED	2	4	10	10
Age-dependent adjustment factor	ADAF	10	3	3	1
ED * ADAF	-	20	12	30	10
Mutagenic mode-of-action factor (years)	MMOAF	20+12+30+10=72			

7. Enter measured soil gas data (*optional)*

If you have measured soil gas concentrations from your site, these can be entered on the "**Measured_Soil_Gas_Conc**" Worksheet, which enables comparisons between predicted concentrations and actual measured concentrations.

The worksheet allows users to enter up to 25 site-specific measured soil gas concentrations by depth. The user should enter depths and measured soil gas concentrations in µg/m^3. These values are automatically plotted on the *Concentration versus Depth Profile* graph in the MODEL sheet to allow users to compare concentrations calculated by the model to concentrations measured on-site. To delete all values in this sheet, press the Clear Inputs button. Clearing this sheet will also delete these values from the *Concentration versus Depth Profile* graph.



Input Measured Soil Gas Concentrations

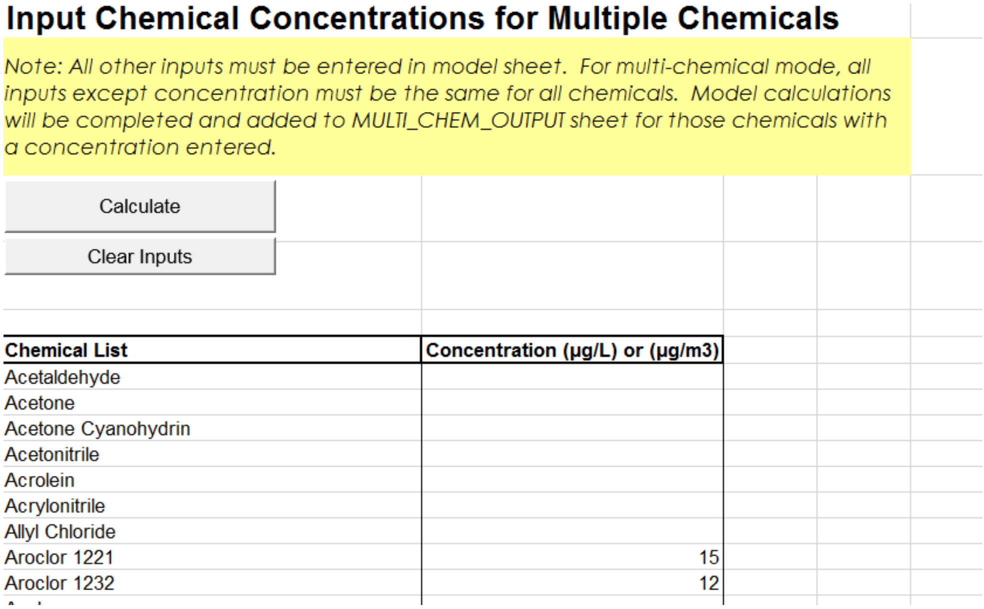
Note: If site-specific data on soil gas concentrations by depth are available, enter those concentrations in the cells below. These data will be plotted on the Concentration versus Depth Profile graph in the Model spreadsheet. Up to 25 concentrations may be entered by the user.

Depth (m)	Measured Soil Gas Concentation (ug/m3)

Figure 8: Measured Soil Gas Concentration Input

3.3 Analyzing Multiple Chemicals Simultaneously

The multiple chemical input sheet (MULT_CHEM_INPUT) allows the user to analyze multiple chemicals simultaneously. Chemicals may be selected by entering the concentrations in µg/L (for groundwater) or µg/m^3(for soil gas) in the cell next to the chemical of interest.. **All other parameters other than the chemical concentration must be entered in the MODEL sheet and must be the same for all chemicals**



Input Chemical Concentrations for Multiple Chemicals

Note: All other inputs must be entered in model sheet. For multi-chemical mode, all inputs except concentration must be the same for all chemicals. Model calculations will be completed and added to MULTI_CHEM_OUTPUT sheet for those chemicals with a concentration entered.

Chemical List	Concentration (µg/L) or (µg/m3)
Acetaldehyde	
Acetone	
Acetone Cyanohydrin	
Acetonitrile	
Acrolein	
Acrylonitrile	
Allyl Chloride	
Aroclor 1221	15
Aroclor 1232	12

Figure 9: Multiple Chemical Input Screen

To run the model, click the calculate button. Model calculations will be completed and added to MULTI_CHEM_OUTPUT sheet for those chemicals with a concentration entered. To reset, press the CLEAR INPUTS button at the top of the worksheet. The Clear Inputs button will delete all concentrations entered in the MULTI_CHEM_INPUT sheet, regardless of whether the user has saved these changes.

The results are in the same format as on the MODEL tab, but there is a column for each chemical.

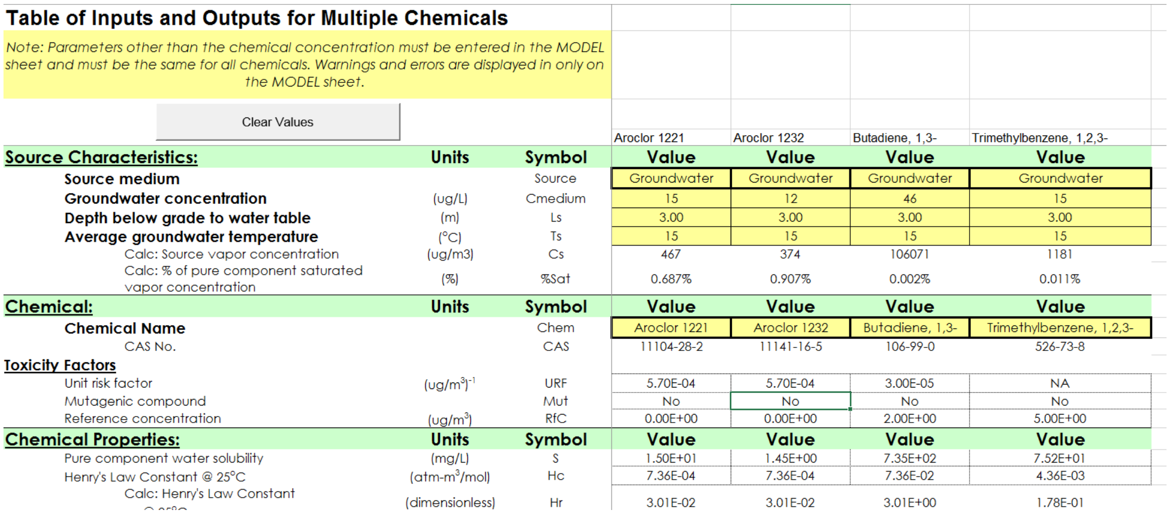


Table of Inputs and Outputs for Multiple Chemicals

Note: Parameters other than the chemical concentration must be entered in the MODEL sheet and must be the same for all chemicals. Warnings and errors are displayed in only on the MODEL sheet.

