

Screening for Environmental Hazards at Sites with Contaminated Soil and Groundwater

Volume 2: Background Documentation for the Development of Tier 1 Environmental Action Levels

Appendices 2-9

Prepared by:

**Hawai'i Department of Health
Environmental Management Division
919 Ala Moana Blvd
Honolulu, Hawai'i 96814**

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Contacts:

Roger Brewer
Hawai'i Department of Health
Environmental Management Division
Hazard Evaluation and Emergency Response
Telephone: 1-808-586-4249
E-mail: roger.brewer@doh.hawaii.gov
<http://hawaii.gov/health/environmental/hazard/index.html>

OR

Roxanne Kwan
Hawai'i Department of Health
Environmental Management Division
Solid and Hazard Waste Branch
Telephone: 1-808-586-4226
E-mail: roxanne.kwan@doh.hawaii.gov

DISCLAIMER

This document, *Evaluation of Environmental Hazards at Sites with Contaminated Soil and Groundwater* (Fall 2011), is a technical report prepared by staff of the Hawai'i Department of Health (HDOH), Environmental Management Division. The document updates and replaces the document *Screening for Environmental Concerns at Sites with Contaminated Soil and Groundwater* (Interim Final, March 2009 and interim updates).

The document provides guidance for identification and evaluation of environmental hazards associated with contaminated soil and groundwater. The Environmental Action Levels (EALs) presented in this document and the accompanying text are specifically *not* intended to serve as: 1) a stand-alone decision making tool, 2) guidance for the preparation of baseline environmental risk assessments, 3) a rule to determine if a waste is hazardous under the state or federal regulations, or 4) a rule to determine when the release of hazardous substances must be reported to the HDOH.

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VOLUME 2: BACKGROUND DOCUMENTATION FOR THE DEVELOPMENT OF TIER 1 SOIL AND GROUNDWATER ACTION LEVELS

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GLOSSARY OF TERMS

AWQC: Aquatic Water Quality Criteria
CCC: Criterion for Continuous Concentration
CCM: Criterion for Maximum Concentration
EPA: Environmental Protection Agency
ESL: Environmental Screening Level
FVC: Final Chronic Value
HIDOH: Hawai'i Department of Health
HH: Human Health-consumption of aquatic organisms
LOEL: Lowest-Observed-Effects Level
MADEP: Massachusetts Department of Environmental Protection
MCL: Maximum Concentration Level
MOEE: Ontario Ministry of Environment and Energy
MTBE: Methyl tert-Butyl Ethylene
PCE: Tetrachloroethylene
PRG: Preliminary Remediation Goals
RBSL: Risk-Based Screening Level
RSL: Regional Screening Level
RWQCB: Regional Water Quality Control Board
TPH: Total Petroleum Hydrocarbons
USEPA: U.S. Environmental Protection Agency
USDOE: U.S. Department of Energy

APPENDIX 2

SUMMARY OF HUMAN HEALTH DIRECT
EXPOSURE MODELS AND DEFAULT INPUT
PARAMETER VALUES

USEPA REGIONAL SCREENING LEVELS USER'S
GUIDE (JUNE 2011, TEXT ONLY)

EQUATIONS FOR DERIVATION OF RISK-BASED SCREENING LEVELS FOR SOIL, INDOOR AIR AND DRINKING WATER

1.0 Introduction

This appendix summarizes models and exposure assumptions used to generate risk-based action levels for soil, tapwater and indoor air that are incorporated into the HDOH Tier 1 Environmental Action Levels presented in Appendix 1. Risk-based action levels for soil and tapwater follow models and assumptions used to develop the USEPA Regional Screening Levels (RSLs, USEPA 2011). The RSLs represent a consolidation of Preliminary Remedial Goals (PRGs) previously published by individual USEPA regions. Previous editions of the HDOH guidance in particular referenced PRGs developed and published by USEPA Region IX (USEPA 2004a).

A copy of the 2011 USEPA RSL User's Guide is attached. This document presents a detailed discussion of the equations and assumptions used to calculate the RSLs. Risk-based soil action levels were developed for the following exposure scenarios:

- Residential direct exposure;
- Commercial/Industrial;
- Construction/Trench Workers.

The USEPA soil RSLs take into account the following routes of exposure:

- Incidental ingestion;
- Inhalation of vapors or dust;
- Dermal absorption.

Soil exposure assumptions for the Outdoor (vs indoor) Worker RSLs were referred to for incorporation in the Appendix 1 lookup tables (refer to Table I-2 in Appendix 1). The primary difference is an assumed soil ingestion rate of 100 mg/day vs 50 mg/day, respectively.

The USEPA RSL guidance only presents risk-based soil action levels for residential and commercial/industrial land use scenarios. A third set of action levels is incorporated into the HDOH Tier 1 EALs for construction and trench workers. A summary of exposure assumptions for all scenarios is provided in Table 1. References for the development of this exposure scenario are discussed in more detail below and in Appendix 1. The soil action levels can be used in site-specific Environmental Hazard Evaluations to evaluate in contaminants in deep or otherwise isolated soils to help target remedial efforts.

Soil action levels for contaminants that pose noncancer health risks were calculated for a target hazard quotient of both 1.0, following the approach used by USEPA, as well as more conservative hazard quotient of 0.2. Soil action levels based on a hazard quotient of 0.2 are carried forward for inclusion in the Tier 1 EAL lookup tables (refer to table A, B and I series). This was done in order to take into account potential cumulative effects posed by the presence of multiple contaminants with similar health effects. In most instances, this results in HDOH soil action levels for noncancer concerns that are one-fifth of the USEPA RSLs. In cases where the USEPA RSL exceeds the theoretical soil saturation level for a given chemical (C_{sat}), however, the difference will be less. As discussed in Appendix 1, C_{sat} is used as the upper limit for direct exposure soil action levels. The USEPA RSL and adjusted DOH action level will be identical both if the RSL and the DOH action level exceed this value. HDOH action levels for some chemicals may also differ slightly from the original USEPA RSL due to rounding inconsistencies between input values in the respective HDOH and USEPA spreadsheets.

The USEPA RSLs for tapwater take into account a similar set of assumed exposure routes:

- Direct ingestion of water;
- Inhalation of vapors during showering or other activities.

Equations used to develop the RSLs and similarly used to develop action levels for this guidance are presented in the attached USEPA RSL User's Guide.

The soil leaching model used in the USEPA RSL guidance was not referred to for use in the Tier 1 EALs. An alternative model used to develop soil action levels for this potential environmental hazard is discussed in Appendix 1.

2.0 Construction/Trench Workers Exposure Scenario

Direct-exposure screening levels for deep soils are calculated based on a construction/trench worker exposure scenario. Exposure assumptions are summarized in Table 1. The assumed exposed skin area and soil ingestion rate are based on guidance presented in the Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites (USEPA 2002). The inhalation rate, body weight, averaging time and target hazard quotient are set equal to assumptions used in the USEPA RSLs (USEPA 2011) for consistency with screening levels for occupational exposure assumptions. The soil adherence factor is taken from trench-worker exposure scenario assumptions developed by the Massachusetts Department of Environmental Protection for use in calculating screening levels for Deep soils (MADEP 1994).

The Massachusetts Department of Environmental Protection assumes exposure durations of three months for noncarcinogens (plus use of subchronic RfDs) and seven years for carcinogens. A seven year (versus three month) exposure duration for carcinogens is used in part because shorter exposure durations were considered to be beyond the limits of cancer risk models. For the purposes of this document, a one-time, three month exposure duration to exposed soils at a site was considered to be inadequate. This may be particularly true for utility workers who re-visit a site numerous times over several years for routine maintenance of underground utilities. As noted in Table 1, a total exposure duration of seven years is assumed for both carcinogens and noncarcinogens. An exposure frequency of 20 days (4 weeks) per year for 7 years yields a total of 140 days total exposure. Construction workers may receive 140 days (roughly 6 months) of exposure in a single year and never visit the site again. Using chronic RfDs (generally less stringent than subchronic RfDs) and spreading the total exposure time over seven years is somewhat conservative but is consistent with the utility worker scenario. A target risk of 1E-06 was used to calculate soil screening levels for carcinogens. A target hazard quotient of 0.2 was used to calculate soil screening levels for noncarcinogens. This is consistent with assumption used to develop screening levels for residential and industrial/commercial exposure scenarios.

The emission of vapors from contaminated soil is based on part on the calculation of a "Volatilization Factor" on a chemical-specific basis (USEPA 2011, see equation in attached RSL guidance manual). A key parameter in this calculation is the term "Q/C," defined as the inversion of the ratio of the mean concentration of a VOC in air to the volatilization flux at the center of site (see VF equation in attachment). A default value of 68.81 is assigned to Q/C for standard residential and commercial/industrial site scenarios. A default Q/C value of 14.31 is assigned for use in trench worker exposure models for calculation of soil action levels for VOCs in order to take into account the potential for poor air flow in trenches (see Table I-3 in Appendix 1).

"Particulate Emission Factors (PEFs)" are intended to relate the concentration of a chemical in soil to the concentration of the chemical in air-borne dust. The PEF used for residential and occupational exposure scenarios (1.316×10^9 mg-kg/mg/m³) was taken directly from the USEPA Region IX Preliminary Remediation Goals guidance document (USEPA 2011). The PEF reflects a concentration of air-borne particulate matter of approximately 0.76 ug/m³. This PEF and associated concentration of air-borne dust was not considered to be adequately conservative of conditions that may occur at construction sites. A revised PEF for this exposure scenario was derived through use of a "Dust Emission Factor" for construction sites developed by the USEPA. The Dust Emission Factor of 1.2 tons of dust per month, per acre is based on USEPA field studies at apartment complex and commercial center developments in semi-

arid areas (USEPA 1974, 1985). Derivation of the construction-site PEF is summarized in Table 4. The derived PEF (1.44E+06 mg-kg/mg/m³) corresponds to a concentration of air-born dust of approximately 700 ug/m³.

3.0 INDOOR AIR

Target levels for indoor air were calculated based on equations incorporated into vapor intrusion spreadsheets published by the USEPA (USEPA 2004b). Refer to Appendix 4 for a copy of this guidance and a more detailed discussion of the equations. The equations are reproduced below for reference.

Equation 1: Residential Exposures to Carcinogenic Contaminants in Indoor Air

$$C_{air}(ug / m^3) = \frac{TR \times AT_c}{EF_{res} \times ED_{res} \times URF}$$

Equation 2: Occupational Exposures to Carcinogenic Contaminants in Indoor Air

$$C_{air}(ug / m^3) = \frac{TR \times AT_c}{EF_{occ} \times ED_{occ} \times URF}$$

Equation 3: Residential Exposures to Noncarcinogenic Contaminants in Indoor Air

$$C_{air}(ug / m^3) = \frac{THQ \times AT_{nc} \times RfC}{EF_{res} \times ED_{res}}$$

Equation 4: Occupational Exposures to Noncarcinogenic Contaminants in Indoor Air

$$C_{air}(ug / m^3) = \frac{THQ \times AT_{nc} \times RfC}{EF_{occ} \times ED_{occ}}$$

where URF is the unit risk factor carcinogens (ug/m³)⁻¹ for and RfC carcinogens (ug/m³) is the reference concentration for noncarcinogens. A summary of URFs and RfCs for specific chemicals is provided in Table H and E-3 of Appendix 1.

REFERENCES

- MADEP, 1994, *Background Documentation for the Development of the MCP Numerical Standards*: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, April 1994.
- USEPA, 1974, *Development of Emission Factors for Fugitive Dust Sources*: U.S. Environmental Protection Agency, Publication No. EPA-450/3-74-037, (prepared by Cowherd, C., Axetell, K., Guenther, C., and Jutze, G., Midwest Research Institute).
- USEPA, 1985, *Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources*: U.S. Environmental Protection Agency, Office of Air and Radiation, Publication No. AP-42, Fourth Edition, September 1985.

- USEPA, 2002, Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites: U.S. Environmental Protection Agency, Solid Waste and Emergency Response, OSWER 9355.4-24, December 2002.
- USEPA, 2004a, Preliminary Remediation Goals: U.S. Environmental Protection Agency, Region IX, October 2002, www.epa.gov/region09/waste/sfund/prg/intro.htm.
- USEPA, 2004b, *User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion Into Buildings*: U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, www.epa.gov/oerrpage/superfundrisk/airmodel/.
- USEPA, 2011a, *Regional Screening Levels*: U.S. Environmental Protection Agency, June 2011, prepared by Oak Ridge National Laboratories, <http://epaprgs.ornl.gov/chemicals/index.shtml>
- USEPA, 2011b, *Exposure Factors Handbook*: U.S. Environmental Protection Agency, Office of Research and Development. September 2011, EPA/600/R-090/052F www.epa.gov

**TABLE 1. HUMAN EXPOSURE PARAMETER DEFINITIONS
AND DEFAULT VALUES**

Symbol	Definition (units)	Default	References (refer to USEPA 2002 for full references)
CSFo	Cancer slope factor oral (mg/kg-d) ⁻¹	--	Chemical specific - Appendix 1, Table H
CSFi	Cancer slope factor inhaled (mg/kg-d) ⁻¹	--	Chemical specific - Appendix 1, Table H
RfDo	Reference dose oral (mg/kg-d)	--	Chemical specific - Appendix 1, Table H
RfDi	Reference dose inhaled (mg/kg-d)	--	Chemical specific - Appendix 1, Table H
TRr/o	Target cancer risk - residential, occupational/ industrial exposure scenario	10 ⁻⁶	USEPA 2011a. See Appendix 1 Table I series and text for exceptions
*TRctw	Target cancer risk - construction/trench worker exposure scenario	10 ⁻⁵	HIDOH (see Appendix 1)
THQ	Target hazard quotient	0.2	USEPA 2011a. See Appendix 1 Table I series and text for exceptions
BWa	Body weight, adult (kg)	70	USEPA 2011a
BWc	Body weight, child (kg)	15	USEPA 2011a
ATc	Average time – carcinogens (days)	25,550	USEPA 2011a
ATn	Average time – noncarcinogens (days)	ED*365	USEPA 2011a
SAar	Exposed surface area, adult res. (cm ² /day)	5,700	USEPA 2011a
SAaw	Exposed surface area, adult occ. (cm ² /day)	3,300	USEPA 2011a
SAC	Exposed surface area, child (cm ² /day)	2,800	USEPA 2011a
*SAac/tw	Exposed surface area, construction/trench worker (cm ² /day)	5,800	USEPA 2011b
AFar	Adherence factor, adult res. (mg/cm ²)	0.07	USEPA 2011a
AFaw	Adherence factor, occupational (mg/cm ²)	0.20	USEPA 2011a
*AFctw	Adherence factor, construction/trench worker (mg/cm ²)	0.51	Massachusetts DEP (1994)
AFc	Adherence factor, child (mg/cm ²)	0.20	USEPA 2011a
ABS	Skin absorption (unitless): chemical specific	--	USEPA 2011a
IRAA	Inhalation rate – adult (m ³ /day)	20	USEPA 2011a
IRAc	Inhalation rate – child (m ³ /day)	10	USEPA 2011a
*IRActw	Inhalation rate – construction/trench worker (m ³ /day)	20	USEPA 2011b
IRWa	Drinking water ingestion – adult (L/day)	2	USEPA 2011a
IRWc	Drinking water ingestion – child (L/day)	1	PEA Cal-EPA (DTSC, 1994)
IRSa	Soil ingestion – adult (mg/day)	100	USEPA 2011a
IRSc	Soil ingestion – child (mg/day)	200	USEPA 2011a)
IRSo	Soil ingestion – occupational (mg/day)	50	USEPA 2011a
*IRSctw	Soil ingestion–construction/trench worker (mg/day)	330	USEPA 2002
Efr	Exposure frequency – residential (d/y)	350	USEPA 2011a
Efo	Exposure frequency – occupational (d/y)	250	USEPA 2011a
*EFctw	Exposure frequency – construction/trench worker (d/y)	20	Massachusetts DEP (1994)
EDr	Exposure duration – residential (years)	30	USEPA 2011a
EDc	Exposure duration – child (years)	6 ^a	USEPA 2011a
EDo	Exposure duration – occupational (years)	25	USEPA 2011a
*EDctw	Exposure duration – construction/trench worker (years)	7	modified from Massachusetts DEP (1994)
IFSadj	Ingestion factor, soils ([mg-yr]/[kg-d])	114	USEPA 2011a
SFSadj	Skin contact factor, soils ([mg-yr]/[kg-d])	361	USEPA 2011a
InhFadj	Inhalation factor ([m ³ -yr]/[kg-d])	11	USEPA 2011a
IFWadj	Ingestion factor, water ([l-yr]/[kg-d])	1.1	USEPA 2011a
VFw	Volatilization factor for water (L/m ³)	0.5	USEPA 2011a
PEFres/oc	Particulate emission factor (m ³ /kg) - residential/occupational exposure scenarios	1.32E+09	USEPA 2011a
*PEFctw	Particulate emission factor (m ³ /kg) - construction/trench worker exposure scenarios	1.44E+06	Based on Construction Site Dust Emission Factors (USEPA 1974, 1985). See attached table.
VFs	Volatilization factor for soil (m ³ /kg)	-	Chemical specific (USEPA 2002, 2011a)
sat	Soil saturation concentration (mg/kg)	-	Chemical specific (USEPA 2002, 2011a)

**TABLE 2. VOLATILIZATION FACTOR PARAMETER DEFINITIONS
AND DEFAULT VALUES**

Parameter	Definition (units)	Default
VF_s	Volatilization factor M^3/kg	--
D_A	Apparent diffusivity (cm^2/s)	--
$Q/C_{default}$	Inverse of the mean conc. at the center of a 0.5-acre square source ($g/m^2\text{-s}$ per kg/m^3)	68.81 (USEPA 2011a)
Q/C_{trench}	Inverse of the mean conc. at the center of a 0.5-acre square source ($g/m^2\text{-s}$ per kg/m^3)	14.31 (USEPA 2002)
T	Exposure interval (s)	9.5×10^8
ρ_b	Dry soil bulk density (g/cm^3)	1.5
θ_a	Air filled soil porosity (L_{air}/L_{soil})	0.28 or n-w
n	Total soil porosity (L_{pore}/L_{soil})	0.43 or $1 - (b/s)$
θ_w	Water-filled soil porosity (L_{water}/L_{soil})	0.15
ρ_s	Soil particle density (g/cm^3)	2.65
D_i	Diffusivity in air (cm^2/s)	Chemical-specific
H	Henry's Law constant ($atm\text{-}m^3/mol$)	Chemical-specific
H'	Dimensionless Henry's Law constant	Calculated from H by multiplying by 41 (USEPA 1991a)
D_w	Diffusivity in water (cm^2/s)	Chemical-specific
K_d	Soil-water partition coefficient (cm^3/g) = $K_{oc} \times f_{oc}$	Chemical-specific
K_{oc}	Soil organic carbon-water partition coefficient (cm^3/g)	Chemical-specific
f_{oc}	Fraction organic carbon in soil (g/g)	0.006 (0.6%)

TABLE 3. PARTICULATE EMISSION FACTOR PARAMETER DEFINITIONS AND DEFAULT VALUES - RESIDENTIAL/OCCUPATIONAL SCENARIOS

Parameter	Definition (units)	Default
*PEF	Particulate emission factor (m ³ /kg)	1.316 x 10 ⁹
Q/C	Inverse of the mean concentration at the center of a 0.5-acre-square source (g/m ² -s per kg/m ³)	90.80
V	Fraction of vegetative cover (unitless)	0.5
Um	Mean annual windspeed (m/s)	4.69
Ut	Equivalent threshold value of windspeed at 7 m (m/s) 11.32	11.32
F(x)	Function dependent on Um/Ut derived using Cowherd (1985) (unitless)	0.194

* Concentration dust in air (mg/m³) = 1/(PEF x (1 kg/1,000,000 mg)) = 0.0007 mg/m³

**TABLE 4. PARTICULATE EMISSION FACTOR FOR
CONSTRUCTION/TRENCH WORKER EXPOSURE SCENARIO**

Dust Generated (moderate to heavy construction) (M_{dust}):			
Dust Emission Factor (EF):	1.2 2400 1089	tons/mo-acre lbs/mo-acre kgs/mo-acre	USEPA 1974, 1985 conversion conversion
Volume Air Passing Over Site Per Month Per Acre (V_{air}):			
Length Perpendicular To Wind (L):	1 43560 4047 64	acre ft ² m ² m	Default EF area conversion conversion $L=Area^{0.5}$
Air Mixing Zone Height (MZ):	2	m	model assumption
Ave Wind Speed (V):	4.69	m/s	USEPA 2004 (default PRG value)
Seconds per 30.4 Day Month (S):	2.63E+06	sec/month	conversion
Volume Air (Volume-air):	1.57E+09	m ³	$Volume-air=L \times MZ \times V \times S$
Average Concentration Dust in Air ($C_{dust-air}$):			
Concentration Dust ($C_{dust-air}$):	6.95E-07 0.695	kg/m ³ mg/m ³	$(C_{air} = M_{dust}/Volume-air)$ conversion
Particulate Emission Factor (PEF):			
Concentration soil in dust ($C_{dust-soil}$):	1,000,000	mg/kg	Model assumption - 100% (1000000 mg/kg) of dust is derived from on-site soil.
PEF:	1.44E+06	(mg/kg)/ (mg/m ³)	$PEF=C_{dust-soil}/C_{dust-air}$

Attachment

Text of USEPA Region IX Preliminary Remediation Goals Document (June 2011)



Mid-Atlantic Risk Assessment

You are here: [EPA Home](#) ` [Mid-Atlantic Risk Assessment](#) Regional Screening Table - User's Guide

User's Guide (May 2011)

Disclaimer

Table of Contents

This guidance sets forth a recommended, but not mandatory, approach based upon currently available information with respect to risk assessment for response actions at CERCLA sites. This document does not establish binding rules. Alternative approaches for risk assessment may be found to be more appropriate at specific sites (e.g., where site circumstances do not match the underlying assumptions, conditions and models of the guidance). The decision whether to use an alternative approach and a description of any such approach should be documented for such sites. Accordingly, when comments are received at individual CERCLA sites questioning the use of the approaches recommended in this guidance, the comments should be considered and an explanation provided for the selected approach.