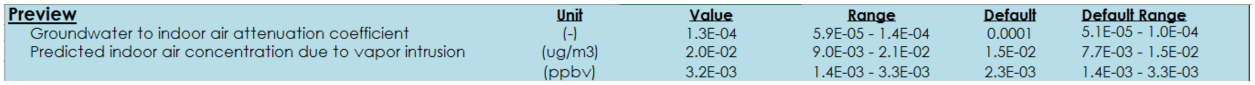
			Aroclor 1221	Aroclor 1232	Butadiene, 1,3-	Trimethylbenzene, 1,2,3-
Source Characteristics:	**Units**	**Symbol**	**Value**	**Value**	**Value**	**Value**
Source medium		Source	Groundwater	Groundwater	Groundwater	Groundwater
Groundwater concentration	(ug/L)	Cmedium	15	12	46	15
Depth below grade to water table	(m)	Ls	3.00	3.00	3.00	3.00
Average groundwater temperature	(°C)	Ts	15	15	15	15
Calc: Source vapor concentration	(ug/m3)	Cs	467	374	106071	1181
Calc: % of pure component saturated vapor concentration	(%)	%Sat	0.687%	0.907%	0.002%	0.011%
Chemical:	**Units**	**Symbol**	**Value**	**Value**	**Value**	**Value**
Chemical Name		Chem	Aroclor 1221	Aroclor 1232	Butadiene, 1,3-	Trimethylbenzene, 1,2,3-
CAS No.		CAS	11104-28-2	11141-16-5	106-99-0	526-73-8
Toxicity Factors						
Unit risk factor	(ug/m^3)$^{-1}$	URF	5.70E-04	5.70E-04	3.00E-05	NA
Mutagenic compound		Mut	No	No	No	No
Reference concentration	(ug/m^3)	RfC	0.00E+00	0.00E+00	2.00E+00	5.00E+00
Chemical Properties:	**Units**	**Symbol**	**Value**	**Value**	**Value**	**Value**
Pure component water solubility	(mg/L)	S	1.50E+01	1.45E+00	7.35E+02	7.52E+01
Henry's Law Constant @ 25°C	(atm-m^3/mol)	Hc	7.36E-04	7.36E-04	7.36E-02	4.36E-03
Calc: Henry's Law Constant	(dimensionless)	Hr	3.01E-02	3.01E-02	3.01E+00	1.78E-01

Figure 10: Multiple Chemical Output

Note that the equilibrium vapor concentration at the source of contamination is limited by the value of aqueous solubility limit (S) for groundwater contamination. For a single contaminant, the vapor concentration cannot be greater than that associated with the solubility limit. This limit also applies in the multiple chemical version of this model, which does not account for solubility changes that may result when chemicals are mixed in groundwater. As a result, groundwater concentrations greater than S will not produce higher vapor concentrations in either the single or multiple chemical versions of the model. If the indoor vapor concentration predicted from a groundwater concentration greater than or equal to the value of S does not exceed the health-based limit in indoor air (target risk or target hazard quotient), the vapor intrusion pathway will not be of concern for that particular chemical. That does not necessarily mean, however, that the subsurface contamination will not be of concern from a groundwater protection standpoint (for example, this model does not consider health risks due to ingestion).The potential for free-phase contamination (e.g., NAPL) must also be addressed.

3.4 Model Results

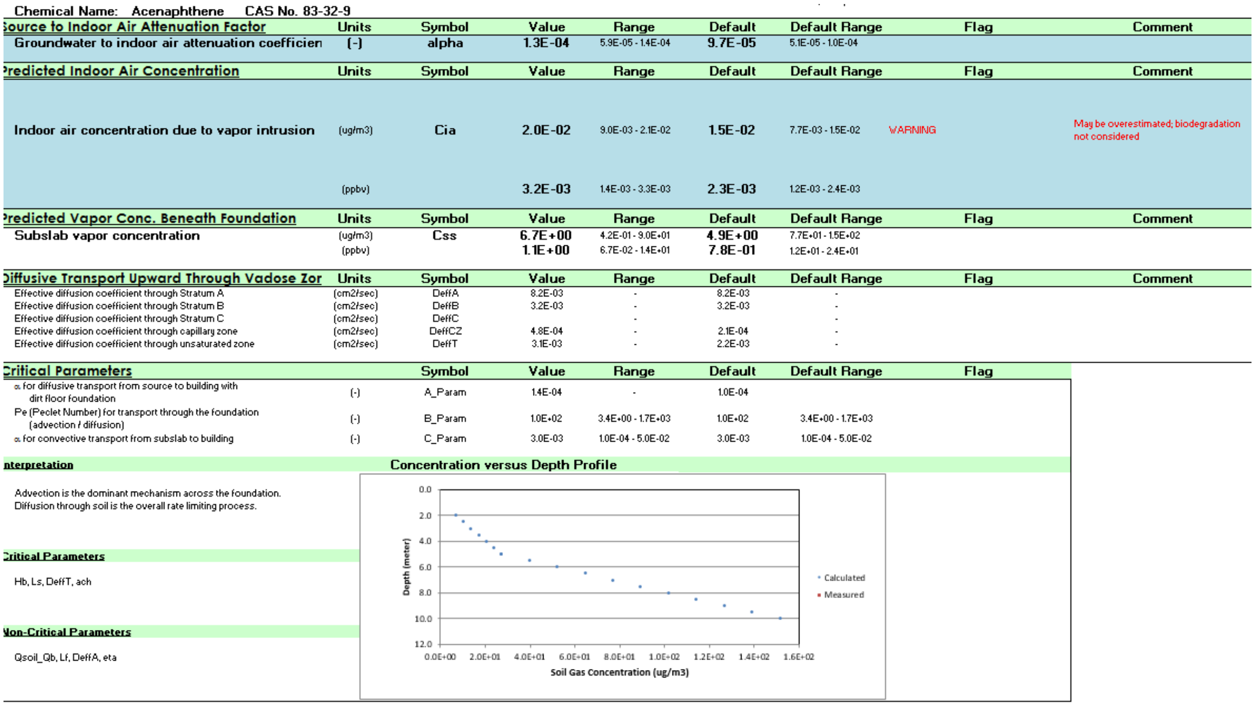
As you enter data into the MODEL spreadsheet, the predicted indoor air concentrations, risk based screening levels, and incremental risk estimates are automatically calculated. Similarly, when data is entered on the “MEASURED_SOIL_GAS_CONC.” tab, those data points are automatically plotted on the Model tab (in the plot of “Concentration versus Depth Profile”). A preview of the results (the media specific attenuation coefficient and the predicted indoor air concentration) are displayed at the top of the workbook, and more detailed results are available immediately below the input tables on the MODEL spreadsheet.



Preview	Unit	Value	Range	Default	Default Range
Groundwater to indoor air attenuation coefficient	(-)	1.3E-04	5.9E-05 - 1.4E-04	0.0001	5.1E-05 - 1.0E-04
Predicted indoor air concentration due to vapor intrusion	(ug/m3)	2.0E-02	9.0E-03 - 2.1E-02	1.5E-02	7.7E-03 - 1.5E-02
	(ppbv)	3.2E-03	1.4E-03 - 3.3E-03	2.3E-03	1.4E-03 - 3.3E-03

Figure 11: Preview pane from the model tab

For both the soil gas and groundwater models, calculations are presented as a risk-based soil gas or groundwater concentration, and the incremental risks associated with a user-provided site-specific soil gas or groundwater concentration. The user should check the message and error summary below the results section to ensure that no error messages are present. If one or more error messages appear, check the appropriate fields.



Chemical Name: Acenaphthene CAS No. 83-32-9

Source to Indoor Air Attenuation Factor	Units	Symbol	Value	Range	Default	Default Range	Flag	Comment
Groundwater to indoor air attenuation coefficien	(-)	alpha	1.3E-04	5.9E-05 - 1.4E-04	9.7E-05	5.1E-05 - 1.0E-04		

Predicted Indoor Air Concentration	Units	Symbol	Value	Range	Default	Default Range	Flag	Comment
Indoor air concentration due to vapor intrusion	(ug/m3)	Cia	2.0E-02	9.0E-03 - 2.1E-02	1.5E-02	7.7E-03 - 1.5E-02	WARNING	May be overestimated; biodegradation not considered
	(ppbv)		3.2E-03	1.4E-03 - 3.3E-03	2.3E-03	1.2E-03 - 2.4E-03		

Predicted Vapor Conc. Beneath Foundation	Units	Symbol	Value	Range	Default	Default Range	Flag	Comment
Subslab vapor concentration	(ug/m3)	Css	6.7E+00	4.2E-01 - 9.0E+01	4.9E+00	7.7E+01 - 1.5E+02		
	(ppbv)		1.1E+00	6.7E-02 - 1.4E+01	7.8E-01	1.2E+01 - 2.4E+01		

Diffusive Transport Upward Through Vadose Zor	Units	Symbol	Value	Range	Default	Default Range	Flag	Comment
Effective diffusion coefficient through Stratum A	(cm2/sec)	DeffA	8.2E-03	-	8.2E-03	-		
Effective diffusion coefficient through Stratum B	(cm2/sec)	DeffB	3.2E-03	-	3.2E-03	-		
Effective diffusion coefficient through Stratum C	(cm2/sec)	DeffC		-		-		
Effective diffusion coefficient through capillary zone	(cm2/sec)	DeffCZ	4.8E-04	-	2.1E-04	-		
Effective diffusion coefficient through unsaturated zone	(cm2/sec)	DeffT	3.1E-03	-	2.2E-03	-		

Critical Parameters		Symbol	Value	Range	Default	Default Range	Flag
α for diffusive transport from source to building with dirt floor foundation	(-)	A_Param	1.4E-04	-	1.0E-04		
Pe (Peclet Number) for transport through the foundation (advection / diffusion)	(-)	B_Param	1.0E+02	3.4E+00 - 1.7E+03	1.0E+02	3.4E+00 - 1.7E+03	
α for convective transport from subslab to building	(-)	C_Param	3.0E-03	1.0E-04 - 5.0E-02	3.0E-03	1.0E-04 - 5.0E-02	

nterpretation

Advection is the dominant mechanism across the foundation.
Diffusion through soil is the overall rate limiting process.

Critical Parameters

Hb, Ls, DeffT, ach

Non-Critical Parameters

Qsoil_Qb, Lf, DeffA, eta

Figure 12: Model Output

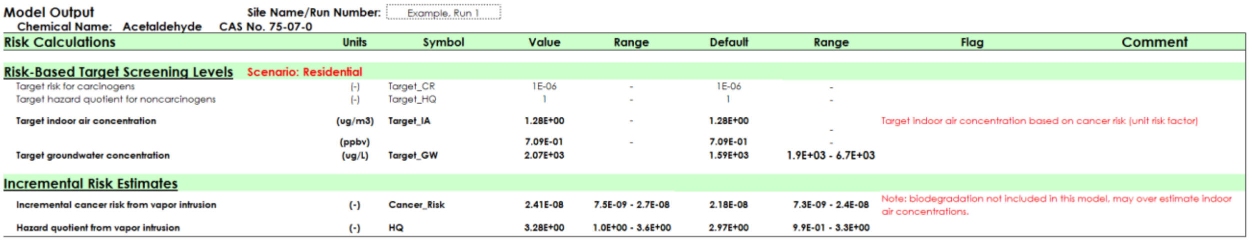
The steady-state indoor air concentration is calculated using Equation 20 in the technical guide (i.e., $C_{building} = \alpha\ C_S$). The value of the vapor concentration at the source of emissions (C_S) is assigned the value of the user-defined soil gas concentration. For groundwater and exterior soil gas options, the value of the steady-state attenuation coefficient (α) in Equation 20 is calculated using Equation 10. For the sub-slab soil gas option, the steady-state air attenuation coefficient (α) is equal to Qsoil/Qbuilding. Because no evaluation has been made of the extent of the source of emissions, steady-state conditions (i.e., a non-diminishing source) must be assumed.

Both the groundwater and soil gas models calculate the groundwater to indoor air attenuation coefficient (α), the indoor air concentration due to vapor intrusion ($C_{building}$), the subslab vapor concentration (Css), and the coefficients for diffusive transport upward through the vadose zone (D_{eff}^{X}, where X=A, B, or C), the capillary zone (D_{eff}^{CZ}), and the unsaturated zone (D_{eff}^{T}). Under the Critical Parameters subsection, the model displays the calculated coefficient of diffusive transport from source to basement with dirt floor (A_{Param}), the Peclet number for transport through the foundation (B_{Param}), and the coefficient for convective transport from subslab into the building (C_{Param}), as derived by Johnson (2002). The model presents the critical and non-critical parameters of the model based on the user input data. The model displays a Concentration versus Depth Profile graph of the predicted soil vapor concentration by depth. If the user elected to enter soil gas concentrations measured at the site in the Measured Soil Gas Concentration sheet, these values will also be displayed in this graph.

Below the model predictions section is an interpretation section which lists whether advection or diffusion is the "dominant mechanism across the foundation" as well as which process limits the rate of vapor intrusion (see Figure 11).The tool calculates which process is the dominant mechanism in the following manner: if the Peclet number for transport through the foundation is less than 0.1, then the tool displays "diffusion is the dominant mechanism across the foundation;" if the Peclet number falls between 0.1 and 3.0, the tooll displays "both diffusion and advection contribute to transport across the foundation;" If the Peclet number is greater than three, the tool displays "advection is the dominant mechanism across the foundation."