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It should also be noted that the screening levels (SLs) in these tables are based upon human health risk and do not address potential ecological risk. Some sites in sensitive ecological settings may also need to be evaluated for potential ecological risk. EPA's guidance "Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessment" <http://www.epa.gov/oswer/riskassessment/ecorisk/ecorisk.htm> contains an eight step process for using benchmarks for ecological effects in the remedy selection process.

1. Introduction

The purpose of this website is to provide default screening tables and a calculator to assist Remedial Project Managers (RPMs), On Scene Coordinators (OSC's), 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 tables or calculator results at their own discretion and they should take care to understand the assumptions incorporated in these results and to apply the SLs appropriately.

The SLs presented in the Generic Tables are chemical-specific concentrations for individual contaminants in air, drinking water and soil that may warrant further investigation or site cleanup. The SLs generated from the calculator may be site-specific concentrations for individual chemicals in soil, air, water and fish. **It should be emphasized that SLs are not cleanup standards.** SLs should not be used as cleanup levels for a CERCLA site until the

other remedy selections identified in the relevant portions of the National Contingency Plan (NCP), 40 CFR Part 300, have been evaluated and considered. PRGs (Preliminary Remediation Goals) is a term used to describe a project team's early and evolving identification of possible remedial goals. PRGs may be initially identified early in the Remedial Investigation/ Feasibility Study (RI/FS) process (e.g., at RI scoping) to select appropriate detection limits for RI sampling. Typically, it is necessary for PRGs to be more generic early in the process and to become more refined and site-specific as data collection and assessment progress. The SLs identified on this website are likely to serve as PRGs early in the process--e.g., at RI scoping and at screening of chemicals of potential concern (COPCs) for the baseline risk assessment. However, once the baseline risk assessment has been performed, PRGs can be derived from the calculator using site-specific risks, and the SLs in the Generic Tables are less likely to apply. PRGs developed in the FS will usually be based on site-specific risks and Applicable or Relevant and Appropriate Requirements (ARARs) and not on generic SLs.

2. Understanding the Screening Tables

2.1 General Considerations

Risk-based SLs are derived from equations combining exposure assumptions with chemical-specific toxicity values.

2.2 Exposure Assumptions

Generic SLs are based on default exposure parameters and factors that represent Reasonable Maximum Exposure (RME) conditions for long-term/chronic exposures and are based on the methods outlined in EPA's [Risk Assessment Guidance for Superfund, Part B Manual \(1991\)](#) and Soil Screening Guidance documents ([1996](#) and [2002](#)).

Site-specific information may warrant modifying the default parameters in the equations and calculating site-specific SLs, which may differ from the values in these tables. In completing such calculations, the user should answer some fundamental questions about the site. For example, information is needed on the contaminants detected at the site, the land use, impacted media and the likely pathways for human exposure.

Whether these generic SLs or site-specific screening levels are used, it is important to clearly demonstrate the equations and exposure parameters used in deriving SLs at a site. A discussion of the assumptions used in the SL calculations should be included in the documentation for a CERCLA site.

2.3 Toxicity Values

In 2003, EPA's Superfund program revised its hierarchy of human health toxicity values, providing three tiers of toxicity values (<http://www.epa.gov/oswer/riskassessment/pdf/hhmemo.pdf>). Three tier 3 sources were identified in that guidance, but it was acknowledged that additional tier 3 sources may exist. The 2003 guidance did not attempt to rank or put the identified tier 3 sources into a hierarchy of their own. However, when developing the screening tables and calculator presented on this website, EPA needed to establish a hierarchy among the tier 3 sources. The toxicity values used as "defaults" in these tables and calculator are consistent with the 2003

guidance. Toxicity values from the following sources in the order in which they are presented below are used as the defaults in these tables and calculator.

1. EPA's Integrated Risk Information System ([IRIS](#))
2. The Provisional Peer Reviewed Toxicity Values ([PPRTVs](#)) derived by EPA's Superfund Health Risk Technical Support Center (STSC) for the EPA Superfund program.
3. The Agency for Toxic Substances and Disease Registry ([ATSDR](#)) minimal risk levels ([MRLs](#))
4. The California Environmental Protection Agency ([OEHHA](#)) Office of Environmental Health Hazard Assessment's Chronic Reference Exposure Levels ([RELS](#)) from December 18, 2008 and the [Cancer Potency Values](#) from July 21, 2009.
5. In the Fall 2009, this new source of toxicity values used was added: screening toxicity values in an appendix to certain PPRTV assessments. While we have less confidence in a screening toxicity value than in a PPRTV, we put these ahead of HEAST toxicity values because these appendix screening toxicity values are more recent and use current EPA methodologies in the derivation, and because the PPRTV appendix screening toxicity values also receive external peer review.
6. The EPA Superfund program's Health Effects Assessment Summary. (Note that the [HEAST](#) website of toxicity values for chemical contaminants is not open to users outside of EPA, but values can be obtained for use on Superfund sites by contacting Rich Kapuscinski at Kapuscinski.Rich@epa.gov).

Users of these screening tables and calculator wishing to consider using other toxicity values, including toxicity values from additional sources, may find the discussions and seven preferences on selecting toxicity values in the attached Environmental Council of States paper useful for this purpose ([ECOS website](#), [ECOS paper](#)).

When using toxicity values, users are encouraged to carefully review the basis for the value and to document the basis of toxicity values used on a CERCLA site.

2.3.1 Reference Doses

The current, or recently completed, EPA toxicity assessments used in these screening tables (IRIS and PPRTVs) define a reference dose, or RfD, as an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from a NOAEL, LOAEL, or benchmark dose, or using categorical regression, with uncertainty factors generally applied to reflect limitations of the data used. RfDs are generally the toxicity value used most often in evaluating noncancer health effects at Superfund sites. Various types of RfDs are available depending on the critical effect (developmental or other) and the length of exposure being evaluated (chronic or subchronic). Some of the SLs in these tables also use Agency for Toxic Substances and Disease Registry (ATSDR) chronic oral minimal risk levels (MRLs) as an oral chronic RfD. Screening toxicity values in an appendix to certain PPRTV assessments were added to the hierarchy in the fall of 2009. The HEAST RfDs used in these SLs were based upon then current EPA toxicity methodologies, but did not use the more recent benchmark dose or

categorical regression methodologies. Chronic oral reference doses and ATSDR chronic oral MRLs are expressed in units of (mg/kg-day).

2.3.1.1 Chronic Reference Doses

Chronic oral RfDs are specifically developed to be protective for long-term exposure to a compound. As a guideline for Superfund program risk assessments, chronic oral RfDs generally should be used to evaluate the potential noncarcinogenic effects associated with exposure periods greater than 7 years (approximately 10 percent of a human lifetime). However, this is not a bright line. Note, that ATSDR defines chronic exposure as greater than 1 year for use of their values. The calculator requires the user to select between chronic and subchronic toxicity values.

2.3.1.2 Subchronic Reference Doses

Subchronic oral RfDs are specifically developed to be protective for short-term exposure to a compound. As a guideline for Superfund program risk assessments, subchronic oral RfDs should generally be used to evaluate the potential noncarcinogenic effects of exposure periods between two weeks and seven years. However, this is not a bright line. Note, that ATSDR defines subchronic exposure as less than 1 year for use of their values. The calculator requires the user to select between chronic and subchronic toxicity values.

2.3.2 Reference Concentrations

The current, or recently completed, EPA toxicity assessments used in these screening tables (IRIS and PPRTV assessments) define a reference concentration (RfC) as an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from a NOAEL, LOAEL, or benchmark concentration, or using categorical regression with uncertainty factors generally applied to reflect limitations of the data used. Various types of RfCs are available depending on the critical effect (developmental or other) and the length of exposure being evaluated (chronic or subchronic). These screening tables also use ATSDR chronic inhalation MRLs as a chronic RfC, intermediate inhalation MRLs as a subchronic RfC and California Environmental Protection Agency (chronic) Reference Exposure Levels (RELs) as chronic RfCs. Screening toxicity values in an appendix to certain PPRTV assessments were added to the hierarchy in the fall of 2009. These screening tables may also use some RfCs from EPA's HEAST tables.

2.3.2.1 Chronic Reference Concentrations

The chronic inhalation reference concentration is generally used for continuous or near continuous inhalation exposures that occur for 7 years or more. However, this is not a bright line, and ATSDR chronic MRLs are based on exposures longer than 1 year. EPA chronic inhalation reference concentrations are expressed in units of (mg/m³). Cal EPA RELs are presented in µg/m³ and have been converted to mg/m³ for use in these screening tables. Some ATSDR inhalation MRLs are derived in parts per million (ppm) and some in mg/m³. For use in this table all were converted into mg/m³. The calculator requires the user to select between chronic and subchronic toxicity values.

2.3.2.2 Subchronic reference Concentrations

The subchronic inhalation reference concentration is generally used for exposures that are between 2 weeks and 7 years. However, this is not a bright line, and ATSDR subchronic MRLs are based on exposures less than 1 year. EPA subchronic inhalation reference concentrations are expressed in units of (mg/m³). Cal EPA RELs are presented in µg/m³ and have been converted to mg/m³ for use in these screening tables. Some ATSDR intermediate inhalation MRLs are derived in parts per million (ppm) and some in mg/m³. For use in this table all were converted into mg/m³. The calculator requires the user to select between chronic and subchronic toxicity values.

2.3.3 Slope Factors

A slope factor and the accompanying weight-of-evidence determination are the toxicity data most commonly used to evaluate potential human carcinogenic risks. Generally, the slope factor is a plausible upper-bound estimate of the probability of a response per unit intake of a chemical over a lifetime. The slope factor is used in risk assessments to estimate an upper-bound lifetime probability of an individual developing cancer as a result of exposure to a particular level of a potential carcinogen. Slope factors should always be accompanied by the weight-of-evidence classification to indicate the strength of the evidence that the agent is a human carcinogen.

Oral slope factors are toxicity values for evaluating the probability of an individual developing cancer from oral exposure to contaminant levels over a lifetime. Oral slope factors are expressed in units of (mg/kg-day)⁻¹. When available, oral slope factors from EPA's IRIS or PPRTV assessments are used. The ATSDR does not derive cancer toxicity values (e.g. slope factors or inhalation unit risks). Some oral slope factors used in these screening tables were derived by the California Environmental Protection Agency, whose methodologies are quite similar to those used by EPA's IRIS and PPRTV assessments. Screening toxicity values in an appendix to certain PPRTV assessments were added to the hierarchy in the fall of 2009. When oral slope factors are not available in IRIS then PPRTVs, Cal EPA assessments, PPRTV appendices or values from HEAST are used.

2.3.4 Inhalation Unit Risk

The IUR is defined as the upper-bound excess lifetime cancer risk estimated to result from continuous exposure to an agent at a concentration of 1 µg/m³ in air. Inhalation unit risk toxicity values are expressed in units of (µg/m³)⁻¹.

When available, inhalation unit risk values from EPA's IRIS or PPRTV assessments are used. The ATSDR does not derive cancer toxicity values (e.g. slope factors or inhalation unit risks). Some inhalation unit risk values used in these screening tables were derived by the California Environmental Protection Agency, whose methodologies are quite similar to those used by EPA's IRIS and PPRTV assessments. Screening toxicity values in an appendix to certain PPRTV assessments were added to the hierarchy in the fall of 2009. When inhalation unit risk values are not available in IRIS then PPRTVs, Cal EPA assessments, PPRTV appendices or values from HEAST are used.

2.3.5 Toxicity Equivalence Factors

Some chemicals are members of the same family and exhibit similar toxicological properties; however, they differ in the degree of toxicity. Therefore, a toxicity equivalence factor (TEF)

must first be applied to adjust the measured concentrations to a toxicity equivalent concentration.

The following table contains the various dioxin-like toxicity equivalency factors for Dioxins, Furans and PCBs (Van den Berg et al. 2006), which are the World Health Organization 2005 values.

Dioxin Toxicity Equivalence Factors

	Dioxins and Furans		TEF
Chlorinated dibenzo-p-dioxins			
	2,3,7,8-TCDD		1
	1,2,3,7,8-PeCDD		1
	1,2,3,4,7,8-HxCDD		0.1
	1,2,3,6,7,8-HxCDD		0.1
	1,2,3,7,8,9-HxCDD		0.1
	1,2,3,4,6,7,8-HpCDD		0.01
	OCDD		0.0003
Chlorinated dibenzofurans			
	2,3,7,8-TCDF		0.1
	1,2,3,7,8-PeCDF		0.03
	2,3,4,7,8-PeCDF		0.3
	1,2,3,4,7,8-HxCDF		0.1
	1,2,3,6,7,8-HxCDF		0.1
	1,2,3,7,8,9-HxCDF		0.1
	2,3,4,6,7,8-HxCDF		0.1
	1,2,3,4,6,7,8-HpCDF		0.01
	1,2,3,4,7,8,9-HpCDF		0.01
	OCDF		0.0003
PCBs			
	IUPAC No.	Structure	
>Non-ortho	77	3,3',4,4'-TetraCB	0.0001
	81	3,4,4',5-TetraCB	0.0003
	126	3,3',4,4',5-PeCB	0.1
	169	3,3',4,4',5,5'-HxCB	0.03
>Mono-ortho	105	2,3,3',4,4'-PeCB	0.00003
	114	2,3,4,4',5-PeCB	0.00003
	118	2,3',4,4',5-PeCB	0.00003
	123	2',3,4,4',5-PeCB	0.00003
	156	2,3,3',4,4',5-HxCB	0.00003
	157	2,3,3',4,4',5'-HxCB	0.00003
	167	2,3',4,4',5,5'-HxCB	0.00003

	189	2,3,3',4,4',5,5'-HpCB	0.00003
>Di-ortho*	170	2,2',3,3',4,4',5-HpCB	0.0001
	180	2,2',3,4,4',5,5'-HpCB	0.00001

* Di-ortho values come from Ahlborg, U.G., et al. (1994), which are the WHO 1994 values from Toxic equivalency factors for dioxin-like PCBs: Report on WHO-ECEH and IPCS consultation, December 1993 *Chemosphere*, Volume 28, Issue 6, March 1994, Pages 1049-1067.

Carcinogenic polycyclic aromatic hydrocarbons

Provisional Guidance for Quantitative Risk Assessment of Polycyclic Aromatic Hydrocarbons (EPA/600/R-93/089, July 1993), recommends that a toxicity equivalency factor (TEF) be used to convert concentrations of carcinogenic polycyclic aromatic hydrocarbons (cPAHs) to an equivalent concentration of benzo(a)pyrene when assessing the cancer risks posed by these substances from oral exposures. These TEFs are based on the potency of each compound relative to that of benzo(a)pyrene. For the toxicity value database, these TEFs have been applied to the toxicity values. Although this is not in complete agreement with the direction in the aforementioned documents, this approach was used so that toxicity values could be generated for each cPAH. Additionally, it should be noted that computationally it makes little difference whether the TEFs are applied to the concentrations of cPAHs found in environmental samples or to the toxicity values as long as the TEFs are not applied to both. However, if the adjusted toxicity values are used, the user will need to sum the risks from all cPAHs as part of the risk assessment to derive a total risk from all cPAHs. A total risk from all cPAHs is what is derived when the TEFs are applied to the environmental concentrations of cPAHs and not to the toxicity values. These TEFs are not needed and should not be used with the Cal EPA Inhalation Unit Risk Values used, nor should they be used when calculating non-cancer risk. See FAQ no. 15.

The following table presents the TEFs for cPAHs recommended in *Provisional Guidance for Quantitative Risk Assessment of Polycyclic Aromatic Hydrocarbons*.

Toxicity Equivalency Factors for Carcinogenic Polycyclic Aromatic Hydrocarbons

Compound	TEF
Benzo(a)pyrene	1.0
Benz(a)anthracene	0.1
Benzo(b)fluoranthene	0.1
Benzo(k)fluoranthene	0.01
Chrysene	0.001
Dibenz(a,h)anthracene	1.0
Indeno(1,2,3-c,d)pyrene	0.1

2.4 Chemical-specific Parameters

Several chemical specific parameters are needed for development of the SLs.

2.4.1 Sources

Many sources are used to populate the database of chemical-specific parameters. They are briefly described below.

1. The Estimation Programs Interface (EPI) Suite™ was developed by the US Environmental Protection Agency's Office of Pollution Prevention and Toxics and Syracuse Research Corporation (SRC). These programs estimate various chemical-specific properties. The calculations for these SL tables use the experimental values for a property over the estimated values.
2. EPA Soil Screening Level (SSL) Exhibit C-1.
3. WATER8, which has been replaced with WATER9.
4. Syracuse Research Corporation (SRC). 2005. CHEMFATE Database. SRC. Syracuse, NY. Accessed July 2005.
5. Syracuse Research Corporation (SRC). 2005. PHYSPROP Database. SRC. Syracuse, NY. Accessed July 2005.
6. Yaws' Handbook of Thermodynamic and Physical Properties of Chemical Compounds. Knovel, 2003.
(<http://www.knovel.com>).
7. EPA Soil Screening Level (SSL) Table C.4
(<http://www.epa.gov/superfund/health/conmedia/soil/index.htm>).
8. Baes, C.F. 1984. Oak Ridge National Laboratory. A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture. <http://homer.ornl.gov/baes/documents/ornl5786.html>. Values are also found in Superfund Chemical Data Matrix (SCDM)
(<http://www.epa.gov/superfund/sites/npl/hrsres/tools/scdm.htm>).
9. NIOSH Pocket Guide to Chemical Hazards (NPG), NIOSH Publication No. 97-140, February 2004. (<http://www.cdc.gov/niosh/npg/npg.html>).
10. CRC Handbook of Chemistry and Physics . (Various Editions)
11. Perry's Chemical Engineers' Handbook (Various Editions). McGraw-Hill. Online version available at: http://www.knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2203&VerticalID=0. Green, Don W.; Perry, Robert H. (2008).
12. Lange's Handbook of Chemistry (Various Editions). Online version available at: http://www.knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=1347&VerticalID=0. Speight, James G. (2005). McGraw-Hill.
13. U.S. EPA 2004. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Final.

OSWER 9285.7-02EP.July 2004. [Document](http://www.epa.gov/oswer/riskassessment/ragse/index.htm) and website <http://www.epa.gov/oswer/riskassessment/ragse/index.htm>><http://www.epa.gov/oswe>

2.4.2 Hierarchy by Parameter

Generally the hierarchies below will work for organic and inorganic compounds.

1. Organic Carbon Partition Coefficient (K_{oc}) (L/kg). Not applicable for inorganics. EPI estimated values; SSL, Yaw estimated values; EPI experimental values; Yaw Experimental values
2. Dermal Permeability Constant (K_p) (cm/hr). EPI estimated values; RAGS Part E.
3. Molecular Weight (MW) (g/mole). EPI; CRC89; PERRY; LANGE; YAWS
4. Water Solubility (S) (mg/L). EPI experimental values; SSL; CRC; PERRY; LANGE; YAWS experimental values; Yaws estimated values; EPI estimated values; PHYSPROP
5. Unitless Henry's Law Constant (H'). EPI experimental values; SSL; YAWS experimental values; EPI estimated values; PHYSPROP
6. Henry's Law Constant (atm-m³/mole). EPI experimental values; SSL; YAWS experimental values; EPI estimated values; PHYSPROP
7. Diffusivity in Air (D_{ia}) (cm²/s). WATER9 equations; SSL
8. Diffusivity in Water (D_{iw}) (cm²/s). WATER9 equations; SSL
9. Fish Bioconcentration Factor (BCF) (L/kg). EPI experimental values; EPI estimated values
10. Soil-Water Partition Coefficient (K_d) (cm³/g). SSL; BAES
11. Density (g/cm³). CRC; PERRY; LANGE; IRIS

3. Using the SL Tables

The "[Generic Tables](#)" page provides generic concentrations in the absence of site-specific exposure assessments. These concentrations can be used for:

Prioritizing multiple sites or operable units or areas of concern within a facility or exposure units

Setting risk-based detection limits for contaminants of potential concern (COPCs)

Focusing future site investigation and risk assessment efforts (e.g., selecting COPCs for the baseline risk assessment)

Identifying contamination which may warrant cleanup

Identifying sites, or portions of sites, which warrant no further action or investigation

Initial cleanup goals when site-specific data are lacking

Generic SLs are provided for multiple exposure pathways and for chemicals with both carcinogenic and noncarcinogenic effects. A Summary Table is provided that contains SLs corresponding to either a 10^{-6} risk level for carcinogens or a Hazard Quotient (HQ) of 1 for non-carcinogens. The summary table identifies whether the SL is based on cancer or noncancer effects by including a "c" or "n" after the SL. The Supporting Tables provide SLs corresponding to a 10^{-6} risk level for carcinogens and an HQ of 1 for noncarcinogens. Site specific SLs corresponding to an HQ of less than 1 may be appropriate for those sites where multiple chemicals are present that have RfDs or RfCs based on the same toxic endpoint. Site specific SLs based upon a cancer risk greater than 10^{-6} can be calculated and may be appropriate based upon site specific considerations. However, caution is recommended to ensure that cumulative cancer risk for all actual and potential carcinogenic contaminants found at the site does not have a residual (after site cleanup, or when it has been determined that no site cleanup is required) cancer risk exceeding 10^{-4} . Also, changing the target risk or HI may change the balance between the cancer and noncancer endpoints. At some concentrations, the cancer-risk concerns predominate; at other concentrations, noncancer-HI concerns predominate. The user must take care to consider both when adjusting target risks and hazards.