The results section displays which process limits the rate of vapor intrusion based on the following criteria: diffusion is considered the overall rate limiting process if the Peclet number is greater than 3.0 *and* the ratio of the coefficient for diffusive transport to the coefficient for convective transport (A_Param/C_Param) is less than 0.1. Advection is considered the overall rate-limiting process when the Peclet number is greater than 3.0 *and* the ratio of the coefficient for diffusive transport to the coefficient for convective transport (A_Param/C_Param) is greater than ten.

Below the predicted air concentrations, the model calculates both the risk-based target screening levels and the incremental cancer and non-cancer (hazard quotient) risk estimates.



Model Output Site Name/Run Number: Example, Run 1
Chemical Name: Acetaldehyde CAS No. 75-07-0

Risk Calculations	Units	Symbol	Value	Range	Default	Range	Flag	Comment
Risk-Based Target Screening Levels Scenario: Residential								
Target risk for carcinogens	(-)	Target_CR	1E-06	-	1E-06	-		
Target hazard quotient for noncarcinogens	(-)	Target_HQ	1	-	1	-		
Target indoor air concentration	(ug/m3)	Target_IA	1.28E+00	-	1.28E+00	-		Target indoor air concentration based on cancer risk (unit risk factor)
	(ppbv)		7.09E-01	-	7.09E-01	-		
Target groundwater concentration	(ug/L)	Target_GW	2.07E+03		1.59E+03	1.9E+03 - 6.7E+03		
Incremental Risk Estimates								
Incremental cancer risk from vapor intrusion	(-)	Cancer_Risk	2.41E-08	7.5E-09 - 2.7E-08	2.18E-08	7.3E-09 - 2.4E-08		Note: biodegradation not included in this model, may over estimate indoor air concentrations.
Hazard quotient from vapor intrusion	(-)	HQ	3.28E+00	1.0E+00 - 3.6E+00	2.97E+00	9.9E-01 - 3.3E+00		

Figure 13: Risk Calculations

Target screening levels are calculated for both the target indoor air concentration and the target source (soil gas or groundwater) concentration. The target indoor air concentration is provided in both µg/m^3 and in ppbv and the target source concentration is calculated in µg/m^3 for soil gas and µg/L for groundwater concentrations. In the comment column, the model notes whether the target indoor air concentration is based on cancer risk (IUR) or non-cancer toxicity (reference concentration).

The "Incremental Risk Estimates" subsection shows the indoor exposure soil gas or groundwater concentration for either a carcinogen or non-carcinogen, as appropriate. When a contaminant is both a carcinogen and a non-carcinogen, the risk-based indoor exposure concentration is set equal to the lower of these two values. For mutagenic compounds, the incremental risk is calculated using the mutagenic mode of action adjustment factor as the exposure duration.

3.4.1 Prediction Ranges

Because there is considerable uncertainty and debate about appropriate values for $Q_{soil}/Q_{building}$, we have added ranges for all model outputs dependent on that parameter, including attenuation factors, indoor air concentration, and risk. The range is derived from the minimum and maximum values for $Q_{soil}/Q_{building}$ documented in the literature: 0.001 – 0.05.

For each value dependent on the value of $Q_{soil}/Q_{building}$, we calculated the smallest and largest possible results based on the known range. The model reports the range both for site specific values (in the "Range" column in the results) and default parameters (in the "Default Range" column). The range output does not take into account all possible value combinations for *all* parameters; only $Q_{soil}/Q_{building}$. This column is intended to give an estimate of the reasonable values for predicted attenuation factors and indoor air concentrations, and a sense of how much your model predictions depend on your specifications for air exchange rates.

3.4.2 Interpretation of Results

The models described herein are theoretical approximations of complex physical and chemical processes and as such should not be used in a deterministic fashion (i.e., to generate a single outcome). At the least, a range of outcomes should be explored focusing on the most sensitive model input variables. In general, using the central tendency default values for input variables will result in central tendency air concentrations. With a realistic range of outcomes, the risk manager may assess the uncertainty in the model predictions.

From a conceptual point of view, the vapor intrusion model provides a theoretical description of the processes involved in vapor intrusion from subsurface soils or groundwater into indoor structures. Sampling to obtain site-specific information for key parameters can reduce the uncertainty of the calculated indoor air concentrations. Typically, this involves measuring soil gas concentrations and other soil properties very near or below an actual structure. It should be recognized that soil gas sampling results outside the footprint of the building may or may not be representative of the soil gas concentrations directly below the structure. For solid building floors in contact with the soil (e.g., concrete slabs), the soil gas directly beneath the floor may be considerably higher than that adjacent to the structure. This situation is typically due to a vapor accumulation effect underneath the near impermeable floor.

Once a representative average concentration is determined, all vapor directly below the areal extent of the building is presumed to enter the structure. The soil gas concentration, along with the building ventilation rate and the soil gas flow rate into the building, will determine the indoor concentration. When using the soil gas models, it must be remembered that no analysis has been made concerning the source of contamination. Therefore, the calculated indoor concentration is assumed to be steady-state. The procedures described in API (1998) can be used to calibrate the diffusion transport considerations of the J&E tool as well as for calibrating the tool for transformation processes (e.g., biodegradation). The reader is also referred to U.S. EPA (1992) for a more detailed discussion of applying soil gas measurements to indoor vapor intrusion.

Finally, calibration and verification of the model have been limited due to the paucity of suitable data. Research is needed to provide spatially and temporally correlated measurements during different seasons, at different locations, with different buildings, and over a range of different contaminants such that the accuracy of the model may be determined.

3.5 Supporting Spreadsheets

The workbook contains several supporting spreadsheets that are used in the model calculations, but do not require user input or display results. The remaining sheets contain tables on soil properties, building characteristics, chemical properties, the coefficients of variation and references. These changes and supporting information should be called out in the documentation for the model runs.

SOIL DATA SHEET (SOIL_DATA)

This sheet contains the soil properties for the soils selected for inclusion in the model. This table contains the van Genuchten water retention curve parameters as well as the average soil water retention curve data of Hers (2002) and Schaap and Leij (1998) and the mean grain diameter data of Nielson and Rogers (1990) by SCS soil type, and the mean dry bulk density from Ley et al. (1994).

CHEMICAL DATA SHEET (CHEM_DATA)

The chemical data sheet provides a summary of the chemical and toxicological properties of the chemical(s) selected for analysis. All data in the chemical data sheet are protected.

BUILDING DATA SHEET (BLDG_DATA)

The building data sheet provides a summary of the properties of the foundation type selected (basement with slab, basement with dirt floor, slab-on-grade, closed crawlspace with slab, and closed crawlspace with dirt floor). All data in the building data sheet are protected.

COEFFICIENT OF VARIATION SHEETS (SOIL_CV_DATA)

The coefficients of variation for certain soil parameters are listed by soil type in the SOIL_CV_DATA sheet. All data in these sheets are protected.

REFERENCE SOURCES SHEET (Reference Sources)

This sheet displays the list of references for the ranges and coefficients of variation for each parameter in the model.

U.S. EPA REGIONAL SCREENING LEVEL TABLES (ParametersSummary and ToxSummary)

The values in the Chemical Data sheet are from the Chemical Specific Parameters (params_sl_table) and the Residential Air Supporting table (resair_sl_table), available at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/index.htm (U.S. EPA, 2015b). The data in these two sheets are protected.

VERSION NOTES SHEET (Version Notes)

This sheet lists changes and updates made to the model.

4. Input Variables and Default Assumptions

The EPA implementation of the J&E model requires many input values. This section reviews all of the inputs and reasonable ranges for their values, reviews the sensitivity of the model to changes in input parameters, and includes a justification of the default assumptions.

4.1 Input Parameters

The J&E Model as constructed within the accompanying spreadsheet requires a variety of input variables. Tables 7 through 11 provide a list of all major input variables and include the units, the range of practical values, the default value, and the coefficient of variation (when available). The model displays defaults and ranges for input parameters as appropriate. Version 6.0 uses central estimates as defaults for most key parameters. The user may modify the default value within the bounds of the reported variation in estimates in order to address site-specific issues or to conduct uncertainty analyses. The user may change default values for toxicity factors, building characteristics, vadose zone characteristics, and exposure time parameters.

To provide a measure of the variation in estimates for each of the input parameters, the model includes a coefficient of variation (CV) for most input values. The coefficient of variation is defined as the standard deviation of a variable divided by the mean. CV values listed in the "building characteristics" sections are from CalTOX Version 6.0. CV values for the "vadose zone characteristics" section are based on Weaver and Tillman (2005) and Tillman and Weaver (2006).

Table 7: Range of Values for Model Input Parameters: Source Characteristics

Input Parameter	**Units**	**Variable Name**	**Range**	**Default Value**	**Coefficient of Variation**	**Equation Number**
Groundwater						
Groundwater concentration	µg/L	Cmedium	user-defined		NA	1
Depth below grade to water table	m	Ls	Vary to 50[a]	user-defined	0.27	user-defined
Average groundwater temperature	°C	Ts	3 to 25[b]	15	0.2	user-defined
Soil Gas						
Soil gas concentration	µg/m³	Cmedium	user-defined		NA	1
Depth below grade to soil gas sample	m	Ls	Vary to 50[a]	user-defined	0.27	user-defined
Average vadose zone temperature	°C	Ts	3 to 30	15	0.5	user-defined

a. Johnson (2002)
b. Collins (1925)

Table 8: Range of Values for Model Input Parameters: Chemical Toxicity Factors and Properties

Input Parameter	**Units**	**Variable Name**	**Range**	**Default Value**	**Coefficient of Variation[a]**
Chemical Toxicity Factors					
Inhalation Unit Risk	(µg/m³)⁻¹	IUR	Specific to chemical, see CHEM_DATA sheet		NA
Reference concentration	µg/m³	RfC	Specific to chemical, see CHEM_DATA sheet		NA
Chemical Properties					
Pure component water solubility	mg/L	S	Specific to chemical, see CHEM_DATA sheet		NA
Henry's Law Constant @ 25°C	atm-m³/mol	Hc	Specific to chemical, see CHEM_DATA sheet		NA
Diffusivity in air	cm²/s	Dair	Specific to chemical, see CHEM_DATA sheet		NA

Diffusivity in water	cm^2/s	Dwater	Specific to chemical, see CHEM_DATA sheet	NA

a. Coefficients of variation values from CalTOX, Version 6.0

Table 9: Range of Values for Model Input Parameters: Building Characteristics

Input Parameter	Units	Variable Name	Range	Default Value	Coefficient of Variation	Equation Number
Basement w/ slab scenario						
Depth below grade to base of foundation	m	Lb	0.1-2.44[a]	2	NA	user-defined
Foundation thickness	m	Lf	0.1-0.15	0.1	NA	user-defined
Fraction of foundation area with cracks	-	eta	0.0001 to 0.001[a]	0.001 (0.1%)	1.00	user-defined
Enclosed space floor area	m^2	Abf	80 to 200[a]	150	NA	user-defined
Enclosed space mixing height	m	Hb	2.44 to 4.88[a]	3.66	0.25[c]	user-defined
Indoor air exchange rate	1/hr	ach	0.1 to 1.5[a]	0.45[d]	1.00	user-defined
Qsoil/Qbuilding	-	Qsoil_Qb	0.0003 to 0.03[b]	0.003	1.24	17
Building ventilation rate	m^3/hr	Qb	NA	247.1	0.3[c]	18
Average vapor flow into building	m^3/hr	Qsoil	NA	0.74	NA	19
Basement w/ dirt floor scenario						
Depth below grade to base of foundation	m	Lb	0.1-2.44[a]	2	NA	user-defined
Foundation thickness	m	Lf	NA	0	NA	user-defined
Fraction of foundation area with cracks	-	eta	NA	1.00 (100%)	1.00	user-defined
Enclosed space floor area	m^2	Abf	80 to 200[a]	150	NA	user-defined
Enclosed space mixing height	m	Hb	2.44 to 4.88[a]	3.66	0.25[c]	user-defined
Indoor air exchange rate	1/hr	ach	0.1 to 1.5[a]	0.45	1.00	user-defined

Input Parameter	Units	Variable Name	Range	Default Value	Coefficient of Variation	Equation Number
Qsoil/Qbuilding	-	Qsoil_Qb	0.0003 to 0.03[b]	NA	1.24	17
Building ventilation rate	m^3/hr	Qb	NA	247.1	0.3[c]	18
Average vapor flow into building	m^3/hr	Qsoil	NA	NA	NA	19
Closed crawl space w/ slab scenario						
Depth below grade to base of foundation	m	Lb	0.1-2.44[a]	1	NA	user-defined
Foundation thickness	m	Lf	0.1-0.15	0.1	NA	user-defined
Fraction of foundation area with cracks	-	eta	0.0001 to 0.001[a]	0.001 (0.1%)	1.00	user-defined
Enclosed space floor area	m^2	Abf	80 to 200[a]	150	NA	user-defined
Enclosed space mixing height	m	Hb	0.5 – 1.30	1.30	0.25[c]	user-defined
Indoor air exchange rate	1/hr	ach	0.1 to 1.5[a]	0.45	1.00	user-defined
Qsoil/Qbuilding	-	Qsoil_Qb	0.0003 to 0.03[b]	0.003	1.24	17
Building ventilation rate	m^3/hr	Qb	NA	87.8	0.3[c]	18
Average vapor flow into building	m^3/hr	Qsoil	NA	0.26	NA	19
Closed crawl space w/ dirt floor scenario						
Depth below grade to base of foundation	m	Lb	0.1-2.44[a]	1	NA	user-defined
Foundation thickness	m	Lf	NA	0	NA	user-defined
Fraction of foundation area with cracks	-	eta	NA	1.00 (100%)	1.00	user-defined
Enclosed space floor area	m^2	Abf	80 to 200[a]	150	NA	user-defined
Enclosed space mixing height	m	Hb	0.5 – 1.30	1.30	0.25[c]	user-defined
Indoor air exchange rate	1/hr	ach	0.1 to 1.5[a]	0.45	1.00	user-defined
Qsoil/Qbuilding	-	Qsoil_Qb	0.0003 to 0.03[b]	NA	1.24	17
Building ventilation rate	m^3/hr	Qb	NA	87.8	0.3[c]	18
Average vapor flow into building	m^3/hr	Qsoil	NA	NA	NA	19