Tables are provided in either MS Excel or in PDF format. The following lists the tables provided and a description of what is contained in each:

Summary Table - provides a list of contaminants, toxicity values, MCLs and the lesser (more protective) of the cancer and noncancer SLs for resident soil, industrial soil, resident air, industrial air and tapwater.

Residential Soil Supporting Table - provides a list of contaminants, toxicity values and the cancer and noncancer SLs for resident soil.

Industrial Soil Supporting Table - provides a list of contaminants, toxicity values and the cancer and noncancer SLs for industrial soil.

Residential Air Supporting Table - provides a list of contaminants, toxicity values and the cancer and noncancer SLs for resident air.

Industrial Air Supporting Table - provides a list of contaminants, toxicity values and the cancer and noncancer SLs for industrial air.

Residential Tapwater Supporting Table - provides a list of contaminants, toxicity values, MCLs and the cancer and noncancer SLs for tapwater.

3.1 Developing a Conceptual Site Model

When using generic SLs at a site, the exposure pathways of concern and site conditions should match those used in developing the SLs presented here. (Note, however, that future uses may not match current uses. Future uses are potential site uses that may occur in the future. At Superfund sites, future uses should be considered as well as current uses. RAGS Part A, Chapter 6, provides guidance on selecting future-use receptors.) Thus, it is necessary to develop a conceptual site model (CSM) to identify likely contaminant source areas, exposure pathways, and potential receptors. This information can be used to determine the applicability of SLs at the site and the need for additional information. The final CSM diagram

represents linkages among contaminant sources, release mechanisms, exposure pathways, and routes and receptors based on historical information. It summarizes the understanding of the contamination problem. A separate CSM for ecological receptors can be useful. Part 2 and Attachment A of the Soil Screening Guidance for Superfund: Users Guide (EPA 1996) contains the steps for developing a CSM.

As a final check, the CSM should address the following questions:

Are there potential ecological concerns?

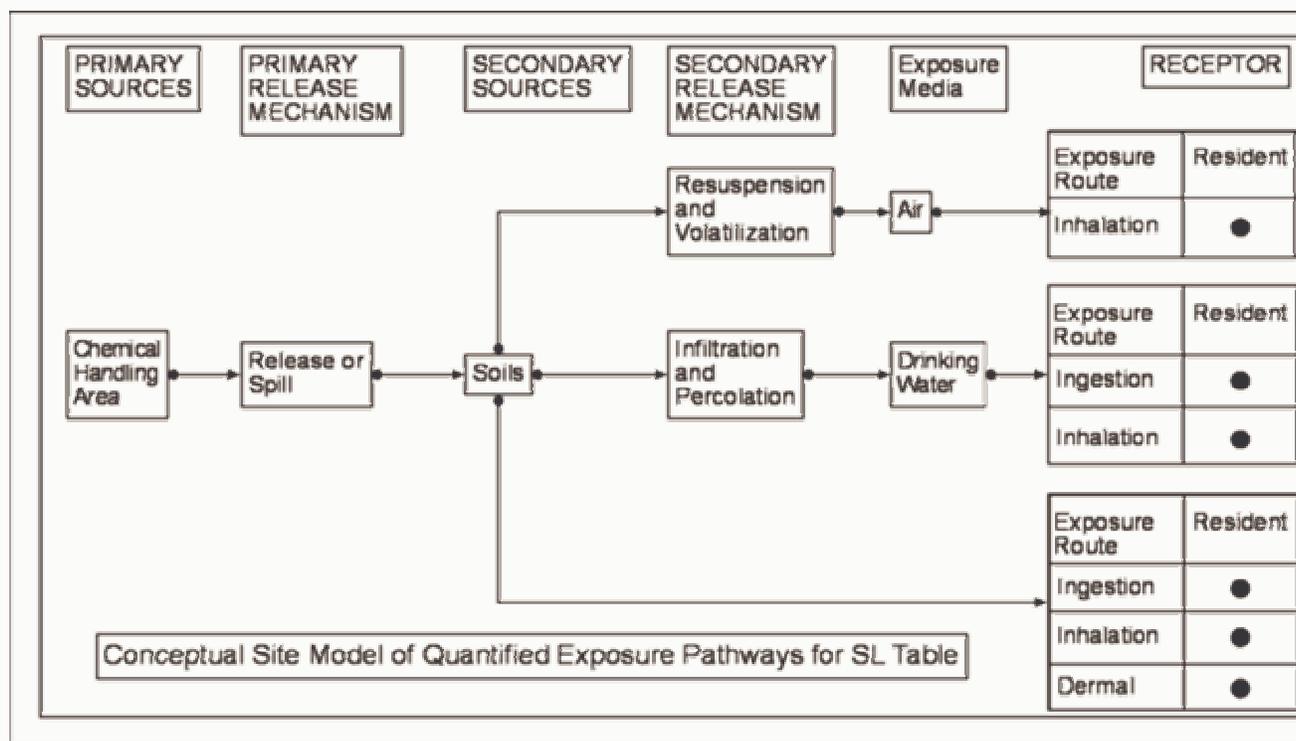
Is there potential for land use other than those used in the SL calculations (i.e., residential and commercial/industrial)?

Are there other likely human exposure pathways that were not considered in development of the SLs?

Are there unusual site conditions (e.g. large areas of contamination, high fugitive dust levels, potential for indoor air contamination)?

The SLs and later PRGs may need to be adjusted to reflect the answers to these questions.

Below is a potential CSM of the quantified pathways addressed in the SL Tables.



3.2 Background

EPA may be concerned with two types of background at sites: naturally occurring and anthropogenic. Natural background is usually limited to metals whereas anthropogenic (i.e. human-made) "background" includes both organic and inorganic contaminants.

Please note that the SL tables, which are purely risk-based, may yield SLs lower than naturally occurring background concentrations of some chemicals in some areas. However, background considerations may be incorporated into the assessment and investigation of sites, as acknowledged in existing EPA guidance. Background levels should be addressed as they are for other contaminants at CERCLA sites. For further information see EPA's guidance [Role of Background in the CERCLA Cleanup Program](#), April 2002, (OSWER 9285.6-07P) and [Guidance for Comparing Background and Chemical Concentration in Soil for CERCLA Sites](#), September 2002, (OSWER 9285.7-41).

Generally EPA does not clean up below natural background. In some cases, the predictive risk-based models generate SL concentrations that lie within or even below typical background concentrations for the same element or compound. Arsenic, aluminum, iron and manganese are common elements in soils that have background levels that may exceed risk-based SLs. This does not mean that these metals cannot be site-related, or that these metals should automatically be attributed to background. Attribution of chemicals to background is a site-specific decision; consult your regional risk assessor.

Where anthropogenic "background" levels exceed SLs and EPA has determined that a response action is necessary and feasible, EPA's goal will be to develop a comprehensive response to the widespread contamination. This will often require coordination with different authorities that have jurisdiction over the sources of contamination in the area.

3.3 Potential Problems

As with any risk based screening table or tool, the potential exists for misapplication. In most cases, this results from not understanding the intended use of the SLs or PRGs. In order to prevent misuse of the SLs, the following should be avoided:

Applying SLs to a site without adequately developing a conceptual site model that identifies relevant exposure pathways and exposure scenarios.

Not considering the effects from the presence of multiple contaminants, where appropriate.

Use of the SLs as cleanup levels without adequate consideration of the other NCP remedy selection criteria on CERCLA sites.

Use of SL as cleanup levels without verifying numbers with a toxicologist or regional risk assessor.

Use of outdated SLs when tables have been superseded by more recent values.

Not considering the effects of additivity when screening multiple chemicals.

Applying inappropriate target risks or changing a cancer target risk without considering its effect on noncancer, or vice versa.

Not performing additional screening for pathways not included in these SLs (e.g., vapor intrusion, fish consumption).

Adjusting SLs upward by factors of 10 or 100 without consulting a toxicologist or regional risk assessor.

4. Technical Support Documentation

The SLs consider human exposure to individual contaminants in air, drinking water and soil. The equations and technical discussion are aimed at developing risk-based SLs or PRGs. The following text presents the land use equations and their exposure routes. [Table 1](#) presents the definitions of the variables and their default values. Any alternative values or assumptions used in developing SLs on a site should be presented with supporting rationale in the decision document on CERCLA sites.

4.1 Residential Soil

4.1.1 Noncancer

The residential soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{\text{res-soil-nc-ing}} \text{ (mg/kg)} = \frac{THQ \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times ED_c \text{ (6 years)} \right) \times BW_c \text{ (15 Kg)}}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED_c \text{ (6 year)} \times \frac{1}{RID_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)} \times IRS_c \left(\frac{200 \text{ mg}}{\text{day}} \right) \times \frac{10^{-6} \text{ K}}{1 \text{ mg}}}$$

inhalation of particulates emitted from soil,

$$SL_{\text{res-soil-nc-inh}} \text{ (mg/kg)} = \frac{THQ \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times ED_c \text{ (6 years)} \right)}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED_c \text{ (6 year)} \times ET_{rs} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \frac{1}{RIC \left(\frac{\text{mg}}{\text{m}^3} \right)}}$$

dermal contact with soil,

$$SL_{\text{res-soil-nc-der}} \text{ (mg/kg)} = \frac{THQ \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times ED_c \text{ (6 years)} \right) \times BW_c}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED_c \text{ (6 year)} \times \frac{1}{\left(RID_o \left(\frac{\text{mg}}{\text{Kg-day}} \right) \times GI_{ABS} \right)} \times SA_c \left(\frac{2800 \text{ cm}^2}{\text{day}} \right)}$$

Total.

$$SL_{\text{res-soil-nc-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{res-soil-nc-ing}}} + \frac{1}{SL_{\text{res-soil-nc-der}}} + \frac{1}{SL_{\text{res-soil-nc-inh}}}}$$

4.1.2 Carcinogenic

The residential soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{\text{res-sol-ca-ing}} \text{ (mg/kg)} = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times IFS_{\text{adj}} \left(\frac{114 \text{ mg-Year}}{\text{Kg-day}} \right) \times \left(\frac{10^{-6} \text{ Kg}}{\text{mg}} \right)}$$

where:

$$IFS_{\text{adj}} \left(\frac{114 \text{ mg-Year}}{\text{Kg-day}} \right) = \frac{ED_c \text{ (6 years)} \times IRS_c \left(\frac{200 \text{ mg}}{\text{day}} \right)}{BW_c \text{ (15 Kg)}} + \frac{ED_r - ED_c \text{ (24 years)} \times IRS_a \left(\frac{100 \text{ mg}}{\text{day}} \right)}{BW_a \text{ (70 Kg)}}$$

inhalation of particulates emitted from soil,

$$SL_{\text{res-sol-ca-inh}} \text{ (mg/kg)} = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 y)} \right)}{IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right) \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times \left[\frac{1}{VF_s \left(\frac{\text{m}^3}{\text{Kg}} \right)} + \frac{1}{PEF_w \left(\frac{\text{m}^3}{\text{Kg}} \right)} \right]}$$

dermal contact with soil,

$$SL_{\text{res-sol-ca-der}} \text{ (mg/kg)} = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{\left[\frac{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \right] \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times DFS_{\text{adj}} \left(\frac{361 \text{ mg-Year}}{\text{Kg-day}} \right) \times ABS_d \times E}$$

where:

$$DFS_{\text{adj}} \left(\frac{361 \text{ mg-Year}}{\text{Kg-day}} \right) = \frac{ED_c \text{ (6 years)} \times SA_c \left(\frac{2800 \text{ cm}^2}{\text{day}} \right) \times AF_c \left(\frac{0.2 \text{ mg}}{\text{cm}^2} \right)}{BW_c \text{ (15 Kg)}} + \frac{ED_r - ED_c \text{ (24 years)} \times SA_a \left(\frac{2800 \text{ cm}^2}{\text{day}} \right) \times AF_a \left(\frac{0.2 \text{ mg}}{\text{cm}^2} \right)}{BW_a \text{ (70 Kg)}}$$

Total.

$$SL_{\text{res-sol-ca-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{res-sol-ca-ing}}} + \frac{1}{SL_{\text{res-sol-ca-der}}} + \frac{1}{SL_{\text{res-sol-ca-inh}}}}$$

4.1.3 Mutagenic

The residential soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{\text{res-sol-mu-ing}} \text{ (mg/kg)} = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times IFSM_{\text{adj}} \left(\frac{489.5 \text{ mg-Year}}{\text{Kg-day}} \right) \times \left(\frac{10^{-6}}{n} \right)}$$

where:

$$IFSM_{\text{adj}} \left(\frac{489.5 \text{ mg-Year}}{\text{Kg-day}} \right) = \frac{ED_{0-2} \text{ (yr)} \times IRS_c \left(\frac{200 \text{ mg}}{\text{day}} \right) \times 10}{BW_c \text{ (15 Kg)}} + \frac{ED_{2-6} \text{ (yr)} \times IRS_c \left(\frac{200 \text{ mg}}{\text{day}} \right) \times 3}{BW_c \text{ (15 Kg)}} + \frac{ED_{6-16} \text{ (yr)} \times IRS_a \left(\frac{100 \text{ mg}}{\text{day}} \right) \times 3}{BW_a \text{ (70 Kg)}} + \frac{ED_{16-30} \text{ (yr)} \times IRS_a \left(\frac{100 \text{ mg}}{\text{day}} \right) \times 1}{BW_a \text{ (70 Kg)}}$$

inhalation of particulates emitted from soil,

$$SL_{\text{res-sol-mu-inh}} \text{ (mg/kg)} = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ET_{rs} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right) \times \left[\left(ED_{0-2} \text{ (yrs)} \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 10 \right) + \left(ED_{2-6} \text{ (yrs)} \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 3 \right) + \left(ED_{6-16} \text{ (yrs)} \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 3 \right) + \left(ED_{16-30} \text{ (yrs)} \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 1 \right) \right]}$$

dermal contact with soil,

$$SL_{\text{res-sol-mu-der}} \text{ (mg/kg)} = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{\left[\frac{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \right] \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times DFSM_{\text{adj}} \left(\frac{1445 \text{ mg-Year}}{\text{Kg-day}} \right) \times AB}$$

where:

$$DFSM_{\text{adj}} \left(\frac{1445 \text{ mg-Year}}{\text{Kg-day}} \right) = \frac{ED_{0-2} \text{ (yr)} \times AF_c \left(\frac{0.2 \text{ mg}}{\text{cm}^2} \right) \times SA_c \left(\frac{2800 \text{ cm}^2}{\text{day}} \right) \times 10}{BW_c \text{ (15 Kg)}} + \frac{ED_{2-6} \text{ (yr)} \times AF_c \left(\frac{0.2 \text{ mg}}{\text{cm}^2} \right) \times SA_c \left(\frac{2800 \text{ cm}^2}{\text{day}} \right) \times 3}{BW_c \text{ (15 Kg)}} + \frac{ED_{6-16} \text{ (yr)} \times AF_a \left(\frac{0.07 \text{ mg}}{\text{cm}^2} \right) \times SA_a \left(\frac{5700 \text{ cm}^2}{\text{day}} \right) \times 3}{BW_a \text{ (70 Kg)}} + \frac{ED_{16-30} \text{ (yr)} \times AF_a \left(\frac{0.07 \text{ mg}}{\text{cm}^2} \right) \times SA_a \left(\frac{5700 \text{ cm}^2}{\text{day}} \right) \times 1}{BW_a \text{ (70 Kg)}}$$

Total.

$$SL_{\text{res-sol-mu-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{res-sol-mu-ing}}} + \frac{1}{SL_{\text{res-sol-mu-der}}} + \frac{1}{SL_{\text{res-sol-mu-inh}}}}$$

4.1.4 Vinyl Chloride - Carcinogenic

The residential soil land use equations, presented here, contain the following exposure routes:

incidental ingestion of soil,

$$SL_{\text{res-soil-ca-vc-ing}} \text{ (mg/kg)} = \frac{TR}{\left[\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times IFS_{\text{adj}} \left(\frac{114 \text{ mg-yr}}{\text{kg-d}} \right) \times \frac{10^{-6} \text{ Kg}}{1 \text{ mg}}}{AT \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)} \right]} \left[\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times IRS_c \left(\frac{200 \text{ mg}}{\text{day}} \right) \times \frac{10^{-6} \text{ Kg}}{1 \text{ mg}}}{BW_c (15 \text{ kg})} \right]$$

inhalation of particulates emitted from soil,

$$SL_{\text{res-soil-ca-vc-inh}} \text{ (mg/kg)} = \frac{TR}{\left[\frac{IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times EF \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED (30 \text{ years}) \times ET_{\text{rs}} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right) \times VF \left(\frac{\text{m}^3}{\text{kg}} \right)} \right]} \left[\frac{IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1}}{VF \left(\frac{\text{m}^3}{\text{kg}} \right)} \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right) \right]$$

dermal contact with soil,

$$SL_{\text{res-soil-ca-vc-der}} \text{ (mg/kg)} = \frac{TR}{\left[\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times DFS_{\text{adj}} \left(\frac{361 \text{ mg-yr}}{\text{kg-day}} \right) \times ABS_d^{-1}}{AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)} \right]} \left[\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \times SA_c \left(\frac{2800 \text{ cm}^2}{\text{day}} \right) \times AF_c \left(\frac{0.2 \text{ mg}}{\text{cm}^2} \right) \times ABS \times \frac{10^{-6} \text{ Kg}}{1 \text{ mg}}}{BW_c (15 \text{ kg})} \right]$$

Total.

$$SL_{\text{res-soil-ca-vc-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{res-soil-ca-vc-ing}}} + \frac{1}{SL_{\text{res-soil-ca-vc-der}}} + \frac{1}{SL_{\text{res-soil-ca-vc-inh}}}}$$

A number of studies have shown that inadvertent ingestion of soil is common among children 6 years old and younger (Calabrese et al. 1989, Davis et al. 1990, Van Wijnen et al. 1990). Therefore, the dose method uses an age-adjusted soil ingestion factor that takes into account the difference in daily soil ingestion rates, body weights, and exposure duration for children from 1 to 6 years old and others from 7 to 30 years old. The equation is presented below. This health-protective approach is chosen to take into account the higher daily rates of soil ingestion in children as well as the longer duration of exposure that is anticipated for a long-term resident. For more on this method, see [RAGS Part B](#).

4.2 Composite Worker Soil

This landuse is for developing industrial default screening levels that are presented in the [Generic Tables](#).