Input Parameter	Units	Variable Name	Range	Default Value	Coefficient of Variation	Equation Number
Slab-on-grade scenario						
Depth below grade to base of foundation	m	Lb	0.1-2.44[a]	0.1	NA	user-defined
Foundation thickness	m	Lf	0.1-0.15	0.1	NA	user-defined
Fraction of foundation area with cracks	-	eta	0.00019 to 0.0019[a]	0.001	1.00	user-defined
Enclosed space floor area	m^2	Abf	80 to 200[a]	150	NA	user-defined
Enclosed space mixing height	m	Hb	2.13 to 3.05[a]	2.44	0.25[c]	user-defined
Indoor air exchange rate	1/hr	ach	0.1 to 1.5[a]	0.45	1.00	user-defined
Qsoil/Qbuilding	-	-	0.0003 to 0.03[b]	0.003	1.24	17
Building ventilation rate	m^3/hr	Qb	NA	164.7	0.3[c]	18
Average vapor flow into building	m^3/hr	Qsoil	NA	0.49	NA	19

a. U.S. EPA (2004)
b. U. S. EPA (2012)
c. CalTOX, Version 6.0
d. U.S. EPA (2011) and U.S. EPA (2012)

Table 10: Range of Values for Model Input Parameters: Vadose Zone Characteristics

Input Parameter	Units	Variable Name	Range	Default Value	Coefficient of Variation
Stratum thickness	m	hSX[a]	User-defined		
Stratum total porosity	-	ηSX[a]	Specific to soil texture, see Table 13[b]		
Stratum water-filled porosity	-	ηwSX[a]	Specific to soil texture, see Table 13[c,d]		
Stratum bulk density	g/cm^3	ρSX[a]	Specific to soil texture, see Table 13[b]		
Height of capillary fringe	m	hcz	Specific to soil texture, see Table 13		
Capillary zone total porosity	-	ncz	Specific to soil texture, see Table 13[e]		
Capillary zone water filled porosity	-	nwcz	Specific to soil texture, see Table 13[e]		

a. X=A, B, or C
b. Coefficients of variation based on Weaver and Tillman (2005)

c. U.S. EPA (2004)
d. Coefficients of variation based on Tillman and Weaver (2006)
e. Coefficients of variation based on CalTOX, Version 6.0

Table 11: Range of Values for Model Input Parameters: Exposure Parameters

Input Parameter	Units	Variable Name	Range	Default Value	Coefficient of Variation
Target risk for carcinogens	-	Target_CR	NA	1.00E-06	NA
Target hazard quotient for non-carcinogens	-	Target_HQ	NA	1	NA
Averaging time for carcinogens	yrs	ATc	NA	70	NA
Averaging time for non-carcinogens	yrs	ATnc	NA	30	NA
Exposure duration	yrs	ED	NA	26	NA
Exposure frequency	days/yr	EF	NA	350	NA
Exposure time	hrs/24 hrs	ET	NA	24	NA
Mutagenic mode-of-action factor	yrs	MMOAF	NA	76	NA

4.2 Sensitivity Analysis

Table 12 provides an indication of the effect of an increase in key input parameters on the predicted vapor concentration in the building. The results are shown as either an increase or a decrease in the in-building concentration ($C_{building}$). An increase in the building concentration will result in an increase in the risk when forward-calculating from an initial soil gas or groundwater concentration. When reverse-calculating to a risk-based “acceptable” soil gas or groundwater concentration, an increase in the hypothetical unit building concentration will result in a lower “acceptable” soil gas or groundwater concentration.

Table 12: Effect of an Increase in Input Parameter Values on In-Building Concentration (Cbuilding)

Input parameter increased	Effect on building concentration
Media initial concentration (C_{medium})[a]	Increase
Depth below grade to base of foundation (L_b)	Increase
Indoor air exchange rate (ach)	Decrease

Building volume[b](L_b xA_b)	Decrease
Soil total porosity (nSX[c])	Increase
Soil dry bulk density (rhoSX[c])	Decrease

[a] This parameter is applicable only when forward-calculating risk.

[b] Used with building air exchange rate to calculate building ventilation rate.

[c] Where X=soil stratum A, B, or C

4.3 Soil related input values

Soil-dependent properties are provided in Table 13 for soils classified according to the US SCS system. If site soils are not classified according to the US SCS, Table 14 can be used to assist in selecting an appropriate SCS soil type corresponding to the available site lithologic information. Note that the selection of the soil texture class should be biased towards the coarsest soil type of significance, as determined by the site characterization program.

Table 13: Soil-Dependent Properties for the Vapor Intrusion Model

SCS Soil Name	**Total porosity**	**Water-filled porosity**	**Bulk density**	**Saturated hydraulic conductivity (class average)**	**Capillary zone water filled porosity**	**Capillary zone height**
	n	*nw*	*rho*	*Ks*	*n,cz*	*h,cz*
	(cm³/cm³)	*(cm³/cm³)*	*(g/cm³)*	*(cm/h)*	*(cm³/cm³)*	*(cm)*
Clay	0.459	0.215	1.43	0.61	0.412	81.52
Clay Loam	0.442	0.168	1.48	0.34	0.375	46.88
Loam	0.399	0.148	1.59	0.50	0.332	37.50
Loamy Sand	0.390	0.076	1.62	4.38	0.303	18.75
Sand	0.375	0.054	1.66	26.78	0.253	17.05
Sandy Clay	0.385	0.197	1.63	0.47	0.355	30.00
Sandy Clay Loam	0.384	0.146	1.63	0.55	0.333	25.86
Sandy Loam	0.387	0.103	1.62	1.60	0.320	25.00
Silt	0.489	0.167	1.35	1.82	0.382	163.04
Silt Loam	0.439	0.18	1.49	0.76	0.349	68.18

Silty Clay	0.481	0.216	1.38	0.40	0.424	192.31
Silty Clay Loam	0.482	0.198	1.37	0.46	0.399	133.93

SCS Soil Name	**van Genuchten parameter**[a]	**van Genuchten curve shape parameter**	**van Genuchten parameter [(1/(1-N)]**	**van Genuchten soil water retention parameter**	**Mean grain diameter**	**nw range**
	a_1	*N*	*M*	q_r	*(-)*	*(-)*
	(1/cm)	*(-)*	*(-)*	*(cm^3/cm^3)*	*(cm)*	*(cm^3/cm^3)*
Clay	0.01496	1.253	0.2019	0.098	0.0092	0.098 - 0.33
Clay Loam	0.01581	1.416	0.2938	0.079	0.016	0.079 - 0.26
Loam	0.01112	1.472	0.3207	0.061	0.020	0.061 - 0.24
Loamy Sand	0.03475	1.746	0.4273	0.049	0.040	0.049 - 0.1
Sand	0.03524	3.177	0.6852	0.053	0.044	0.053 - 0.055
Sandy Clay	0.03342	1.208	0.1722	0.117	0.025	0.117 - 0.28
Sandy Clay Loam	0.02109	1.330	0.2481	0.063	0.029	0.063 - 0.23
Sandy Loam	0.02667	1.449	0.3099	0.039	0.030	0.039 - 0.17
Silt	0.00658	1.679	0.4044	0.050	0.0046	0.05 - 0.28
Silt Loam	0.00506	1.663	0.3987	0.065	0.011	0.065 - 0.3
Silty Clay	0.01622	1.321	0.2430	0.111	0.0039	0.11 - 0.32
Silty Clay Loam	0.00839	1.521	0.3425	0.090	0.0056	• - 0.31

[a] Point of inflection in the water retention curve where dn/dh is maximal, with n equal to the water filled porosity in the capillary zone and h equal to air-entry pressure head (cm).

Table 14: Recommendations for Selection of Soil Type

If your boring log indicates that the following materials are the predominant soil types:	**Then you should use the following texture classification when obtaining the attenuation factor:**
Sand or Gravel or **Sand and Gravel**, with less than about 12 % fines, where “fines” are smaller than 0.075 mm in size.	Sand
Sand or Silty Sand, with about 12 % to 25 % fines	Loamy Sand

Silty Sand, with about 20 % to 50 % fines	Sandy Loam
Silt and Sand or Silty Sand or Clayey, Silty Sand or Sandy Silt or Clayey, Sandy Silt, with about 45 to 75 % fines	Loam
Sandy Silt or Silt, with about 50 to 85 % fines	Silt Loam

These input parameters were developed from the best available soil-physics science, available studies of building characteristics, and expert opinion. The following sections provide justification for the building-related and soil-dependent input parameter values selected as default values for the J&E Model.

4.4 Justification of default soil properties

The default soil-dependent parameters (Table 13) represent mean or typical values, rather than the most conservative value, in order to avoid overly conservative estimates of attenuation factors and indoor air concentration. Consequently, selecting a soil type and corresponding typical soil property value may not accurately or conservatively represent a given site. Note also that Table 7does not provide estimates of soil properties for very coarse soil types, such as gravel, gravelly sand, and sandy gravel, etc., which also may be present in the vadose zone. In cases where the vadose zone is characterized by very coarse materials, the J&E Model may not provide a conservative estimate of the attenuation factor.

The J&E Model is sensitive to the value of soil moisture content. Unfortunately, little information exists on measured moisture contents below buildings. Therefore, the typical approach is to use a water retention model (e.g., van Genuchten model) to approximate moisture contents. For the unsaturated zone, the selected default value for soil moisture is a value equal to halfway between the residual saturation value and field capacity, using the van Genuchten model-predicted values for U.S. SCS soil types. For the capillary transition zone, a moisture content corresponding to the air entry pressure head is calculated by using the van Genuchten model. When compared to other available water retention models, the van Genuchten model yields somewhat lower water contents, which results in more conservative estimates of attenuation factor. The soil moisture contents listed in Table 7 are based on agricultural samples, which are likely to have higher water contents than soils below building foundations and, consequently result in less-conservative estimates of the attenuation factor.

The values for the mean grain diameter for the U.S. SCS soil types in Table 12 are taken from Nielson and Rogers (1990). These values are used to calculate the height of the capillary fringe via Equation 7b (h_{cz} = 0.15/[0.2*(Mean Grain Diameter)]). This equation is a simplified version of Equation 7a, as the model assumes a groundwater temperature between 5°C and 25°C (as described above in Section 2.3). The larger the mean grain diameter, the smaller the capillary fringe height will be. This approach to calculating the capillary fringe values leads to a value for clay much larger than for silty clay loam, silt, and silty clay, as clay includes more sand-sized (and therefore larger) particles than those other classifications.

4.5 Justification of default building properties

4.5.1 Indoor Air Exchange Rate (AEH)

The default indoor air exchange rate in Version 6.0 is 0.45 AEH and is listed in the model in row 43. EPA changed this default value from the previous version of the model, which used a default of 0.25 AEH. The new default value is based on information presented in the Exposure Factors Handbook (U.S. EPA, 2011), which recommends a median air exchange rate of 0.45 air changes per hour (ACH) based on an analysis of multiple studies involving nearly 3,000 measurements by Koontz and Rector (1995). This value is the central estimate of air changes per hour across all census regions. The analysis by Koontz and Rector is considered the best available data on air exchange rates in the United States (U.S. EPA, 2011).

Koontz and Rector used statistical techniques to correct for the geographic and seasonal imbalances in the data. They found the 10th, 50th and 90th percentile values were 0.18, 0.45, and 1.26 ACH, respectively. In a previous analysis of the same database, Murray and Burmaster (1995) considered seasonal and climatic effects. They found air exchange rates varied depending on season and climatic region, with lower air exchange rates in winter months and colder climates and higher exchange rates in summer months and warmer climates. Vapor intrusion is expected to be of most concern during colder periods (when house depressurization due to the stack effect is expected to be most significant).

4.5.2 Fraction of Foundation Area with Cracks (eta)

The default value for the fraction of the foundation area with cracks (crack ratio) is 0.001 for basement or closed crawl space with slab house and for slab-on-grade house; 1.00 for basement or closed crawl space with dirt floor. The model displays this value on row 35 in the MODEL sheet. The crack ratio is related to the crack width. Assuming a square house and that the only crack is a continuous edge crack between the foundation slab and wall ("perimeter crack"), the crack ratio (CR) and crack width (CW) are related as follows:

$$CR = CW \ \times 4 \times (Surface\ Foundation\ Area)^{\left(\frac{0.5}{Subsurface\ Foundation\ Area}\right)}$$

Little information is available on crack width or crack ratio. One approach used by radon researchers is to back-calculate crack ratios using a model for soil gas flow through cracks and the results of measured soil gas flow rates into a building. For example, the back-calculated values for a slab/wall edge crack based on soil gas-entry rates reported in Little *et al.* (1992),Revzan *et al.* (1991), and Nazaroff *et al.* (1985) range from about 0.0001 to 0.001. Another possible approach is to measure crack openings, although in practice these measurements are difficult to do. Figley and Snodgrass (1993) present data from 10 houses where edge crack measurements were made. At the eight houses where cracks were observed, the crack widths ranged from hairline cracks up to 5 mm wide, while the total crack length per house ranged from 2.5 m to 17.3 m. Most crack widths were less than 1 mm. The suggested defaults for crack ratio in regulatory guidance, literature, and models also vary. In ASTM E1739-95, a default crack ratio of 0.01 is used. The crack ratios suggested in the VOLASOIL model (developed by the Dutch Ministry of Environment, Waitz et al 1996) range from 0.0001 to 0.000001. The VOLASOIL model values correspond to values for a "good" and "bad" foundation, respectively. The crack ratio used by Johnson and Ettinger (1991) for illustrative purposes ranged from 0.001 to 0.01. The selected default values fall within the ranges observed.