4.2.1 Noncancer

The composite worker soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{\text{w-sol-nc-ing}} \text{ (mg/kg)} = \frac{THQ \times AT_{\text{ow}} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{\text{ow}} \text{ (25 years)} \right) \times BW_{\text{ow}} \text{ (70 Kg)}}{EF_{\text{iw}} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{\text{ow}} \text{ (25 years)} \times \frac{1}{RfD_o \left(\frac{\text{mg}}{\text{kg-day}} \right)} \times IR_{\text{ow}} \left(100 \frac{\text{mg}}{\text{day}} \right) \times \left(\right)}$$

inhalation of particulates emitted from soil,

$$SL_{\text{w-sol-nc-inh}} \text{ (mg/kg)} = \frac{THQ \times AT_{\text{ow}} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{\text{ow}} \text{ (25 years)} \right)}{EF_{\text{iw}} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{\text{ow}} \text{ (25 years)} \times ET_{\text{ws}} \left(\frac{8 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \frac{1}{RfC}}$$

dermal exposure,

$$SL_{\text{w-sol-nc-der}} \text{ (mg/kg)} = \frac{THQ \times AT_{\text{ow}} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{\text{ow}} \text{ (25 years)} \right)}{EF_{\text{iw}} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{\text{ow}} \text{ (25 years)} \times \left(\frac{1}{RfD_o \left(\frac{\text{mg}}{\text{kg-day}} \right) \times GIABS} \right) \times SA_{\text{ow}} \left(\right)}$$

Total.

$$SL_{w-sol-nc-tot} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{w-sol-nc-ing}} + \frac{1}{SL_{w-sol-nc-der}} + \frac{1}{SL_{w-sol-nc-inh}}}$$

4.2.2 Carcinogenic

The composite worker soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{w-sol-ca-ing} \text{ (mg/kg)} = \frac{TR \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times BW_{ow} \text{ (70 Kg)}}{EF_{iw} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times CSF_0 \left(\frac{\text{mg}}{\text{kg-day}} \right)^{-1} \times IR_{ow} \left(100 \frac{\text{mg}}{\text{day}} \right) \times}$$

inhalation of particulates emitted from soil,

$$SL_{w-sol-ca-inh} \text{ (mg/kg)} = \frac{TR \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{EF_{iw} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times ET_{ws} \left(\frac{8 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times IUR}$$

dermal exposure,

$$SL_{w-sol-ca-der} \text{ (mg/kg)} = \frac{TR \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times BW_{ow}}{EF_{iw} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times \left(\frac{CSF_0 \left(\frac{\text{mg}}{\text{kg-day}} \right)^{-1}}{GIABS} \right) \times SA_{ow} \left(\frac{3300 \text{ cm}^2}{\text{day}} \right)}$$

Total.

$$SL_{w-sol-ca-tot} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{w-sol-ca-ing}} + \frac{1}{SL_{w-sol-ca-der}} + \frac{1}{SL_{w-sol-ca-inh}}}$$

4.3 Indoor Worker Soil

The indoor worker soil land use is not provided in the Generic Tables but SLs can be created by using the Calculator to modify the exposure parameters for the composite worker to match the equations that follow.

4.3.1 Noncancer

The indoor worker soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{iw-nc-ing} \text{ (mg/kg)} = \frac{THQ \times AT_{iw} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{iw} \text{ (25 years)} \right) \times BW_{iw} \text{ (70 Kg)}}{EF_{iw} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{iw} \text{ (25 years)} \times \frac{1}{RfD_o \left(\frac{\text{mg}}{\text{kg-day}} \right)} \times IR_{iw} \left(50 \frac{\text{mg}}{\text{day}} \right) \times \left(\frac{10^{-6}}{1 \text{ m}} \right)}$$

inhalation of particulates emitted from soil,

$$SL_{iw-nc-inh} \text{ (mg/kg)} = \frac{THQ \times AT_{iw} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{iw} \text{ (25 years)} \right)}{EF_{iw} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{iw} \text{ (25 years)} \times ET_{ws} \left(\frac{8 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \frac{1}{RfC \left(\frac{\text{mg}}{\text{m}^3\text{-day}} \right)}}$$

Total.

$$SL_{iw-nc-tot} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{iw-nc-ing}} + \frac{1}{SL_{iw-nc-inh}}}$$

4.3.2 Carcinogenic

The indoor worker soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{iw-ca-ing} \text{ (mg/kg)} = \frac{TR \times AT_{iw} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times BW_{iw} \text{ (70 Kg)}}{EF_{iw} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{iw} \text{ (25 years)} \times CSF_o \left(\frac{\text{mg}}{\text{kg-day}} \right)^{-1} \times IR_{iw} \left(50 \frac{\text{mg}}{\text{day}} \right) \times \left(\frac{10^{-6}}{1 \text{ m}} \right)}$$

inhalation of particulates emitted from soil,

$$SL_{iw-ca-inh} \text{ (mg/kg)} = \frac{TR \times AT_{iw} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{EF_{iw} \left(250 \frac{\text{days}}{\text{year}} \right) \times ED_{iw} \text{ (25 years)} \times ET_{ws} \left(\frac{8 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times IUR \left(\frac{\mu\text{g}}{\text{m}^3\text{-day}} \right)}$$

Total.

$$SL_{iw-ca-tot} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{iw-ca-ing}} + \frac{1}{SL_{iw-ca-inh}}}$$

4.4 Outdoor Worker Soil

The outdoor worker soil land use is not provided in the Generic Tables but SLs can be created by using the Calculator to modify the exposure parameters for the composite worker to match the equations that follow.

4.4.1 Noncancer

The outdoor worker soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{ow-sol-nc-ing} \text{ (mg/kg)} = \frac{THQ \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{ow} \text{ (25 years)} \right) \times BW_{ow} \text{ (70 Kg)}}{EF_{ow} \left(225 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times \frac{1}{RfD_o \left(\frac{\text{mg}}{\text{kg-day}} \right)} \times IR_{ow} \left(100 \frac{\text{mg}}{\text{day}} \right)}$$

inhalation of particulates emitted from soil,

$$SL_{ow-sol-nc-inh} \text{ (mg/kg)} = \frac{THQ \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{ow} \text{ (25 years)} \right)}{EF_{ow} \left(225 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times ET_{ws} \left(\frac{8 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \frac{1}{RfI_o}}$$

dermal exposure,

$$SL_{ow-sol-nc-der} \text{ (mg/kg)} = \frac{THQ \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{ow} \text{ (25 years)} \right)}{EF_{ow} \left(225 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times \left(\frac{1}{RfD_o \left(\frac{\text{mg}}{\text{kg-day}} \right) \times GIABS} \right) \times SA_{ow}}$$

Total.

$$SL_{ow-sol-nc-tot} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{ow-sol-nc-ing}} + \frac{1}{SL_{ow-sol-nc-der}} + \frac{1}{SL_{ow-sol-nc-inh}}}$$

4.4.2 Carcinogenic

The outdoor worker soil land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil,

$$SL_{ow-sol-ca-ing} \text{ (mg/kg)} = \frac{TR \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times BW_{ow} \text{ (70 Kg)}}{EF_{ow} \left(225 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times CSF_0 \left(\frac{\text{mg}}{\text{kg-day}} \right)^{-1} \times IR_{ow} \left(100 \frac{\text{mg}}{\text{day}} \right)}$$

inhalation of particulates emitted from soil,

$$SL_{ow-sol-ca-inh} \text{ (mg/kg)} = \frac{TR \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times BW_{ow} \text{ (70 Kg)}}{EF_{ow} \left(225 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times ET_{ws} \left(\frac{8 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times IU_{inh}}$$

dermal exposure,

$$SL_{ow-sol-ca-der} \text{ (mg/kg)} = \frac{TR \times AT_{ow} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times BW_{ow} \text{ (70 Kg)}}{EF_{ow} \left(225 \frac{\text{days}}{\text{year}} \right) \times ED_{ow} \text{ (25 years)} \times \left(\frac{CSF_0 \left(\frac{\text{mg}}{\text{kg-day}} \right)^{-1}}{GIABS} \right) \times SA_{ow} \left(\frac{3300 \text{ cm}^2}{\text{day}} \right)}$$

Total.

$$SL_{ow-sol-ca-tot} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{ow-sol-ca-ing}} + \frac{1}{SL_{ow-sol-ca-der}} + \frac{1}{SL_{ow-sol-ca-inh}}}$$

4.5 Recreational Soil or Sediment

4.5.1 Noncancer

The recreational soil or sediment land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil or sediment,

$$SL_{rec-sol-nc-ing} \text{ (mg/kg)} = \frac{THQ \times AT_{rec} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{recsc} \text{ (years)} \right) \times BW_{recsc} \text{ (Kg)}}{EF_{recsc} \left(\frac{\text{days}}{\text{year}} \right) \times ED_{recsc} \text{ (years)} \times \frac{1}{RID_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)} \times IRS_{recsc} \left(\frac{200 \text{ mg}}{\text{day}} \right)}$$

inhalation of particulates emitted from soil or sediment,

$$SL_{\text{rec-sol-nc-inh}} \text{ (mg/kg)} = \frac{\text{THQ} \times \text{AT}_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times \text{ED}_{\text{recsc}} \text{ (years)} \right)}{\text{EF}_{\text{recsc}} \left(\frac{\text{days}}{\text{year}} \right) \times \text{ED}_{\text{recsc}} \text{ (year)} \times \text{ET}_{\text{recsc}} \left(\frac{\text{hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \frac{1}{\text{RfC}}}$$

dermal contact with soil or sediment,

$$SL_{\text{rec-sol-nc-der}} \text{ (mg/kg)} = \frac{\text{THQ} \times \text{AT}_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times \text{ED}_{\text{recsc}} \text{ (years)} \right) \times \text{E}}{\text{EF}_{\text{recsc}} \left(\frac{\text{days}}{\text{year}} \right) \times \text{ED}_{\text{recsc}} \text{ (year)} \times \frac{1}{\left(\text{RfD}_o \left(\frac{\text{mg}}{\text{Kg-day}} \right) \times \text{GIABS} \right)} \times \text{SA}_{\text{recsc}}}$$

Total.

$$SL_{\text{rec-sol-nc-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{rec-sol-nc-ing}}} + \frac{1}{SL_{\text{rec-sol-nc-der}}} + \frac{1}{SL_{\text{rec-sol-nc-inh}}}}$$

4.5.2 Carcinogenic

The recreational soil or sediment land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil or sediment,

$$SL_{\text{rec-sol-ca-ing}} \text{ (mg/kg)} = \frac{\text{TR} \times \text{AT}_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times \text{LT (70 years)} \right)}{\text{CSF}_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times \text{IFS}_{\text{adj}} \left(\frac{\text{mg}}{\text{Kg}} \right) \times \left(\frac{10^{-6} \text{ Kg}}{\text{mg}} \right)}$$

where:

$$\text{IFS}_{\text{rec-adj}} \left(\frac{\text{mg}}{\text{Kg}} \right) = \frac{\text{ED}_{\text{recsc}} \text{ (years)} \times \text{EF}_{\text{recsc}} \left(\frac{\text{days}}{\text{year}} \right) \times \text{IRS}_{\text{recsc}} \left(\frac{200 \text{ mg}}{\text{day}} \right)}{\text{BW}_{\text{recsc}} \text{ (Kg)}} + \frac{\text{ED}_{\text{recsa}} \text{ (years)} \times \text{EF}_r}{\text{BW}_{\text{recsa}} \text{ (Kg)}}$$

inhalation of particulates emitted from soil or sediment,

$$SL_{\text{rec-sol-ca-inh}} \text{ (mg/kg)} = \frac{\text{TR} \times \text{AT}_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times \text{LT (70 years)} \right)}{\text{IUR} \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right) \times \text{EF}_{\text{recs}} \left(\frac{\text{days}}{\text{year}} \right) \times \left[\frac{1}{\text{VF}_s \left(\frac{\text{m}^3}{\text{Kg}} \right)} + \frac{1}{\text{PEF}_w \left(\frac{\text{m}^3}{\text{Kg}} \right)} \right] \times \text{ED}_{\text{recs}} \text{ (years)} \times \text{ET}_{\text{recs}} \left(\frac{\text{hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right)}$$

dermal contact with soil or sediment,

$$SL_{\text{rec-sol-ca-der}} \text{ (mg/kg)} = \frac{TR \times AT_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{\left(\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \right) \times DFS_{\text{adj}} \left(\frac{\text{mg}}{\text{Kg}} \right) \times ABS_d \times \left(\frac{10^{-6} \text{ Kg}}{\text{mg}} \right)}$$

where:

$$DFS_{\text{rec-adj}} \left(\frac{\text{mg}}{\text{Kg}} \right) = \frac{ED_{\text{recsc}} \text{ (years)} \times EF_{\text{recsc}} \left(\frac{\text{days}}{\text{year}} \right) \times SA_{\text{recsc}} \left(\frac{\text{cm}^2}{\text{day}} \right) \times AF_{\text{recsc}} \left(\frac{\text{mg}}{\text{cm}^2} \right)}{BW_{\text{recsc}} \text{ (Kg)}} + \frac{ED_{\text{rec}}}{BW_{\text{recsc}} \text{ (Kg)}}$$

Total.

$$SL_{\text{rec-sol-ca-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{rec-sol-ca-ing}}} + \frac{1}{SL_{\text{rec-sol-ca-der}}} + \frac{1}{SL_{\text{rec-sol-ca-inh}}}}$$

4.5.3 Mutagenic

The recreational soil or sediment land use equation, presented here, contains the following exposure routes:

incidental ingestion of soil or sediment,

$$SL_{\text{rec-sol-mu-ing}} \text{ (mg/kg)} = \frac{TR \times AT_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times IFSM_{\text{adj}} \left(\frac{\text{mg}}{\text{Kg}} \right) \times \left(\frac{10^{-6} \text{ Kg}}{\text{mg}} \right)}$$

where:

$$IFSM_{\text{rec-adj}} \left(\frac{\text{mg}}{\text{Kg}} \right) = \frac{ED_{0-2} \text{ (yr)} \times EF_{0-2} \left(\frac{\text{days}}{\text{year}} \right) \times IRS_{0-2} \left(\frac{200 \text{ mg}}{\text{day}} \right) \times 10}{BW_{0-2} \text{ (Kg)}} + \frac{ED_{2-6} \text{ (yr)} \times EF_{2-6} \left(\frac{\text{days}}{\text{year}} \right) \times IRS_{2-6} \left(\frac{200 \text{ mg}}{\text{day}} \right) \times 10}{BW_{2-6} \text{ (Kg)}} + \frac{ED_{6-16} \text{ (yr)} \times EF_{6-16} \left(\frac{\text{days}}{\text{year}} \right) \times IRS_{6-16} \left(\frac{100 \text{ mg}}{\text{day}} \right) \times 3}{BW_{6-16} \text{ (Kg)}} + \frac{ED_{16-30} \text{ (yr)} \times EF_{16-30} \left(\frac{\text{days}}{\text{year}} \right) \times IRS_{16-30} \left(\frac{100 \text{ mg}}{\text{day}} \right) \times 3}{BW_{16-30} \text{ (Kg)}}$$

inhalation of particulates emitted from soil or sediment,

$$SL_{\text{rec-sol-mu-inh}} \text{ (mg/kg)} = \frac{TR \times AT_{\text{rec}} \left(\frac{365 \text{ da}}{\text{year}} \right)}{\left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \left(\frac{1000 \text{ } \mu\text{g}}{\text{mg}} \right) \times \left[\frac{1}{VF_s \left(\frac{\text{m}^3}{\text{Kg}} \right)} + \frac{1}{PEF_w \left(\frac{\text{m}^3}{\text{Kg}} \right)} \right] \times \left[\left(ED_{0-2} \text{ (yrs)} \times EF_{0-2} \left(\frac{\text{days}}{\text{year}} \right) \times ET_{0-2} \left(\frac{\text{hours}}{\text{day}} \right) \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 10 \right) + \left(ED_{6-16} \text{ (yrs)} \times EF_{6-16} \left(\frac{\text{days}}{\text{year}} \right) \times ET_{6-16} \left(\frac{\text{hours}}{\text{day}} \right) \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 3 \right) \right]}$$

dermal contact with soil or sediment,

$$SL_{\text{rec-sol-mu-der}} \text{ (mg/kg)} = \frac{TR \times AT_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)}{\left[\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \right] \times DF_{\text{SM}_{\text{adj}}} \left(\frac{\text{mg}}{\text{Kg}} \right) \times ABS_d \times \left(\frac{10^{-6} \text{ Kg}}{\text{mg}} \right)}$$

where:

$$DF_{\text{SM}_{\text{rec-adj}}} \left(\frac{\text{mg}}{\text{Kg}} \right) = \frac{ED_{0-2} \text{ (yr)} \times EF_{0-2} \left(\frac{\text{days}}{\text{year}} \right) \times AF_{0-2} \left(\frac{\text{mg}}{\text{cm}^2} \right) \times SA_{0-2} \left(\frac{\text{cm}^2}{\text{day}} \right) \times 10}{BW_{0-2} \text{ (Kg)}} + \frac{ED_{2-6} \text{ (yr)} \times EF_{2-6} \left(\frac{\text{days}}{\text{year}} \right) \times AF_{2-6} \left(\frac{\text{mg}}{\text{cm}^2} \right) \times SA_{2-6} \left(\frac{\text{cm}^2}{\text{day}} \right) \times 10}{BW_{2-6} \text{ (Kg)}} + \frac{ED_{6-16} \text{ (yr)} \times EF_{6-16} \left(\frac{\text{days}}{\text{year}} \right) \times AF_{6-16} \left(\frac{\text{mg}}{\text{cm}^2} \right) \times SA_{6-16} \left(\frac{\text{cm}^2}{\text{day}} \right) \times 3}{BW_{6-16} \text{ (Kg)}} + \frac{ED_{16} \text{ (yr)} \times EF_{16} \left(\frac{\text{days}}{\text{year}} \right) \times AF_{16} \left(\frac{\text{mg}}{\text{cm}^2} \right) \times SA_{16} \left(\frac{\text{cm}^2}{\text{day}} \right) \times 3}{BW_{16} \text{ (Kg)}}$$

Total.

$$SL_{\text{rec-sol-mu-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{rec-sol-mu-ing}}} + \frac{1}{SL_{\text{rec-sol-mu-der}}} + \frac{1}{SL_{\text{rec-sol-mu-inh}}}}$$

4.5.4 Vinyl Chloride - Carcinogenic

The recreational soil or sediment land use equations, presented here, contain the following exposure routes:

incidental ingestion of soil or sediment,

$$SL_{\text{rec-soil-ca-vc-ing}} \text{ (mg/kg)} = \frac{TR}{\left[\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times EF_{\text{recs}} \left(\frac{\text{days}}{\text{year}} \right) \times IFS_{\text{rec-adj}} \left(\frac{\text{mg-yr}}{\text{kg-d}} \right) \times \frac{10^{-6} \text{Kg}}{1 \text{ mg}}}{AT_{\text{recs}} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)} + \frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times IRS_{\text{recsc}} \left(\frac{200 \text{ mg}}{\text{day}} \right) \times \frac{10^{-6} \text{Kg}}{1 \text{ mg}}}{BW_{\text{recsc}} \text{ (kg)}} \right]}$$

inhalation of particulates emitted from soil or sediment,

$$SL_{\text{rec-soil-ca-vc-inh}} \text{ (mg/kg)} = \frac{TR}{\left[\frac{IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times EF_{\text{recs}} \left(\frac{\text{days}}{\text{year}} \right) \times ED_{\text{recs}} \text{ (years)} \times ET_{\text{recs}} \left(\frac{\text{hours}}{\text{day}} \right) \times \left(AT_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times VF \left(\frac{\text{m}^3}{\text{kg}} \right) \right)}{\frac{IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1}}{VF \left(\frac{\text{m}^3}{\text{kg}} \right)} \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)} \right]}$$

dermal contact with soil or sediment,

$$SL_{\text{rec-soil-ca-vc-der}} \text{ (mg/kg)} = \frac{TR}{\left[\frac{\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \times EF_{\text{recs}} \left(\frac{\text{days}}{\text{year}} \right) \times DFS_{\text{rec-adj}} \left(\frac{361 \text{ mg-yr}}{\text{kg-day}} \right) \times ABS_c}{AT_{\text{recs}} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right)} + \frac{\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \times SA_{\text{recsc}} \left(\frac{\text{cm}^2}{\text{day}} \right) \times AF_{\text{recsc}} \left(\frac{\text{mg}}{\text{cm}^2} \right) \times ABS \times \frac{10^{-6} \text{Kg}}{1 \text{ mg}}}{BW_{\text{recsc}} \text{ (kg)}} \right]}$$

Total.

$$SL_{\text{rec-soil-ca-vc-tot}} \text{ (mg/kg)} = \frac{1}{\frac{1}{SL_{\text{rec-soil-ca-vc-ing}}} + \frac{1}{SL_{\text{rec-soil-ca-vc-der}}} + \frac{1}{SL_{\text{rec-soil-ca-vc-inh}}}}$$

A number of studies have shown that inadvertent ingestion of soil is common among children 6 years old and younger (Calabrese et al. 1989, Davis et al. 1990, Van Wijnen et al. 1990). Therefore, the dose method uses an age-adjusted soil ingestion factor that takes into account the difference in daily soil ingestion rates, body weights, and exposure duration for children from 1 to 6 years old and others from 7 to 30 years old. The equation is presented below. This health-protective approach is chosen to take into account the higher daily rates of soil ingestion in children as well as the longer duration of exposure that is anticipated for a long-term resident. For more on this method, see [RAGS Part B](#).

4.6 Recreational Surface Water

4.6.1 Noncarcinogenic

The surface water land use equation, presented here, contains the following exposure routes:

incidental ingestion of water,

$$SL_{\text{rec-water-nc-ing}} (\mu\text{g/L}) = \frac{\text{THQ} \times \text{AT}_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times \text{ED}_{\text{recwc}} (\text{years}) \right) \times \text{BW}_{\text{recv}}}{\text{EF}_{\text{recwc}} \left(\frac{\text{days}}{\text{year}} \right) \times \text{ED}_{\text{recwc}} (\text{years}) \times \frac{1}{\text{RfD}_o \left(\frac{\text{mg}}{\text{kg-d}} \right)} \times \text{IRW}_{\text{recwc}} \left(\frac{0.05 \text{ L}}{\text{hr}} \right)}$$

dermal,

FOR INORGANICS:

$$SL_{\text{rec-water-nc-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right) \times \left(\frac{1000 \text{ cm}^3}{\text{L}} \right)}{K_p \left(\frac{\text{cm}}{\text{hr}} \right) \times ET_{\text{recwc}} \left(\frac{\text{hours}}{\text{event}} \right)}$$

FOR ORGANICS:

$$\text{IF } ET_{\text{recwc}} \left(\frac{\text{hours}}{\text{event}} \right) \leq t^* (\text{hr}), \text{ then } SL_{\text{rec-water-nc-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{ev}} \right)}{2 \times FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \sqrt{6 \times \tau_{\text{ever}}}}$$

or,

$$\text{IF } ET_{\text{recwc}} \left(\frac{\text{hours}}{\text{event}} \right) > t^* (\text{hr}), \text{ then } SL_{\text{rec-water-nc-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{ev}} \right)}{FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \times \left[\frac{ET_{\text{recwc}} \left(\frac{\text{hr}}{\text{ev}} \right)}{1+B} \right]}$$

where:

$$DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right) = \frac{\text{THQ} \times AT_{\text{recw}} \left(\frac{365 \text{ days}}{\text{year}} \times ED_{\text{recwc}} (\text{years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{\left(\frac{1}{RfD_o \left(\frac{\text{mg}}{\text{Kg} \cdot \text{day}} \right) \times GIABS} \right) \times EV_{\text{recwc}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwc}} (\text{years}) \times f}$$

Total.

$$SL_{\text{rec-water-nc-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{rec-water-nc-ing}}} + \frac{1}{SL_{\text{rec-water-nc-der}}}}$$

4.6.2 Carcinogenic

The surface water land use equation, presented here, contains the following exposure routes:

incidental ingestion of water,

$$SL_{\text{rec-water-ca-ing}} (\mu\text{g/L}) = \frac{TR \times AT_{\text{recw}} \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{CSF_0 \left(\frac{\text{mg}}{\text{kg-day}} \right)^{-1} \times IFW_{\text{adj}} \left(\frac{\text{L}}{\text{Kg}} \right)}$$

where:

$$IFW_{\text{adj}} \left(\frac{\text{L}}{\text{Kg}} \right) = \frac{EV_{\text{recwc}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwc}} (\text{years}) \times EF_{\text{recwc}} \left(\frac{\text{days}}{\text{year}} \right) \times ET_{\text{recwc}} \left(\frac{\text{L}}{\text{kg}} \right)}{BW_{\text{recwc}} (\text{Kg})}$$

$$\frac{EV_{\text{recwa}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwa}} (\text{years}) \times EF_{\text{recwa}} \left(\frac{\text{days}}{\text{year}} \right) \times ET_{\text{recwa}} \left(\frac{\text{L}}{\text{kg}} \right)}{BW_{\text{recwa}} (\text{Kg})}$$

dermal,

FOR INORGANICS:

$$SL_{\text{rec-water-ca-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right) \times \left(\frac{1000 \text{ cm}^3}{\text{L}} \right)}{K_p \left(\frac{\text{cm}}{\text{hr}} \right) \times ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right)}$$

FOR ORGANICS:

$$\text{IF } ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right) \leq t^* (\text{hr}), \text{ then } SL_{\text{rec-water-ca-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right)}{2 \times FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \sqrt{6 \times \tau_{\text{event}}}}$$

or,

$$\text{IF } ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right) > t^* (\text{hr}), \text{ then } SL_{\text{rec-water-ca-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right)}{FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \times \left[\frac{ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right)}{1+B} \right]}$$

where:

$$DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right) = \frac{TR \times AT_{\text{recw}} \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{\left(\frac{CSF_o \left(\frac{\text{mg}}{\text{kg} \cdot \text{day}} \right)^{-1}}{GIABS} \right) \times DFW_{\text{adj}} \left(\frac{\text{cm}^2 \cdot \text{event}}{\text{kg}} \right)}$$

where :

$$DFW_{\text{adj}} \left(\frac{\text{cm}^2 \cdot \text{event}}{\text{kg}} \right) = \frac{EV_{\text{recwc}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwc}} (\text{years}) \times EF_{\text{recwc}} \left(\frac{\text{days}}{\text{year}} \right) \times SA_{\text{recwc}} (\text{cm}^2)}{BW_{\text{recwc}} (\text{kg})} + \frac{EV_{\text{recwa}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwa}} (\text{years}) \times EF_{\text{recwa}} \left(\frac{\text{days}}{\text{year}} \right) \times SA_{\text{recwa}} (\text{cm}^2)}{BW_{\text{recwa}} (\text{kg})}$$

and:

$$ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right) = \frac{\left(ET_{\text{recwc}} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{\text{recwc}} (\text{years}) \right) + \left(ET_{\text{recwa}} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{\text{recwa}} (\text{years}) \right)}{ED_{\text{recwc}} (\text{years}) + ED_{\text{recwa}} (\text{years})}$$

Total.

$$SL_{\text{rec-water-ca-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{rec-water-ca-ing}}} + \frac{1}{SL_{\text{rec-water-ca-der}}}}$$

4.6.3 Mutagenic

The surface water land use equation, presented here, contains the following exposure routes:

incidental ingestion of water,

$$SL_{\text{rec-water-mu-ing}} (\mu\text{g/L}) = \frac{TR \times AT_{\text{recw}} \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times IFWM_{\text{rec-adj}} \left(\frac{\text{L}}{\text{Kg}} \right)}$$

where:

$$IFWM_{\text{rec-adj}} \left(\frac{\text{L}}{\text{Kg}} \right) = \frac{ED_{0-2} (\text{yr}) \times EF_{0-2} \left(\frac{\text{days}}{\text{year}} \right) \times IRW_{0-2} \left(\frac{0.05 \text{ L}}{\text{hr}} \right) \times EV_{0-2} \left(\frac{\text{events}}{\text{day}} \right) \times ET_{0-2} \left(\frac{\text{hr}}{\text{day}} \right)}{BW_{0-2} (\text{Kg})} + \frac{ED_{2-6} (\text{yr}) \times EF_{2-6} \left(\frac{\text{days}}{\text{year}} \right) \times IRW_{2-6} \left(\frac{0.05 \text{ L}}{\text{hr}} \right) \times EV_{2-6} \left(\frac{\text{events}}{\text{day}} \right) \times ET_{2-6} \left(\frac{\text{hr}}{\text{day}} \right)}{BW_{2-6} (15)} + \frac{ED_{6-16} (\text{yr}) \times EF_{6-16} \left(\frac{\text{days}}{\text{year}} \right) \times IRW_{6-16} \left(\frac{0.05 \text{ L}}{\text{hr}} \right) \times EV_{6-16} \left(\frac{\text{events}}{\text{day}} \right) \times ET_{6-16} \left(\frac{\text{hr}}{\text{day}} \right)}{BW_{6-16} (\text{Kg})} + \frac{ED_{16-30} (\text{yr}) \times EF_{16-30} \left(\frac{\text{days}}{\text{year}} \right) \times IRW_{16-30} \left(\frac{0.05 \text{ L}}{\text{hr}} \right) \times EV_{16-30} \left(\frac{\text{events}}{\text{day}} \right) \times ET_{16-30} \left(\frac{\text{hr}}{\text{day}} \right)}{BW_{16-30} (\text{Kg})}$$

dermal,

FOR INORGANICS:

$$SL_{\text{rec-water-mu-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\text{ug}}{\text{cm}^2 \cdot \text{event}} \right) \times \left(\frac{1000 \text{ cm}^3}{\text{L}} \right)}{K_p \left(\frac{\text{cm}}{\text{hr}} \right) \times ET_{\text{recw-madj}} \left(\frac{\text{hours}}{\text{event}} \right)}$$

FOR ORGANICS:

$$\text{IF } ET_{\text{recw-madj}} \left(\frac{\text{hours}}{\text{event}} \right) \leq t^* (\text{hr}), \text{ then } SL_{\text{rec-water-mu-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\text{ug}}{\text{cm}^2 \cdot \text{event}} \right)}{2 \times FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \sqrt{6 \times t_{\text{event}}}}$$

or,

$$\text{IF } ET_{\text{recw-madj}} \left(\frac{\text{hours}}{\text{event}} \right) > t^* (\text{hr}), \text{ then } SL_{\text{rec-water-mu-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}}}{FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \times \left[\frac{ET_{\text{recw-madj}}}{1 + ET_{\text{recw-madj}}} \right]}$$

where:

$$DA_{\text{event}} \left(\frac{\text{ug}}{\text{cm}^2 \cdot \text{event}} \right) = \frac{TR \times AT_{\text{recw}} \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{\left[\frac{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \right] \times DFWM_{\text{rec-adj}} \left(\frac{\text{events} \cdot \text{cm}^2}{\text{kg}} \right)}$$

$$\text{where : } DFWM_{\text{rec-adj}} \left(\frac{\text{events} \cdot \text{cm}^2}{\text{kg}} \right) = \left[\begin{array}{l} \frac{EV_{\text{recw } 0-2} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{0-2} (\text{years})}{B^1} \\ \frac{EV_{\text{recw } 2-6} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{2-6} (\text{years})}{B^2} \\ \frac{EV_{\text{recw } 6-16} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{6-16} (\text{years})}{B^3} \\ \frac{EV_{\text{recw } 16-30} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{16-30} (\text{years})}{B^4} \end{array} \right]$$

and:

$$ET_{\text{recw-madj}} \left(\frac{\text{hours}}{\text{event}} \right) = \frac{\left(ET_{\text{recw}0-2} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{0-2} (\text{years}) + ET_{\text{recw}2-6} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{2-6} \right. \\ \left. + ET_{\text{recw}6-16} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{6-16} (\text{years}) + ET_{\text{recw}16-30} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{16-30} (\text{years}) \right)}{ED_{0-2} (\text{years}) + ED_{2-6} (\text{years}) + ED_{6-16} (\text{years}) + ED_{16-30} (\text{years})}$$

Total.

$$SL_{\text{rec-water-mu-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{rec-water-mu-ing}}} + \frac{1}{SL_{\text{rec-water-mu-der}}}}$$

4.6.4 Vinyl Chloride - Carcinogenic

The surface water land use equation, presented here, contains the following exposure routes:

incidental ingestion of water,

$$SL_{\text{rec-water-ca-vc-ing}} (\mu\text{g/L}) = \frac{TR}{\left[\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times IFW_{\text{rec-adj}} \left(\frac{\text{L}}{\text{Kg}} \right) \times \left(\frac{\text{mg}}{1000 \mu\text{g}} \right)}{AT_{\text{rec}} \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)} + \frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times ET_{\text{recwc}} \left(\frac{\text{hr}}{\text{day}} \right) \times IRW_{\text{recwc}} \frac{0.05 \text{ L}}{\text{hr}} \times \left(\frac{\text{mg}}{1000 \mu\text{g}} \right)}{BW_{\text{recwc}} (\text{kg})} \right]}$$

where:

$$IFW_{\text{rec-adj}} \left(\frac{\text{L}}{\text{Kg}} \right) = \frac{EV_{\text{recwc}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwc}} (\text{years}) \times EF_{\text{recwc}} \left(\frac{\text{days}}{\text{year}} \right) \times ET_{\text{recwc}}}{BW_{\text{recwc}} (\text{Kg})} \\ + \frac{EV_{\text{recwa}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwa}} (\text{years}) \times EF_{\text{recwa}} \left(\frac{\text{days}}{\text{year}} \right) \times ET_{\text{recwa}}}{BW_{\text{recwa}} (\text{Kg})}$$

dermal,

$$\text{IF } ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right) \leq t^* \text{ (hr), then } SL_{\text{rec-water-vc-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right)}{2 \times FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \sqrt{6 \times t_{\text{event}}}}$$

or,

$$\text{IF } ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right) > t^* \text{ (hr), then } SL_{\text{rec-water-vc-der}} (\mu\text{g/L}) = \frac{DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2} \right)}{FA \times K_p \left(\frac{\text{cm}}{\text{hr}} \right) \times \left[\frac{ET_{\text{recw-adj}} \left(\frac{\text{hr}}{\text{event}} \right)}{1+B} \right]}$$

where:

$$DA_{\text{event}} \left(\frac{\mu\text{g}}{\text{cm}^2 \cdot \text{event}} \right) = \frac{TR}{\left(\frac{\left(\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1}}{GIABS} \right) \times DFW_{\text{adj}} \left(\frac{\text{cm}^2 \cdot \text{events}}{\text{kg}} \right)}{AT_{\text{recw}} \left(\frac{365 \text{ days}}{\text{year}} \times LT \text{ (70 years)} \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)} \right) + \left(\frac{\left(\frac{CSF_0 \left(\frac{\text{mg}}{\text{Kg-day}} \right)}{GIABS} \right)}{E} \right)}$$

where:

$$DFW_{\text{adj}} \left(\frac{\text{cm}^2 \cdot \text{event}}{\text{kg}} \right) = \frac{EV_{\text{recwc}} \left(\frac{\text{events}}{\text{day}} \right) \times ED_{\text{recwc}} \text{ (years)} \times EF_{\text{recwc}} \left(\frac{\text{days}}{\text{year}} \right) \times SA_c \text{ (cm}^2\text{)}}{BW_c \text{ (Kg)}} + \dots$$

and:

$$ET_{\text{recw-adj}} \left(\frac{\text{hours}}{\text{event}} \right) = \frac{\left(ET_{\text{recwc}} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{\text{recwc}} \text{ (years)} \right) + \left(ET_{\text{recwa}} \left(\frac{\text{hours}}{\text{event}} \right) \times ED_{\text{recwa}} \text{ (years)} \right)}{ED_{\text{recwc}} \text{ (years)} + ED_{\text{recwa}} \text{ (years)}}$$

Total.

$$SL_{\text{rec-water-ca-vc-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{rec-water-ca-vc-ing}}} + \frac{1}{SL_{\text{rec-water-ca-vc-der}}}}$$

4.7 Tapwater

The Tapwater calculations do not include the dermal exposure route. It was determined that too many analytes were outside of the EPA Superfund Dermal Risk Assessment Guidance (RAGS Part E)'s Effective Predictive Domain (EPD) to include a dermal permeability constant

(Kp). Some of these were significant analytes, such as persistent chlorinated organics, including PCBs. Kp can be determined from the molecular weight and the logKow for organic compounds. Compounds with very high log Kows are outside of the EPD. Section 3.1.2 of RAGS Part E provides more detail.

4.7.1 Noncarcinogenic

The tapwater land use equation, presented here, contains the following exposure routes:

ingestion of water,

$$SL_{\text{water-nc-ing}} (\mu\text{g/L}) = \frac{\text{THQ} \times \text{AT}_r \left(\frac{365 \text{ days}}{\text{year}} \times \text{ED}_r (30 \text{ years}) \right) \times \text{BW}_a (70 \text{ Kg}) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{\text{EF}_r \left(350 \frac{\text{days}}{\text{year}} \right) \times \text{ED}_r (30 \text{ years}) \times \frac{1}{\text{RfD}_o \left(\frac{\text{mg}}{\text{kg-d}} \right)} \times \text{IRW}_a \left(\frac{2 \text{ L}}{\text{day}} \right)}$$

inhalation of volatiles,

$$SL_{\text{water-nc-inh}} (\mu\text{g/L}) = \frac{\text{THQ} \times \text{AT}_r \left(\frac{365 \text{ days}}{\text{year}} \times \text{ED}_r (30 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{\text{EF}_r \left(350 \frac{\text{days}}{\text{year}} \right) \times \text{ED}_r (30 \text{ years}) \times \text{ET}_{\text{rw}} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \frac{1}{\text{RfC} \left(\frac{\text{mg}}{\text{m}^3\text{-d}} \right)}}$$

Total.

$$SL_{\text{water-nc-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{water-nc-ing}}} + \frac{1}{SL_{\text{water-nc-inh}}}}$$

4.7.2 Carcinogenic

The tapwater land use equation, presented here, contains the following exposure routes:

ingestion of water,

$$SL_{\text{water-ca-ing}} (\mu\text{g/L}) = \frac{\text{TR} \times \text{AT}_r \left(\frac{365 \text{ days}}{\text{year}} \times \text{LT} (70 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{\text{EF}_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times \text{CSF}_o \left(\frac{\text{mg}}{\text{kg-day}} \right)^{-1} \times \left(\text{IFW}_{\text{adj}} \left(\frac{1.086 \text{ L-Year}}{\text{Kg-day}} \right) \right)}$$

where:

$$\text{IFW}_{\text{adj}} \left(\frac{1.086 \text{ L-Year}}{\text{Kg-day}} \right) = \frac{\text{ED}_c (6 \text{ years}) \times \text{IRW}_c \left(\frac{1 \text{ L}}{\text{day}} \right)}{\text{BW}_c (15 \text{ Kg})} + \frac{\text{ED}_r - \text{ED}_c (24 \text{ years}) \times \text{IRW}_a \left(\frac{2 \text{ L}}{\text{day}} \right)}{\text{BW}_a (70 \text{ Kg})}$$

inhalation of volatiles,

$$SL_{\text{water-ca-inh}} (\mu\text{g/L}) = \frac{\text{TR} \times \text{AT}_r \left(\frac{365 \text{ days}}{\text{year}} \times \text{LT} (70 \text{ years}) \right)}{\text{EF}_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times \text{ED}_r (30 \text{ years}) \times \text{ET}_{\text{rw}} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \text{IUR} \left(\frac{\mu\text{g}}{\text{m}^3\text{-d}} \right)}$$

Total.

$$SL_{\text{water-ca-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{water-ca-ing}}} + \frac{1}{SL_{\text{water-ca-inh}}}}$$

4.7.3 Mutagenic

The tapwater land use equation, presented here, contains the following exposure routes:

ingestion of water,

$$SL_{\text{water-mu-ing}} (\mu\text{g/L}) = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times IFWM_{\text{adj}} \left(\frac{3.39 \text{ L-Year}}{\text{Kg-day}} \right)}$$

where:

$$IFWM_{\text{adj}} \left(\frac{3.39 \text{ L-Year}}{\text{Kg-day}} \right) = \frac{ED_{0-2} (\text{yr}) \times IRW_c \left(\frac{1 \text{ L}}{\text{day}} \right) \times 10}{BW_c (15 \text{ Kg})} + \frac{ED_{2-6} (\text{yr}) \times IRW_c \left(\frac{1 \text{ L}}{\text{day}} \right) \times 3}{BW_c (15 \text{ Kg})} + \frac{ED_{6-16} (\text{yr}) \times IRW_a \left(\frac{2 \text{ L}}{\text{day}} \right) \times 3}{BW_a (70 \text{ Kg})} + \frac{ED_{16-30} (\text{yr}) \times IRW_a \left(\frac{2 \text{ L}}{\text{day}} \right) \times 1}{BW_a (70 \text{ Kg})}$$

inhalation of volatiles,

$$SL_{\text{water-mu-inh}} (\mu\text{g/L}) = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times K \left(\frac{0.5 \text{ L}}{\text{m}^3} \right) \times ET_{\text{rw}} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \left[\left(ED_{0-2} (\text{yrs}) \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 10 \right) + \left(ED_{2-6} (\text{yrs}) \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 3 \right) + \left(ED_{6-16} (\text{yrs}) \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 3 \right) + \left(ED_{16-30} (\text{yrs}) \times IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times 1 \right) \right]}$$

Total.

$$SL_{\text{water-mu-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{water-mu-ing}}} + \frac{1}{SL_{\text{water-mu-inh}}}}$$

4.7.4 Vinyl Chloride - Carcinogenic

The tapwater land use equation, presented here, contains the following exposure routes:

ingestion of water,

$$SL_{\text{res-water-ca-vc-ing}} (\mu\text{g/L}) = \frac{TR}{\left[\frac{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times IFW_{\text{adj}} \left(\frac{1.086 \text{ L-yr}}{\text{kg-day}} \right) \times \left(\frac{\text{mg}}{1000 \mu\text{g}} \right)}{AT \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)} + \frac{CSF_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times IRW_c \left(\frac{1 \text{ L}}{\text{day}} \right) \times \left(\frac{\text{mg}}{1000 \mu\text{g}} \right)}{BW_c (15 \text{ kg})} \right]}$$

inhalation of volatiles,

$$SL_{\text{res-water-ca-vc-inh}} (\mu\text{g/L}) = \frac{TR}{\left[\frac{IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times EF \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED (30 \text{ years}) \times ET_{\text{rw}} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{\text{mg}}{1000 \mu\text{g}} \right)}{AT \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)} + \left(IUR \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1} \times K \left(\frac{0.5 \text{ L}}{\text{m}^3} \right) \right) \right]}$$

Total.

$$SL_{\text{res-water-ca-vc-tot}} (\mu\text{g/L}) = \frac{1}{\frac{1}{SL_{\text{res-water-ca-vc-ing}}} + \frac{1}{SL_{\text{res-water-ca-vc-inh}}}}$$