4.5.3 Enclosed Space Floor Area (A_{bf})

The default building area is 150 m^2, based on the following information:

1. Default values used in the Superfund User's Guide (9.61 m by 9.61 m or 92.4 m^2)
2. Default values used by the Michigan Environmental Science Board (2001), as documented in Part 201, Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria: Technical Support Document (10.5 m by 10.5 m of 111.5 m^2).

The Michigan document (2001) indicates that the 111.5 m^2 area approximately corresponds to the 10th percentile floor space area for a residential single-family dwelling, based on statistics compiled by the U.S. Department of Commerce (DOC) and U.S. Housing and Urban Development (HUD). The subsurface foundation area is a function of the building area, and depth to the base of the foundation, which is fixed. This value, however, is easy to measure at a site, and site specific information should always be used if possible.

For commercial buildings, we used a value of 1500m^2 – this is the median value reported in the Department of Energy's (DOE) Commercial Buildings Energy Consumption Survey (CBECS) microdata (DOE 2012), after filtering out buildings without basements. This survey is national survey of commercial buildings, first conducted in 1979, and included a sample of 6,710 buildings in 50 states and DC, and is referenced in the EPA exposure factors handbook (US EPA, 2011). We used the median, rather than the average, to control for outliers – in this case, very large shopping malls.

4.5.4 Enclosed Space Mixing Height (H_b)

For residential properties, the default value for the enclosed space mixing height is 2.44 m for slab-on-grade scenario; 3.66 m for both basement scenarios; and 1.30 m for both closed crawl space scenarios.

The J&E Model assumes that subsurface volatiles migrating into the building are completely mixed within the building volume, which is determined by the building area and mixing height. The building mixing height will depend on a number of factors including building height; heating, ventilation, and air conditioning (HVAC) system operation, environmental factors such as indoor-outdoor pressure differentials and wind loading, and seasonal factors. For a single-story house, the variation in mixing height can be approximated by using the room height. For a multi-story house or apartment building, the mixing height will be greatest for houses with HVAC systems that result in significant air circulation (e.g., forced-air heating systems). Mixing heights would likely be less for houses with electrical baseboard heaters. It is likely that mixing height is, to some degree, correlated to the building air exchange rate.

Little data are available that provide for direct inference of mixing height. There are few sites, with a small number of houses where indoor air contaminant concentrations were above background, and where both measurements at ground level and the second floor were made (Colorado Department of Transportation (CDOT), Redfields, Eau Claire). Persons familiar with the data sets for these sites indicate that in most cases a fairly significant reduction in concentrations (factor of two or greater) was observed, although at one site (Eau Claire, “S” residence), the indoor trichloroethylene (TCE) concentrations were similar in both the basement and second floor of the house. For the CDOT site apartments, there was an approximate five-fold reduction between the concentrations measured for the first floor and second floor units (Mr. Jeffrey Kurtz, EMSI, personal communication, June 2002). Less mixing would be expected for an apartment because there are fewer cross-floor connections than for a house. The value chosen for a basement house scenario (3.66 m) would be representative of a two-fold reduction or attenuation in vapor concentrations between floors. The user may change these values based on site-specific data.

For commercial buildings, we used the medium floor height reported for building with basements from the CBECS survey, which was 3 m (US DOE 2012). As reported above, this value only applies for single story buildings with basements, and may be different due to ventilation systems or attenuation across multiple floors.

4.5.5 $Q_{soil}/Q_{building}(Q_{soil\_}Q_b)$

This version of the J&E Model allows the user to input the value for $Q_{soil}/Q_{building}$ for slab-on-grade or basement with slab floor foundation or enter site specific values for Q_{soil} and $Q_{building}$ independently. In default mode, using the ratio, the user may elect to keep the default value of 0.003 or enter a value based on site-specific data.[2] The model then calculates the building ventilation rate ($Q_{building}$) and the average vapor flow rate into the building (Q_{soil}) from this ratio and the specified air exchange rate in the building. If the user chooses the default values for $Q_{soil}/Q_{building}$, the Q_{soil} calculated is 0.49 m^3/hr for slab-on-grade and 0.74 m^3/hr for

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[2] This value for $Q_{soil}/Q_{building}$ is based on the observed median value from the US EPA’s vapor intrusion database (US EPA 2012). This value is not applicable to buildings with dirt floors.

basement with slab foundation. The model adjusts this ratio if the user specifies a site-specific air exchange rate (ach), which would affect $Q_{building}$.

The previous version of the J&E Model allowed the user to choose whether to input values of Q_{soil} or to permit the model to calculate Q_{soil}. The calculation of Q_{soil} was based on other input parameters and allowed the model to potentially calculate unreasonable Q_{soil} values. This version allows the user to use a ratio for $Q_{soil}/Q_{building}$, as recommended in an analysis by Johnson (2002), *or* enter site specific data for Q_{soil} and $Q_{building}$.

Johnson (2002) suggested a reasonable range of $Q_{soil}/Q_{building}$values of 0.0001 to 0.05 based on a review of the literature. Published ranges of values for $Q_{soil}/Q_{building}$ include 0.003 to 0.001 (Fischer et al., 1996), 0.003 to 0.02 (Mose and Mushrush, 1999), 0.0016 (Little et al., 1992), and 0.00006 to 0.0002 (Olson and Corsi, 2001). The default value used in Version 6.0 is 0.003, based on the median values reported in US EPA 2012.

4.6 Default Assumptions Disclaimer

The default values in this spreadsheet tool were developed and included as a starting point for site specific investigations. Whenever possible, default values should be replaced with measured data. Some default values, specifically Q_S/Q_B and eta (η), are assigned for illustrative purposes, and are intended to be used for exploratory analyses. Because there are limited values available in the literature for reasonable estimates, these parameters are subject to uncertainty. Users are encouraged to try a range of values for these parameters to see how they impact the final result and understand the sensitivity of the model. The input parameters listed in Tables 7-13 are considered default parameters for a first-tier assessment, which should in most cases provide a reasonably (but not overly) conservative estimate of the vapor intrusion attenuation factor for a site.

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