4.8 Resident Air

4.8.1 Noncarcinogenic

The air land use equation, presented here, contains the following exposure routes:

inhalation

$$SL_{\text{res-air-nc}} (\mu\text{g}/\text{m}^3) = \frac{THQ \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times ED_r (30 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED_r (30 \text{ years}) \times ET_{\text{ra}} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \frac{1}{RfC \left(\frac{\text{mg}}{\text{m}} \right)}}$$

4.8.2 Carcinogenic

The air land use equation, presented here, contains the following exposure routes:

inhalation

$$SL_{res-air-ca} \left(\mu\text{g}/\text{m}^3 \right) = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED_r (30 \text{ years}) \times ET_{ra} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times IUR \left(\mu\text{g}/\text{m}^3 \right)}$$

4.8.3 Vinyl Chloride - Carcinogenic

The air land use equation, presented here, contains the following exposure routes:

inhalation

$$SL_{res-air-ca-vinyl \text{ chloride}} \left(\mu\text{g}/\text{m}^3 \right) = \frac{TR}{IUR \left(\mu\text{g}/\text{m}^3 \right)^{-1} + \frac{IUR \left(\mu\text{g}/\text{m}^3 \right)^{-1} \times EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ED_r (30 \text{ years})}{AT_r \left(\frac{365 \text{ days}}{\text{year}} \right) \times LT (70 \text{ years})}}$$

4.8.4 Mutagenic

The air land use equation, presented here, contains the following exposure routes:

inhalation

$$SL_{res-air-mu} \left(\mu\text{g}/\text{m}^3 \right) = \frac{TR \times AT_r \left(\frac{365 \text{ days}}{\text{year}} \times LT (70 \text{ years}) \right)}{EF_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times ET_{ra} \left(\frac{24 \text{ hours}}{\text{day}} \right) \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \left[\left(ED_{0-2} (\text{yrs}) \times IUR \left(\mu\text{g}/\text{m}^3 \right)^{-1} \times 10 \right) + \left(ED_{2-6} (\text{yrs}) \times IUR \left(\mu\text{g}/\text{m}^3 \right)^{-1} \times 3 \right) + \left(ED_{6-16} (\text{yrs}) \times IUR \left(\mu\text{g}/\text{m}^3 \right)^{-1} \times 3 \right) + \left(ED_{16-30} (\text{yrs}) \times IUR \left(\mu\text{g}/\text{m}^3 \right)^{-1} \times 1 \right) \right]}$$

4.9 Worker Air

4.9.1 Noncarcinogenic

The air land use equation, presented here, contains the following exposure routes:

Inhalation

$$SL_{w-air-nc} \left(\mu\text{g}/\text{m}^3 \right) = \frac{\text{THQ} \times \text{AT}_w \left(\frac{365 \text{ days}}{\text{year}} \times \text{ED}_r (25 \text{ years}) \right) \times \left(\frac{1000 \mu\text{g}}{\text{mg}} \right)}{\text{EF}_w \left(\frac{250 \text{ days}}{\text{year}} \right) \times \text{ED}_w (25 \text{ years}) \times \text{ET}_w \left(\frac{8 \text{ hr}}{24 \text{ hr}} \right) \times \frac{1}{\text{RfC} \left(\frac{\text{mg}}{\text{m}^3} \right)}}$$

4.9.2 Carcinogenic

The air land use equation, presented here, contains the following exposure routes:

Inhalation

$$SL_{w-air-ca} \left(\mu\text{g}/\text{m}^3 \right) = \frac{\text{TR} \times \text{AT}_w \left(\frac{365 \text{ days}}{\text{year}} \times \text{LT} (70 \text{ years}) \right)}{\text{EF}_w \left(\frac{250 \text{ days}}{\text{year}} \right) \times \text{ED}_w (25 \text{ years}) \times \text{ET}_w \left(\frac{8 \text{ hr}}{24 \text{ hr}} \right) \times \text{IUR} \left(\frac{\mu\text{g}}{\text{m}^3} \right)^{-1}}$$

4.10 Ingestion of Fish

The ingestion of fish exposure route is not provided in the Generic Tables but SLs can be created by using the Calculator and the equations that follow:

4.10.1 Noncarcinogenic

The ingestion of fish equation, presented here, contains the following exposure route:

consumption of fish.

$$SL_{res-fsh-nc-ing} \left(\text{mg}/\text{kg} \right) = \frac{\text{THQ} \times \text{AT}_r \left(\frac{365 \text{ days}}{\text{year}} \times \text{ED}_r (30 \text{ years}) \right) \times \text{BW}_a (70 \text{ Kg})}{\text{EF}_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times \text{ED}_r (30 \text{ year}) \times \frac{1}{\text{RfD}_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)} \times \text{IRF}_a \left(\frac{5.4 \times 10^4 \text{ mg}}{\text{day}} \right) \times}$$

4.10.2 Carcinogenic

The ingestion of fish equation, presented here, contains the following exposure route:

consumption of fish.

$$SL_{res-fsh-ca-ing} \left(\text{mg}/\text{kg} \right) = \frac{\text{TR} \times \text{AT}_r \left(\frac{365 \text{ days}}{\text{year}} \times \text{LT} (70 \text{ years}) \right) \times \text{BW}_a (70 \text{ Kg})}{\text{EF}_r \left(\frac{350 \text{ days}}{\text{year}} \right) \times \text{ED}_r (30 \text{ year}) \times \text{CSF}_o \left(\frac{\text{mg}}{\text{Kg-day}} \right)^{-1} \times \text{IRF}_a \left(\frac{5.4 \times 10^4 \text{ mg}}{\text{day}} \right)}$$

Note: the consumption rate for fish is not age adjusted for this land use. Also the SL calculated for fish is not for soil, like for the agricultural land uses, but is for fish tissue.

4.11 Soil to Groundwater

These equations are used to calculate screening levels in soil (SSLs) that are protective of groundwater. SSLs are either back-calculated from protective risk-based ground water concentrations or based on MCLs. The SSLs were designed for use during the early stages of a site evaluation when information about subsurface conditions may be limited. Because of this constraint, the equations used are based on conservative, simplifying assumptions about the release and transport of contaminants in the subsurface. Migration of contaminants from soil to groundwater can be envisioned as a two-stage process: (1) release of contaminant in soil leachate and (2) transport of the contaminant through the underlying soil and aquifer to a receptor well. The SSL methodology considers both of these fate and transport mechanisms.

SSLs are provided for metals in the Generic Tables based on Kds from the Soil Screening Guidance Exhibit C-4. According to Appendix C,

"Exhibit C-4 provides pH-specific soil-water partition coefficients (Kd) for metals. Site-specific soil pH measurements can be used to select appropriate Kd values for these metals. Where site-specific soil pH values are not available, values corresponding to a pH of 6.8 should be used."

If a metal is not listed in Exhibit C-4, Kds were taken from Baes, C. F. 1984. Kds for organic compounds are calculated from Koc and the fraction of organic carbon in the soil (foc). Kd for metals are listed below.

Chemical	CAS	Kd	Reference
Aluminum	7429-90-5	1.50E+03	Baes, C.F. 1984
Antimony (metallic)	7440-36-0	4.50E+01	SSG 9355.4-23 July 1996
Arsenic, Inorganic	7440-38-2	2.90E+01	SSG 9355.4-23 July 1996
Barium	7440-39-3	4.10E+01	SSG 9355.4-23 July 1996
Beryllium and compounds	7440-41-7	7.90E+02	SSG 9355.4-23 July 1996
Boron And Borates Only	7440-42-8	3.00E+00	Baes, C.F. 1984
Bromate	15541-45-4	7.50E+00	Baes, C.F. 1984
Cadmium (Diet)	7440-43-9	7.50E+01	SSG 9355.4-23 July 1996
Cadmium (Water)	7440-43-9	7.50E+01	SSG 9355.4-23 July 1996
Chlorine	7782-50-5	2.50E-01	Baes, C.F. 1984
Chromium (III) (Insoluble Salts)	16065-83-1	1.80E+06	SSG 9355.4-23 July 1996
Chromium Salts	0-00-3	8.50E+02	Baes, C.F. 1984
Chromium VI (chromic acid mists)	18540-29-9	1.90E+01	SSG 9355.4-23 July 1996

Chromium VI (particulates)	18540-29-9	1.90E+01	SSG 9355.4-23 July 1996
Chromium, Total (1:6 ratio Cr VI : Cr III)	7440-47-3	1.80E+06	SSG 9355.4-23 July 1996
Cobalt	7440-48-4	4.50E+01	Baes, C.F. 1984
Copper	7440-50-8	3.50E+01	Baes, C.F. 1984
Cyanide (CN-)	57-12-5	9.90E+00	SSG 9355.4-23 July 1996
Fluorine (Soluble Fluoride)	7782-41-4	1.50E+02	Baes, C.F. 1984
Iron	7439-89-6	2.50E+01	Baes, C.F. 1984
Lead and Compounds	7439-92-1	9.00E+02	Baes, C.F. 1984
Lithium	7439-93-2	3.00E+02	Baes, C.F. 1984
Magnesium	7439-95-4	4.50E+00	Baes, C.F. 1984
Manganese (Diet)	7439-96-5	6.50E+01	Baes, C.F. 1984
Manganese (Water)	7439-96-5	6.50E+01	Baes, C.F. 1984
Mercury (elemental)	7439-97-6	5.20E+01	SSG 9355.4-23 July 1996
Mercury, Inorganic Salts	0-01-7	5.20E+01	SSG 9355.4-23 July 1996
Molybdenum	7439-98-7	2.00E+01	Baes, C.F. 1984
Nickel Soluble Salts	7440-02-0	6.50E+01	SSG 9355.4-23 July 1996
Phosphorus, White	7723-14-0	3.50E+00	Baes, C.F. 1984
Selenium	7782-49-2	5.00E+00	SSG 9355.4-23 July 1996
Silver	7440-22-4	8.30E+00	SSG 9355.4-23 July 1996
Sodium	7440-23-5	1.00E+02	Baes, C.F. 1984
Strontium, Stable	7440-24-6	3.50E+01	Baes, C.F. 1984
Thallium (Soluble Salts)	7440-28-0	7.10E+01	SSG 9355.4-23 July 1996
Thorium	0-23-2	1.50E+05	Baes, C.F. 1984
Tin	7440-31-5	2.50E+02	Baes, C.F. 1984
Titanium	7440-32-6	1.00E+03	Baes, C.F. 1984
Uranium (Soluble Salts)	0-23-8	4.50E+02	Baes, C.F. 1984
Vanadium and Compounds	0-06-6	1.00E+03	SSG 9355.4-23 July 1996
Vanadium, Metallic	7440-62-2	1.00E+03	SSG 9355.4-23 July 1996
Zinc (Metallic)	7440-66-6	6.20E+01	SSG 9355.4-23 July 1996
Zirconium	7440-67-7	3.00E+03	Baes, C.F. 1984

Because Kds vary greatly by soil type, it is highly recommended that site-specific Kds be determined and used to develop SSLs.

The more protective of the carcinogenic and noncarcinogenic SLs is selected to calculate the SSL.

4.11.1 Noncarcinogenic Tapwater Equations for SSLs

The tapwater equations, presented in Section 4.4.1, are used to calculate the noncarcinogenic SSLs for volatiles and nonvolatiles. If the contaminant is a volatile, both ingestion and inhalation exposure routes are considered. If the contaminant is not a volatile, only ingestion is considered.

4.11.2 Carcinogenic Tapwater Equations for SSLs

The tapwater equations, presented in Section 4.4.2, are used to calculate the carcinogenic SSLs for volatiles and nonvolatiles. Sections 4.4.3 and 4.4.4 present the mutagenic and vinyl chloride equations, respectively. If the contaminant is a volatile, both ingestion and inhalation exposure routes are considered. If the contaminant is not a volatile, only ingestion is considered.

4.11.3 Method 1 for SSL Determination

Method 1 employs a partitioning equation for migration to groundwater and defaults are provided. This method is used to generate the download default tables.

method 1.

$$\text{SSL}(\text{mg/kg}) = C_w \left(\frac{\text{mg}}{\text{L}} \right) \times \text{DAF} \times \left[K_d \left(\frac{\text{L}}{\text{kg}} \right) + \left(\frac{\left(\theta_w \left(\frac{\text{L}_{\text{water}}}{\text{L}_{\text{soil}}} \right) + \theta_a \left(\frac{\text{L}_{\text{air}}}{\text{L}_{\text{soil}}} \right) \times H' \right)}{\rho_b \left(\frac{1.5 \text{ kg}}{\text{L}} \right)} \right) \right]$$

where:

$$\theta_a \left(\frac{\text{L}_{\text{air}}}{\text{L}_{\text{soil}}} \right) = n \left(\frac{\text{L}_{\text{water}}}{\text{L}_{\text{soil}}} \right) - \theta_w \left(\frac{0.3 \text{ L}_{\text{water}}}{\text{L}_{\text{soil}}} \right) :$$

$$n \left(\frac{\text{L}_{\text{pore}}}{\text{L}_{\text{soil}}} \right) = 1 \cdot \left(\frac{\rho_b \left(\frac{1.5 \text{ kg}}{\text{L}} \right)}{\rho_s \left(\frac{2.65 \text{ kg}}{\text{L}} \right)} \right) \text{ and}$$

$$K_d \left(\frac{\text{L}}{\text{kg}} \right) = K_{oc} \left(\frac{\text{L}}{\text{kg}} \right) \times f_{oc} \text{ (0.002 unitless)}$$

4.11.4 Method 2 for SSL Determination

Method 2 employs a mass-limit equation for migration to groundwater and site-specific information is required. This method can be used in the calculator portion of this website.

method 2.

$$\text{SSL}(\text{mg/kg}) = \frac{C_w \left(\frac{\text{mg}}{\text{L}} \right) \times \text{DAF} \times I \left(\frac{0.18 \text{ m}}{\text{year}} \right) \times \text{ED} (70 \text{ years})}{\rho_b \left(\frac{1.5 \text{ kg}}{\text{L}} \right) \times d_s (m)}$$

4.11.5 Determination of the Dilution Factor

The SSL values in the download tables are based on a dilution factor of 1. If one wishes to use the calculator to calculate screening levels using the SSL guidance for a 0.5 acre source, then a dilution factor of 20 should be used. If all of the parameters needed to calculate a site-specific dilution factor are known, they may be entered.

dilution factor.

$$\text{Dilution Attenuation Factor (DAF)} = 1 + \frac{K \left(\frac{\text{m}}{\text{year}} \right) \times I \left(\frac{\text{m}}{\text{m}} \right) \times d (m)}{I \left(\frac{0.18 \text{ m}}{\text{year}} \right) \times L (m)}$$

where:

$$d (m) = \left(0.0112 \times L^2 (m) \right)^{0.5} + d_a \times \left[1 - \exp \left(\frac{-L (m) \times I \left(\frac{\text{m}}{\text{year}} \right)}{K \left(\frac{\text{m}}{\text{year}} \right) \times I \left(\frac{\text{m}}{\text{m}} \right) \times d_a (m)} \right) \right]$$

4.12 Supporting Equations and Parameter Discussion

There are two parts of the above land use equations that require further explanation. They are the inhalation variables: the particulate emission factor (PEF) and the volatilization factor (VF).

4.12.1 Particulate Emission Factor (PEF)

Inhalation of contaminants adsorbed to respirable particles (PM10) was assessed using a default PEF equal to $1.36 \times 10^9 \text{ m}^3/\text{kg}$. This equation relates the contaminant concentration in soil with the concentration of respirable particles in the air due to fugitive dust emissions from contaminated soils. The generic PEF was derived using default values that correspond to a receptor point concentration of approximately $0.76 \mu/\text{m}^3$. The relationship is derived by Cowherd (1985) for a rapid assessment procedure applicable to a typical hazardous waste site, where the surface contamination provides a relatively continuous and constant potential for emission over an extended period of time (e.g., years). This represents an annual average emission rate based on wind erosion that should be compared with chronic health criteria; it is not appropriate for evaluating the potential for more acute exposures. Definitions of the input variables are in [Table 1](#).

With the exception of specific heavy metals, the PEF does not appear to significantly affect most soil screening levels. The equation forms the basis for deriving a generic PEF for the inhalation pathway. For more details regarding

specific parameters used in the PEF model, refer to **Soil Screening Guidance: Technical Background Document**. The use of alternate values on a specific site should be justified and presented in an Administrative Record if considered in CERCLA remedy selection.

$$PEF_w = \frac{Q}{C_w} \times \frac{3,600}{0.036 \times (1-V) \times (U_m/U_t)^3 \times F(x)}$$

where

$$\frac{Q}{C_w} = A \times \exp \left[\frac{(\ln A_s - B)^2}{C} \right]$$

Note: the generic PEF evaluates wind-borne emissions and does not consider dust emissions from traffic or other forms of mechanical disturbance that could lead to greater emissions than assumed here.

4.12.2 Volatilization Factor (VF)

The soil-to-air VF is used to define the relationship between the concentration of the contaminant in soil and the flux of the volatilized contaminant to air. VF is calculated from the equation below using chemical-specific properties and either site-measured or default values for soil moisture, dry bulk density, and fraction of organic carbon in soil. The Soil Screening Guidance: User's Guide describes how to develop site measured values for these parameters.

VF is only calculated for volatile organic compounds (VOCs). VOCs, for the purpose of this guidance, are chemicals with a Henry's Law constant of 1×10^{-5} atm-m³/mole or greater and with a molecular weight of less than 200 g/mole.

$$VF = \frac{\frac{Q}{C_w} \times (3.14 \times D_A \times T)^{\frac{1}{2}} \times 10^{-4} \left(\frac{m^2}{cm^2} \right)}{2 \times \rho_b \times D_A}$$

where

$$\frac{Q}{C_w} = A \times \exp \left[\frac{(\ln A_s - B)^2}{C} \right] \text{ and}$$

$$D_A = \frac{\left[\left(\theta_a^{\frac{10}{3}} \times D_{ia} \times H' + \theta_w^{\frac{10}{3}} \times D_{iw} \right) / n^2 \right]}{\rho_b \times K_d + \theta_w + \theta_a \times H'}$$

Diffusivity in Water (cm²/s)

Diffusivity in water can be calculated from the chemical's molecular weight and density, using the following correlation equation based on WATER9 (U.S. EPA, 2001):

$$D_{iw} \left(\frac{\text{cm}^2}{\text{s}} \right) = 0.0001518 \times \left(\frac{T^{\circ}\text{C} + 273.16}{298.16} \right) \times \left(\frac{\text{MW} \left(\frac{\text{g}}{\text{mol}} \right)}{\rho \left(\frac{\text{g}}{\text{cm}^3} \right)} \right)^{-0.6}$$

where

T typically = 25^oC

If density is not available,

$$D_{iw} \left(\frac{\text{cm}^2}{\text{s}} \right) = 0.000222 \times (\text{MW})^{-\left(\frac{2}{3}\right)}$$

If density is not available, diffusivity in water can be calculated using the correlation equation based on U.S. EPA (1987). The value for diffusivity in water must be greater than zero. No maximum limit is enforced.

Diffusivity in Air (cm²/s).

Diffusivity in air can be calculated from the chemical's molecular weight and density, using the following correlation equation based on WATER9 (U.S. EPA, 2001):

$$D_{ia} \left(\frac{\text{cm}^2}{\text{s}} \right) = \frac{0.00229 \times (T^{\circ}\text{C} + 273.16)^{1.5} \times \left[0.034 + \frac{1}{\text{MW} \left(\frac{\text{g}}{\text{mol}} \right)} \right] \times \text{MW}_{\text{cor}}}{\left[\frac{\text{MW} \left(\frac{\text{g}}{\text{mol}} \right)^{0.333}}{2.5 \times \rho \left(\frac{\text{g}}{\text{cm}^3} \right)} + 1.8 \right]^2}$$

where

T typically = 25^oC

$\text{MW}_{\text{cor}} = (1 - 0.000015 \times \text{MW}^2)$ If MW_{cor} is less than 0.4, then MW_{cor} is set to 0.4.

If density is not available,

$$D_{ia} \left(\frac{\text{cm}^2}{\text{s}} \right) = 1.9 \times \left[\text{MW} \left(\frac{\text{g}}{\text{mol}} \right)^{-\left(\frac{2}{3}\right)} \right] \text{ except for dioxins use, } D_{ia} \left(\frac{\text{cm}^2}{\text{s}} \right) = \left(\frac{154}{\text{MW} \left(\frac{\text{g}}{\text{mol}} \right)} \right)^{0.5} \times 0.068$$

If density is not available, diffusivity in air can be calculated using the correlation equation based on U.S. EPA (1987). For dioxins, diffusivity in air can be calculated from the molecular weight using the correlation equation based on EPA's Dioxin Reassessment (U.S. EPA, 2000).

5. Special Considerations

Most of the SLs are readily derived by referring to the above equations. However, there are some cases for which the standard equations do not apply and/or external adjustments to the SLs are recommended. These special case chemicals are discussed below.

5.1 Cadmium

IRIS presents an oral "water" RfD for cadmium for use in assessment of risks to water of 0.0005 mg/kg-day. IRIS also presents an oral "food" RfD for cadmium for use in assessment of risks to soil and biota of 0.001 mg/kg-day. The SLs for Cadmium are based on the oral RfD for "water", which is slightly more conservative (by a factor of 2) than the RfD for "food". Because the SLs are considered screening values, the more conservative RfD is used for cadmium. However, reasonable arguments could be made for applying an RfD for food (instead of the oral RfD for water) for some media such as soils. RAGS Part E, in Exhibit 4-1, presents a GIABS for soil of 2.5% and for water of 5%.

5.2 Lead

EPA has no consensus RfD or CSF for inorganic lead, so it is not possible to calculate SLs as we have done for other chemicals. EPA considers lead to be a special case because of the difficulty in identifying the classic "threshold" needed to develop an RfD.

EPA therefore evaluates lead exposure by using blood-lead modeling, such as the Integrated Exposure-Uptake Biokinetic Model (IEUBK). The EPA Office of Solid Waste has also released a detailed directive on risk assessment and cleanup of residential soil lead. The directive recommends that soil lead levels less than 400 mg/kg are generally safe for residential use. Above that level, the document suggests collecting data and modeling blood-lead levels with the IEUBK model. For the purposes of screening, therefore, 400 mg/kg is recommended for residential soils. For water, we suggest 15 µg/l (the EPA Action Level in water), and for air, the National Ambient Air Quality Standard.

However, caution should be used when both water and soil are being assessed. The IEUBK model shows that if the average soil concentration is 400 mg/kg, an average tap water concentration above 5 µg/L would yield more than 5% of the population above a 10 µg/dL blood-lead level. If the average tap water concentration is 15 µg/L, an average soil concentration greater than 250 mg/kg would yield more than 5% of the population above a 10 µg/dL blood-lead level.

EPA uses a second Adult Lead Model to estimate SLs for an industrial setting. This SL is intended to protect a fetus that may be carried by a pregnant female worker. It is assumed that a cleanup goal that is protective of a fetus will also afford protection for male or female adult workers. The model equations were developed to calculate cleanup goals such that the fetus of a pregnant female worker would not likely have an unsafe concentration of lead in blood.

For more information on EPA's lead models and other lead-related topics, please go to [Addressing Lead at Superfund Sites](#).

5.3 Manganese

The IRIS RfD (0.14 mg/kg-day) includes manganese from all sources, including diet. The author of the IRIS assessment for manganese recommended that the dietary contribution from the normal U.S. diet (an upper limit of 5 mg/day) be subtracted when evaluating non-food (e.g., drinking water or soil) exposures to manganese, leading to a RfD of 0.071 mg/kg-day for non-food items. The explanatory text in IRIS further recommends using a modifying factor of 3 when calculating risks associated with non-food sources due to a number of uncertainties that are discussed in the IRIS file for manganese, leading to a RfD of 0.024 mg/kg-day. This modified RfD has been used in the derivation of some manganese screening levels for soil and water. For more information regarding the Manganese RfD, users are advised to contact the author of the IRIS assessment on Manganese.

5.4 Vanadium Compounds

The oral RfD toxicity value for Vanadium, used in this website, is derived from the IRIS oral RfD for Vanadium Pentoxide by factoring out the molecular weight (MW) of the oxide ion. Vanadium Pentoxide (V2O5) has a molecular weight of 181.88. The two atoms of Vanadium

contribute 56% of the MW. Vanadium Pentoxide's oral RfD of 9E-03 multiplied by 56% gives a Vanadium oral RfD of 5.04E-03.

5.5 Uranium

"Uranium Soluble Salts" uses the IRIS oral RfD of 3E-03 mg/kg-day. For the insoluble salts of Uranium, the oral RfD of 6E-04 mg/kg-day may be used from the Federal Register, Thursday December 7, 2000. Part II, Environmental Protection Agency. 40 CFR Parts 9, 141, and 142 - National Primary Drinking Water Regulations; Radionuclides; Final Rule. p 76713.

5.6 Chromium (VI)

It is recommended that valence-specific data for chromium be collected when chromium is likely to be an important contaminant at a site, and when hexavalent chromium Cr(VI) may exist. For Cr(VI), IRIS shows an air unit risk of 1.2E-2 per ($\mu\text{g}/\text{m}^3$). While the exact ratio of Cr(VI) to Cr(III) in the data used to derive the IRIS air unit risk value is not known, it is likely that both Cr(VI) and Cr(III) were present. The RSLs calculated using the IRIS air unit risk assume that the Cr(VI) to Cr(III) ratio is 1:6. Because of various sources of uncertainty, this assumption may overestimate or underestimate the risk calculated. Users are invited to review the document "Toxicological Review of Hexavalent Chromium" in support of the summary information on Cr(VI) on IRIS to determine whether they believe this ratio applies to their projects and to consider consulting with an EPA regional risk assessor.

In the RSL Table, the Cr(VI) specific value (assuming 100% Cr(VI)) is derived by multiplying the IRIS Cr(VI) value by 7. This is considered to be a health-protective assumption, and is also consistent with the State of California's interpretation of the Mancuso study that forms the basis of Cr(VI)'s estimated cancer potency.

If you are working on a chromium site, you may want to contact the appropriate regulatory officials in your region to determine what their position is on this issue.

The Maximum Contaminant Level (MCL) of 100 $\mu\text{g}/\text{L}$ for "Chromium (total)", from the EPA's MCL listing is applied to the "Chromium, Total" analyte on this website.

The New Jersey Department of Environmental Protection (NJDEP) recently determined that Cr (VI) by ingestion is likely to be carcinogenic in humans. NJDEP derived a new oral cancer slope factor, based on cancer bioassays conducted by the National Toxicology Program (<http://www.state.nj.us/dep/dsr/chromium/soil-cleanup-derivation.pdf>). In addition, EPA's Office of Pesticide Programs (OPP) has concluded that the weight-of-evidence supports that Cr(VI) may act through a mutagenic mode of action following administration via drinking water and has also recommended that Age-Dependent Adjustment Factors (ADAFs) be applied when assessing cancer risks from early-life exposure (< 16 years of age).

Both of these assessments are considered Tier 3 sources and were used to derive the screening levels for Cr(VI). We applied ADAFs for early life exposure via ingestion and inhalation because OPP's proposed mutagenic mode of action for Cr(VI) occurs in all cells, regardless of type. Application of ADAFs for all exposure pathways results in more health-protective screening levels.

5.7 Aminodinitrotoluenes

The IRIS oral RfD of 2E-03 mg/kg-day for 2,4-Dinitrotoluene is used as a surrogate for 2-Amino-4,6-Dinitrotoluene and 4-Amino-2,6-Dinitrotoluene.

5.8 PCBs

Aroclor 1016 is considered "lowest risk" and assigned appropriate toxicity values. All other Aroclors are assigned the high risk toxicity values.

5.9 Xylenes

The IRIS oral RfD of 2E-01 for xylene, mixture is used as a surrogate for the 3 xylene congeners. The earlier RfD values for some xylene isomers were withdrawn from our electronic version of HEAST.

5.10 Soil Saturation Limit (C_{sat})

The soil saturation concentration, C_{sat}, corresponds to the contaminant concentration in soil at which the absorptive limits of the soil particles, the solubility limits of the soil pore water, and saturation of soil pore air have been reached. Above this concentration, the soil contaminant may be present in free phase (i.e., nonaqueous phase liquids (NAPLs) for contaminants that are liquid at ambient soil temperatures and pure solid phases for compounds that are solid at ambient soil temperatures).

Equation 4-10 is used to calculate C_{sat} for each volatile contaminant. As an update to RAGS HHEM, Part B (USEPA 1991a), this equation takes into account the amount of contaminant that is in the vapor phase in soil in addition to the amount dissolved in the soil's pore water and sorbed to soil particles.

Chemical-specific C_{sat} concentrations must be compared with each VF-based SL because a basic principle of the SL volatilization model is not applicable when free-phase contaminants are present. How these cases are handled depends on whether the contaminant is liquid or solid at ambient temperatures. Liquid contaminant that have a VF-based SL that exceeds the C_{sat} concentration are set equal to C_{sat} whereas for solids (e.g., PAHs), soil screening decisions are based on the appropriate SLs for other pathways of concern at the site (e.g., ingestion).

$$C_{\text{sat}} = \frac{S \left(\frac{\text{mg}}{\text{L}} \right)}{\rho_b \left(\frac{\text{Kg}}{\text{L}} \right)} \times \left(K_d \left(\frac{\text{L}}{\text{Kg}} \right) \times \rho_b \left(\frac{\text{Kg}}{\text{L}} \right) + \theta_w \left(\frac{\text{L}_{\text{water}}}{\text{L}_{\text{soil}}} \right) + H' \times \theta_a \left(\frac{\text{L}_{\text{air}}}{\text{L}_{\text{soil}}} \right) \right)$$

where

$$K_d = K_{oc} \left(\frac{\text{L}}{\text{Kg}} \right) \times f_{oc} \left(\frac{\text{g}}{\text{g}} \right)$$

$$\theta_a \left(\frac{\text{L}_{\text{air}}}{\text{L}_{\text{soil}}} \right) = n \left(\frac{\text{L}_{\text{pore}}}{\text{L}_{\text{soil}}} \right) - \theta_w \left(\frac{\text{L}_{\text{water}}}{\text{L}_{\text{soil}}} \right) \text{ and}$$

$$n = 1 - \left(\frac{\rho_b \left(\frac{\text{Kg}}{\text{L}} \right)}{\rho_s \left(\frac{\text{Kg}}{\text{L}} \right)} \right)$$

5.11 SL Theoretical Ceiling Limit

The ceiling limit of 10+5 mg/kg is equivalent to a chemical representing 10% by weight of the soil sample. At this contaminant concentration (and higher), the assumptions for soil contact may be violated (for example, soil adherence and wind-borne dispersion assumptions) due to the presence of the foreign substance itself.

5.12 Target Risk

With the exceptions described previously in Sections 5.6 and 5.7, SLs are chemical concentrations that correspond to fixed levels of risk (i.e., either a one-in-one million [10^{-6}] cancer risk or a noncarcinogenic hazard quotient of 1) in soil, air, and water. In most cases, where a substance causes both cancer and noncancer (systemic) effects, the 10^{-6} cancer risk will result in a more stringent criteria and consequently this value is presented in the printed copy of the Table. SL concentrations that equate to a 10^{-6} cancer risk are indicated by 'ca'. SL concentrations that equate to a hazard quotient of 1 for noncarcinogenic concerns are indicated by 'nc'.

If the SLs are to be used for site screening, it is recommended that both cancer and noncancer-based SLs be used. Both carcinogenic and noncarcinogenic values may be obtained in the Supporting Tables.

Some users of this SL Table may plan to multiply the cancer SL concentrations by 10 or 100 to set 'action levels' for triggering remediation or to set less stringent cleanup levels for a specific site after considering non-risk-based factors such as ambient levels, detection limits, or technological feasibility. This risk management practice recognizes that there may be a range of values that may be 'acceptable' for carcinogenic risk (EPA's risk management range is one-in-a-million [10^{-6}] to one-in-ten thousand [10^{-4}]). However, this practice could lead one to overlook serious noncancer health threats and it is strongly recommended that the user consult with a toxicologist or regional risk assessor before doing this. Carcinogens are indicated by an asterisk (*) in the SL Table where the noncancer SLs would be exceeded if the cancer value that is displayed is multiplied by 100. (***) indicate that the noncancer values would be exceeded if the cancer SL were multiplied by 10. There is no range of

'acceptable' noncarcinogenic 'risk' for CERCLA sites. Therefore, the noncancer SLs should not be multiplied by 10 or 100 when setting final cleanup criteria. In the rare case where noncancer SLs are more stringent than cancer SLs set at one-in-one-million risk, a similar approach has been applied (e.g. 'max').

SL concentrations in the printed Table are risk-based, but for soil there are two important exceptions: (1) for several volatile chemicals, SLs may exceed the soil saturation level ('sat') and (2) SLs may exceed a non-risk based 'ceiling limit' concentration of 10^{+5} mg/kg ('max') for relatively less toxic inorganic and semivolatile contaminant. For more information on the 'sat' value in the SL Table, please see the discussion in Section 5.10. For more information on the 'max' value in the SL Table, please see the discussion in Section 5.11.

With respect to applying a 'ceiling limit' for chemicals other than volatiles, it is recognized that this is not a universally accepted approach. Some within the agency argue that all values should be risk-based to allow for scaling (for example, if the risk-based SL is set at a hazard quotient = 1.0, and the user would like to set the hazard quotient to 0.1 to take into account multiple chemicals, then this is as simple as multiplying the risk-based SL by 1/10th). If scaling is necessary, SL users can do this simply by referring to the Supporting Tables at this website where risk-based soil concentrations are presented for all chemicals.

In spite of the fact that applying a ceiling limit is not a universally accepted approach, this table applies a 'max' soil concentration to the SL Table for the following reasons:

Risk-based SLs for some chemicals in soil exceed unity ($>1,000,000$ mg/kg), which is not possible.

The ceiling limit of 10^{+5} mg/kg is equivalent to a chemical representing 10% by weight of the soil sample. At this contaminant concentration (and higher), the assumptions for soil contact may be violated (for example, soil adherence and wind-borne dispersion assumptions) due to the presence of the foreign substance itself.

SLs currently do not address short-term exposures (e.g., pica children and construction workers). Although extremely high soil SLs are likely to represent relatively non-toxic chemicals, such high values may not be justified if in fact more toxicological data were available for evaluating short-term and/or acute exposures.

5.13 Screening Sites with Multiple Contaminants

The screening levels in the tables are calculated under the assumption that only one contaminant is present. Users needing to screen sites with multiple contaminants should consult with their regional risk assessors. The following sections describe how target risks can be changed to screen against multiple contaminants and how the ratio of concentration to RSL can be used to estimate total risk.

5.13.1 Adjusting Target Risk and Target Hazard Quotient

When multiple contaminants are present at a site the target hazard quotient (THQ) may be modified. The following options are among the commonly used methods to modify the THQ:

1. The [calculator](#) on this website can be used to generate SLs based on any THQ or target cancer risk (TR) deemed appropriate by the user. The THQ input to the

calculator can be modified from the default of 1. How much it should be modified is a user decision, but it could be based upon the number of contaminants being screened together. For example, if one is screening two contaminants together, then the THQ could be modified to 0.5. If ten contaminants are being screened together, then the THQ could be modified to 0.1. The above example weights each chemical equally; it is also possible to weight the chemicals unequally, as long as the total risk meets the desired goal. The decision of how to weight the chemicals is likely to be site-specific, and it is recommended that this decision be made in consultation with the regional risk assessor.

Note that when the TR or THQ is altered, the relationship between cancer-based and noncancer-based SLs may change. At certain risk levels, the cancer-based number may be more conservative; at different risk levels, the noncancer-based number may be more conservative. The data user needs to consider both cancer and noncancer endpoints.

2. Similar to the above approach of using the calculator to recalculate SLs based on non-default target levels, the values in the screening tables themselves can be addressed directly. Consistent with the above logic, although the EPA Superfund Program has not developed guidance on this, it is not uncommon that Superfund sites are screened at a THQ of 0.1. (The cancer-based SLs are already at a target risk of 1E-6 and are usually not adjusted further in this scenario.) SLs based on a THQ of 0.1 can be derived by dividing a default SL by 10. Again, note that altering the target HQ can change the relationship between cancer-based and noncancer-based screening levels; the data user needs to consider both endpoints. Additional approaches or alternatives may exist. When screening actual or potential Superfund sites, users are encouraged to consult with risk assessors in that EPA Regional Office when evaluating or screening contamination at a site with multiple contaminants to see if they may know of another approach or if they have a preference.

5.13.2 Using RSLs to Sum Risk from Multiple Contaminants

RSLs can be used to estimate the total risk from multiple contaminants at a site as part of a screening procedure used by some regions. This methodology, which does not substitute for a baseline risk assessment, is often called the "sum of the ratios" approach. A step-wise approach follows:

1. Perform an extensive records search and compile existing data.
2. Identify site contaminants in the SL Table. Record the SL concentrations for various media and note whether SL is based on cancer risk (indicated by 'c') or noncancer hazard (indicated by 'n'). Segregate cancer SLs from non-cancer SLs and exclude (but don't eliminate) non-risk based SLs 's' or 'm'.
3. For cancer risk estimates, take the site-specific concentration (maximum or 95th percentile of the upper confidence on the mean (UCL)) and divide by the SL concentrations that are designated for cancer evaluation 'c'. Multiply this ratio by 10⁻⁶ to estimate chemical-specific risk for a reasonable maximum exposure (RME). For multiple pollutants, simply add the risk for each chemical. See equation below.

$$\text{Risk} = \left[\left(\frac{\text{conc}_x}{\text{SL}_x} \right) + \left(\frac{\text{conc}_y}{\text{SL}_y} \right) + \left(\frac{\text{conc}_z}{\text{SL}_z} \right) \right] \times 10^{-6}$$

4. For non-cancer hazard estimates, divide the concentration term by its respective non-cancer SL designated as 'n' and sum the ratios for multiple contaminants. The cumulative ratio represents a non-carcinogenic hazard index (HI). A hazard index of 1 or less is generally considered 'safe'. A ratio greater than 1 suggests further evaluation. Note that carcinogens may also have an associated non-cancer SL that is not listed in the SL Table. To obtain these values, the user should view the Supporting Tables. See equation below.

$$\text{Hazard Index} = \left[\left(\frac{\text{conc}_x}{\text{SL}_x} \right) + \left(\frac{\text{conc}_y}{\text{SL}_y} \right) + \left(\frac{\text{conc}_z}{\text{SL}_z} \right) \right]$$

5.14 Deriving Soil Gas SLs

The air SLs could apply to indoor air from, e.g., a vapor intrusion scenario. To model indoor air concentrations from other media (e.g., soil gas, groundwater), consult with regional experts in vapor intrusion.

For more information on EPA's current understanding of this emerging exposure pathway, please refer to EPA's recent draft guidance Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance) (USEPA 2002) available on the web at: <http://www.epa.gov/osw/hazard/correctiveaction/eis/vapor.htm>.

5.15 Mutagens

Some of the cancer causing analytes in this tool operate by a mutagenic mode of action for carcinogenesis. There is reason to surmise that some chemicals with a mutagenic mode of action, which would be expected to cause irreversible changes to DNA, would exhibit a greater effect in early-life versus later-life exposure. Cancer risk to children in the context of the U.S. Environmental Protection Agency's cancer guidelines (U.S. EPA, 2005) includes both early-life exposures that may result in the occurrence of cancer during childhood and early-life exposures that may contribute to cancers later in life. In keeping with this guidance, separate cancer risk equations are presented for mutagens. The mutagen vinyl chloride has a unique set of equations. Consult [Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens, EPA/630/R-03/003F, March 2005](#) for further information.

<http://www.epa.gov/oswer/riskassessment/sghandbook/chemicals.htm> provides more detailed information about which contaminants are considered carcinogenic by a mutagenic mode of action. In addition to the previous document's list of these contaminants, Chromium VI is also now considered carcinogenic by a mutagenic mode of action.

6. Using the Calculator

The [Calculator](#) can be used to generate site-specific SLs or PRGs. The calculator requires the user to make some simple selections. To use the calculator Select a landuse. Next, select

whether you want Default or Site-specific SLs. Selecting default screening levels will reproduce the results in the generic Generic Tables. Selecting Site-Specific will allow you to change exposure parameters. Now pick your analytes. To pick several in a row, depress the left mouse button and drag, then release. Or hold the Ctrl key down and select multiple analytes that are not in a row. Select the output option. Hit the retrieve button. If you selected Site-Specific, the next page allows you to change exposure parameters. Hit the retrieve button. SLs are being calculated. The first table presents the input parameters that were selected. The next table contains the screening levels. This table can be too big to print. The easiest way to manage this table is to move it to a spreadsheet or a database. To copy this table, hold the left mouse key down and drag across the entire table. when done, press Ctrl c to copy. Switch to a spreadsheet and press Ctrl v to paste.

Table 1. Standard Default Factors

Symbol	Definition (units)	Default	Reference
SLs			
SL _{res-air-ca}	Resident Air Carcinogenic ($\mu\text{g}/\text{m}^3$)	Contaminant-specific	Determined in this calculator
SL _{res-air-ca-vinyl chloride}	Resident Air Carcinogenic Vinyl Chloride ($\mu\text{g}/\text{m}^3$)	Vinyl Chloride-specific	Determined in this calculator
SL _{res-air-mu}	Resident Air Mutagenic ($\mu\text{g}/\text{m}^3$)	Mutagen-specific	Determined in this calculator
SL _{res-air-nc}	Resident Air Noncarcinogenic ($\mu\text{g}/\text{m}^3$)	Contaminant-specific	Determined in this calculator
SL _{res-fsh-ca-ing}	Resident Fish Carcinogenic (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-fsh-nc-ing}	Resident Fish Noncarcinogenic (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{water-ca-ing}	Resident Tapwater Groundwater Carcinogenic Ingestion ($\mu\text{g}/\text{L}$)	Contaminant-specific	Determined in this calculator
SL _{water-ca-inh}	Resident Tapwater Groundwater Carcinogenic Inhalation ($\mu\text{g}/\text{L}$)	Contaminant-specific	Determined in this calculator
SL _{water-ca-tot}	Resident Tapwater Groundwater Carcinogenic Total ($\mu\text{g}/\text{L}$)	Contaminant-specific	Determined in this calculator
SL _{res-water-ca-vc-ing}	Resident Tapwater Groundwater Carcinogenic Vinyl Chloride Ingestion ($\mu\text{g}/\text{L}$)	Contaminant-specific	Determined in this calculator
SL _{res-water-ca-vc-inh}	Resident Tapwater Groundwater Carcinogenic Vinyl Chloride Inhalation ($\mu\text{g}/\text{L}$)	Contaminant-specific	Determined in this calculator
SL _{res-water-ca-vc-tot}	Resident Tapwater Groundwater Carcinogenic Vinyl Chloride Total ($\mu\text{g}/\text{L}$)	Contaminant-specific	Determined in this calculator
SL _{water-mu-ing}	Resident Tapwater Groundwater Mutagenic Ingestion ($\mu\text{g}/\text{L}$)	Contaminant-specific	Determined in this calculator
SL _{water-mu-inh}	Resident Tapwater Groundwater Mutagenic Inhalation ($\mu\text{g}/\text{L}$)	Mutagen-specific	Determined in this calculator

SL _{water-mu-tot}	Resident Tapwater Groundwater Mutagenic Total (µg/L)	Contaminant-specific	Determined in this calculator
SL _{water-nc-ing}	Resident Tapwater Groundwater Noncarcinogenic Ingestion (µg/L)	Contaminant-specific	Determined in this calculator
SL _{water-nc-inh}	Resident Tapwater Groundwater Noncarcinogenic Inhalation (µg/L)	Mutagen-specific	Determined in this calculator
SL _{water-nc-tot}	Resident Tapwater Groundwater Noncarcinogenic Total (µg/L)	Contaminant-specific	Determined in this calculator
SL _{res-sol-ca-ing}	Resident Soil Carcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-sol-ca-der}	Resident Soil Carcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-sol-ca-inh}	Resident Soil Carcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-sol-ca-tot}	Resident Soil Carcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-soil-ca-vc-ing}	Resident Soil Carcinogenic Vinyl Chloride Ingestion (mg/kg)	Vinyl Chloride - specific	Determined in this calculator
SL _{res-soil-ca-vc-der}	Resident Soil Carcinogenic Vinyl Chloride Dermal (mg/kg)	Vinyl Chloride-specific	Determined in this calculator
SL _{res-soil-ca-vc-inh}	Resident Soil Carcinogenic Vinyl Chloride Inhalation (mg/kg)	Vinyl Chloride-specific	Determined in this calculator
SL _{res-soil-ca-vc-tot}	Resident Soil Carcinogenic Vinyl Chloride Total (mg/kg)	Vinyl Chloride-specific	Determined in this calculator
SL _{res-sol-mu-ing}	Resident Soil Mutagenic Ingestion (mg/kg)	Mutagen-specific	Determined in this calculator
SL _{res-sol-mu-der}	Resident Soil Mutagenic Dermal (mg/kg)	Mutagen-specific	Determined in this calculator
SL _{res-sol-mu-inh}	Resident Soil Mutagenic Inhalation (mg/kg)	Mutagen-specific	Determined in this calculator
SL _{res-sol-mu-tot}	Resident Soil Mutagenic Total (mg/kg)	Mutagen-specific	Determined in this calculator
SL _{res-sol-nc-ing}	Resident Soil Noncarcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-sol-nc-der}	Resident Soil Noncarcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-sol-nc-inh}	Resident Soil Noncarcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{res-sol-nc-tot}	Resident Soil Noncarcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{w-sol-ca-ing}	Composite Worker Soil Carcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{w-sol-ca-der}	Composite Worker Soil Carcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{w-sol-ca-inh}	Composite Worker Soil Carcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{w-sol-ca-tot}	Composite Worker Soil Carcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator

SL _{w-sol-nc-ing}	Composite Worker Soil Noncarcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{w-sol-nc-der}	Composite Worker Soil Noncarcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{w-sol-nc-inh}	Composite Worker Soil Noncarcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{w-sol-nc-tot}	Composite Worker Soil Noncarcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-ca-ing}	Indoor Worker Soil Carcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-ca-der}	Indoor Worker Soil Carcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-ca-inh}	Indoor Worker Soil Carcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-ca-tot}	Indoor Worker Soil Carcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-nc-ing}	Indoor Worker Soil Noncarcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-nc-der}	Indoor Worker Soil Noncarcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-nc-inh}	Indoor Worker Soil Noncarcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{iw-sol-nc-tot}	Indoor Worker Soil Noncarcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-ca-ing}	Outdoor Worker Soil Carcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-ca-der}	Outdoor Worker Soil Carcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-ca-inh}	Outdoor Worker Soil Carcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-ca-tot}	Outdoor Worker Soil Carcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-nc-ing}	Outdoor Worker Soil Noncarcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-nc-der}	Outdoor Worker Soil Noncarcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-nc-inh}	Outdoor Worker Soil Noncarcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{ow-sol-nc-tot}	Outdoor Worker Soil Noncarcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-sol-ca-ing}	Recreator Soil Carcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator

SL _{rec-sol-ca-der}	Recreator Soil Carcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-sol-ca-inh}	Recreator Soil Carcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-sol-ca-tot}	Recreator Soil Carcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-sol-nc-ing}	Recreator Soil Noncarcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-sol-nc-der}	Recreator Soil Noncarcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-sol-nc-inh}	Recreator Soil Noncarcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-sol-nc-tot}	Recreator Soil Noncarcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
SL _{rec-water-ca-der}	Recreator Surface Water Carcinogenic Dermal (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-ca-ing}	Recreator Surface Water Carcinogenic Ingestion (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-ca-tot}	Recreator Surface Water Carcinogenic Total (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-vc-der}	Recreator Surface Water Carcinogenic Vinyl Chloride Dermal (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-vc-ing}	Recreator Surface Water Carcinogenic Vinyl Chloride Ingestion (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-vc-tot}	Recreator Surface Water Carcinogenic Vinyl Chloride Total (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-nc-der}	Recreator Surface Water Non-Carcinogenic Dermal (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-nc-ing}	Recreator Surface Water Non-Carcinogenic Ingestion (µg/L)	Contaminant-specific	Determined in this calculator
SL _{rec-water-nc-tot}	Recreator Surface Water Non-Carcinogenic Total (µg/L)	Contaminant-specific	Determined in this calculator
Toxicity Values			
RfD _o	Chronic Oral Reference Dose (mg/kg-day)	Contaminant-specific	EPA Superfund hierarchy
RfC	Chronic Inhalation Reference Concentration (mg/m ³)	Contaminant-specific	EPA Superfund hierarchy
CSF _o	Chronic oral Slope Factor (mg/kg-day) ⁻¹	Contaminant-specific	EPA Superfund hierarchy
IUR	Chronic Inhalation Unit Risk (µg/m ³) ⁻¹	Contaminant-specific	EPA Superfund hierarchy
Miscellaneous Variables			
TR	target risk	1 × 10 ⁻⁶	Determined in this calculator
THQ	target hazard quotient	1	Determined in this calculator
K _p	Andelman Volatilization Factor (L/m ³)	0.5	U.S. EPA 1991b (pg. 20)

AT _r	Averaging time - resident (days/year)	365	U.S. EPA 1989 (pg. 6-23)
AT _w	Averaging time - composite worker (days/year)	365	U.S. EPA 1989 (pg. 6-23)
AT _{iw}	Averaging time - indoor worker (days/year)	365	U.S. EPA 1989 (pg. 6-23)
AT _{ow}	Averaging time - outdoor worker (days/year)	365	U.S. EPA 1989 (pg. 6-23)
AT _{rec}	Averaging time - recreator (days/year)	365	U.S. EPA 1989 (pg. 6-23)
LT	Lifetime (years)	70	U.S. EPA 1989 (pg. 6-22)
Ingestion, and Dermal Contact Rates			
IRW _c	Resident Drinking Water Ingestion Rate - Child (L/day)	1	U.S. EPA 1989 (Exhibit 6-11)
IRW _a	Resident Drinking Water Ingestion Rate - Adult (L/day)	2	U.S. EPA 1989 (Exhibit 6-11)
IFW _{adj}	Resident Drinking Water Ingestion Rate - Age-adjusted (L-year/kg-day)	1.086	Calculated using the age adjusted intake factors equation
IFWM _{adj}	Resident Mutagenic Drinking Water Ingestion Rate - Age-adjusted (L-year/kg-day)	3.39	Calculated using the age adjusted intake factors equation
IRS _c	Resident Soil Ingestion Rate - Child (mg/day)	200	U.S. EPA 1991a (pg. 15)
IRS _a	Resident Soil Ingestion Rate - Adult (mg/day)	100	U.S. EPA 1991a (pg. 15)
IFS _{adj}	Resident Soil Ingestion Rate - Age-adjusted (mg-year/kg-day)	114	Calculated using the age adjusted intake factors equation
IFSM _{adj}	Resident Mutagenic Soil Ingestion Rate - Age-adjusted (mg-year/kg-day)	489.5	Calculated using the age adjusted intake factors equation
IR _{iw}	Indoor Worker Soil Ingestion Rate (mg/day)	50	Calculated using the age adjusted intake factors equation
IR _{ow}	Outdoor Worker Soil Ingestion Rate (mg/day)	100	Calculated using the age adjusted intake factors equation
IRW _{recwc}	Recreator Surface Water Ingestion Rate - Child (L/day)		Calculated using the age adjusted intake factors equation
IRW _{recwa}	Recreator Surface Water Ingestion Rate - Adult (L/day)		Calculated using the age adjusted intake factors equation
IFW _{rec-adj}	Recreator Surface Water Ingestion Rate - Age-adjusted (L-year/kg-day)		Calculated using the age adjusted intake factors equation
IRW ₀₋₂	Recreator Surface Water Ingestion Rate - Age Segment 0-2 (L/day)	0.05	U.S. EPA Region 4
IRW ₂₋₆	Recreator Surface Water Ingestion Rate - Age Segment 2-6 (L/day)	0.05	U.S. EPA Region 4

IRW ₆₋₁₆	Recreator Surface Water Ingestion Rate - Age Segment 6-16 (L/day)	0.05	U.S. EPA Region 4
IRW ₁₆₋₃₀	Recreator Surface Water Ingestion Rate - Age Segment 16-30 (L/day)	0.05	U.S. EPA Region 4
IFWM _{rec-adj}	Recreator Mutagenic Surface Water Ingestion Rate - Age-adjusted (L-year/kg-day)		Calculated using the age adjusted intake factors equation
IRS _{recsc}	Recreator Soil Ingestion Rate - Child (mg/day)		Calculated using the age adjusted intake factors equation
IRS _{recsa}	Recreator Soil Ingestion Rate - Adult (mg/day)		Calculated using the age adjusted intake factors equation
IFS _{rec-adj}	Recreator Soil Ingestion Rate - Age-adjusted (mg-year/kg-day)		Calculated using the age adjusted intake factors equation
IRS ₀₋₂	Recreator Soil Ingestion Rate - Age-segment 0-2 (mg/day)	200	U.S. EPA 1991a (pg. 15)
IRS ₂₋₆	Recreator Soil Ingestion Rate - Age-segment 2-6 (mg/day)	200	U.S. EPA 1991a (pg. 15)
IRS ₆₋₁₆	Recreator Soil Ingestion Rate - Age-segment 6-16 (mg/day)	100	U.S. EPA 1991a (pg. 15)
IRS ₁₆₋₃₀	Recreator Soil Ingestion Rate - Age-segment 16-30 (mg/day)	100	U.S. EPA 1991a (pg. 15)
IFSM _{rec-adj}	Recreator Mutagenic Soil Ingestion Rate - Age-adjusted (mg-year/kg-day)		Calculated using the age adjusted intake factors equation
DFS _{adj}	Resident soil dermal contact factor- age-adjusted (mg-year/kg-day)	361	Calculated using the age adjusted intake factors equation
DFSM _{adj}	Resident Mutagenic soil dermal contact factor- age-adjusted (mg-year/kg-day)	1445	Calculated using the age adjusted intake factors equation
DFS _{rec-adj}	Recreator soil dermal contact factor- age-adjusted (mg-year/kg-day)		Calculated using the age adjusted intake factors equation
DFSM _{rec-adj}	Recreator Mutagenic soil dermal contact factor- age-adjusted (mg-year/kg-day)		Calculated using the age adjusted intake factors equation
IRF _a	Fish Ingestion Rate (mg/day)	5.4×10^4	U.S. EPA 1991a (pg. 15)
SA _c	Resident soil surface area - child (cm ²)	2800	U.S. EPA 2002 (Exhibit 1-2)
SA _a	Resident soil surface area - adult (cm ²)	5700	U.S. EPA 2002 (Exhibit 1-2)
SA _{ow}	Worker soil surface area - adult (cm ²)	3300	U.S. EPA 2002 (Exhibit 1-2)
SA _{ow}	Worker soil surface area - adult (cm ²)	3300	U.S. EPA 2002 (Exhibit 1-2)

SA _{recsc}	Recreator soil surface area - child (cm ²)		Calculated using the age adjusted intake factors equation
SA _{recca}	Recreator soil surface area - adult (cm ²)		Calculated using the age adjusted intake factors equation
SA ₀₋₂	Recreator soil surface area - age segment 0-2 (cm ²)		
SA ₂₋₆	Recreator soil surface area - age segment 2-6 (cm ²)		
SA ₆₋₁₆	Recreator soil surface area - age segment 6-16 (cm ²)		
SA ₁₆₋₃₀	Recreator soil surface area - age segment 16-30 (cm ²)		
AF _c	Resident soil adherence factor - child (mg/cm ²)	0.2	U.S. EPA 2002 (Exhibit 1-2)
AF _a	Resident soil adherence factor - adult (mg/cm ²)	0.07	U.S. EPA 2002 (Exhibit 1-2)
AF _{ow}	Worker soil adherence factor - child (mg/cm ²)	0.2	U.S. EPA 2002 (Exhibit 1-2)
AF _{recsc}	Recreator soil adherence factor - child (mg/cm ²)		Calculated using the age adjusted intake factors equation
AF _{recca}	Recreator soil adherence factor - adult (mg/cm ²)		Calculated using the age adjusted intake factors equation
AF ₀₋₂	Recreator soil adherence factor - age segment 0-2 (mg/cm ²)		
AF ₂₋₆	Recreator soil adherence factor - age segment 2-6 (mg/cm ²)		
AF ₆₋₁₆	Recreator soil adherence factor - age segment 6-16 (mg/cm ²)		
AF ₁₆₋₃₀	Recreator soil adherence factor - age segment 16-30 (mg/cm ²)		
BW _c	Recreator Body Weight - child (kg)		Calculated using the age adjusted intake factors equation
BW _{recca}	Recreator Body Weight - adult (kg)		Calculated using the age adjusted intake factors equation
BW ₀₋₂	Recreator Body Weight - age segment 0-2 (kg)		
BW ₂₋₆	Recreator Body Weight - age segment 2-6 (kg)		
BW ₆₋₁₆	Recreator Body Weight - age segment 6-16 (kg)		
BW ₁₆₋₃₀	Recreator Body Weight - age segment 16-30 (kg)		
ABS _d	Fraction of contaminant absorbed dermally from soil (unitless)	Contaminant-specific	U.S. EPA 2004 (Exhibit 3-4)

GIABS	Fraction of contaminant absorbed in gastrointestinal tract (unitless) Note: if the GIABS is >50% then it is set to 100% for the calculation of dermal toxicity values.	Contaminant-specific	U.S. EPA 2004 (Exhibit 4-1)
Exposure Frequency, Exposure Duration, and Exposure Time Variables			
EF _r	Resident Exposure Frequency (days/yr)	350	U.S. EPA 1991a (pg. 15)
EF _{iw}	Indoor Worker Exposure Frequency (days/yr)	250	U.S. EPA 1991a (pg. 15)
EF _{ow}	Outdoor Worker Exposure Frequency (days/yr)	225	U.S. EPA 1991a (pg. 15)
EF _{rec}	Recreator Exposure Frequency (days/yr)		Calculated using the age adjusted intake factors equation
EF _{recwc}	Recreator Exposure Frequency - child (days/yr)		Calculated using the age adjusted intake factors equation
EF _{recwa}	Recreator Exposure Frequency - adult (days/yr)		Calculated using the age adjusted intake factors equation
EF ₀₋₂	Recreator Exposure Frequency - age segment 0-2 (days/yr)		
EF ₂₋₆	Recreator Exposure Frequency - age segment 2-6 (days/yr)		
EF ₆₋₁₆	Recreator Exposure Frequency - age segment 6-16 (days/yr)		
EF ₁₆₋₃₀	Recreator Exposure Frequency - age segment 16-30 (days/yr)		
ED _r	Resident Exposure Duration (yr)	30	U.S. EPA 1991a (pg. 15)
ED _c	Resident Exposure Duration - child (yr)	6	U.S. EPA 1991a (pg. 15)
ED _a	Resident Exposure Duration - adult (yr)	24	U.S. EPA 1991a (pg. 15)
ED _{iw}	Indoor Worker Exposure Duration - (yr)	25	U.S. EPA 1991a (pg. 15)
ED _{ow}	Outdoor Worker Exposure Duration (yr)	25	U.S. EPA 1991a (pg. 15)
ED _{rec}	Recreator Exposure Duration (yr)		Calculated using the age adjusted intake factors equation
ED _{recsc}	Recreator Exposure Duration - child (yr)		Calculated using the age adjusted intake factors equation
ED _{recsa}	Recreator Exposure Duration - adult (yr)		Calculated using the age adjusted intake factors equation
ED ₀₋₂	Exposure Duration - age segment 0-2 (yr)		
ED ₂₋₆	Exposure Duration - age segment 2-6 (yr)		

ED ₆₋₁₆	Exposure Duration - age segment 6-16 (yr)		
ED ₁₆₋₃₀	Exposure Duration - age segment 16-30 (yr)		
ET _{ra}	Resident Ambient Air Exposure Time (hr/hr)	24	
ET _{rs}	Resident Soil Exposure Time (hr/hr)	24	
ET _{recs}	Recreator Soil Exposure Time (hr/hr)		Calculated using the age adjusted intake factors equation
ET _{recsc}	Recreator Soil Exposure Time - child (hr/hr)		Calculated using the age adjusted intake factors equation
ET _{recsa}	Recreator Soil Exposure Time - adult (hr/hr)		Calculated using the age adjusted intake factors equation
ET _{recw}	Recreator Surface Water Exposure Time (hr/hr)		Calculated using the age adjusted intake factors equation
ET _{recwc}	Recreator Surface Water Exposure Time - child (hr/hr)		Calculated using the age adjusted intake factors equation
ET _{recwa}	Recreator Surface Water Exposure Time - adult (hr/hr)		Calculated using the age adjusted intake factors equation
ET ₀₋₂	Recreator Exposure Time - age segment 0-2 (hr/hr)		
ET ₂₋₆	Recreator Exposure Time - age segment 2-6 (hr/hr)		
ET ₆₋₁₆	Recreator Exposure Time - age segment 6-16 (hr/hr)		
ET ₁₆₋₃₀	Recreator Exposure Time - age segment 16-30 (hr/hr)		
ET _{recw-adj}	Recreator Exposure Time - age-adjusted (hr/hr)		Calculated using the age adjusted intake factors equation
EV _{recwc}	Recreator Events - child (events per day)		Calculated using the age adjusted intake factors equation
EV _{recwa}	Recreator Events - adult (events per day)		Calculated using the age adjusted intake factors equation
EV ₀₋₂	Recreator Events - age segment 0-2 (events per day)		
EV ₂₋₆	Recreator Events - age segment 2-6 (events per day)		
EV ₆₋₁₆	Recreator Events - age segment 6-16 (events per day)		
EV ₁₆₋₃₀	Recreator Events - age segment 16-30 (events per day)		
Soil to Groundwater SSL Factor Variables			

I	Infiltration Rate (m/year)	0.18	U.S. EPA. 1996a (pg. 31)
L	source length parallel to ground water flow (m)	site-specific	U.S. EPA. 1996a (pg. 31)
i	hydraulic gradient (m/m)	site-specific	U.S. EPA. 1996a (pg. 31)
K	aquifer hydraulic conductivity (m/year)	site-specific	U.S. EPA. 1996a (pg. 31)
θ_w	water-filled soil porosity (L_{water}/L_{soil})	0.3	U.S. EPA. 1996a (pg. 31)
θ_a	air-filled soil porosity (L_{air}/L_{soil})	$= n - \theta_w$	U.S. EPA. 1996a (pg. 31)
n	total soil porosity (L_{pore}/L_{soil})	$= 1 - (\rho_b/\rho_s)$	U.S. EPA. 1996a (pg. 31)
ρ_s	soil particle density (Kg/L)	2.65	U.S. EPA. 1996a (pg. 31)
ρ_b	dry soil bulk density (kg/L)	1.5	U.S. EPA. 1996a (pg. 31)
H'	Dimensionless Henry Law Constant (unitless)	analyte-specific	EPI Suite
K_d	soil-water partition coefficient (L/kg)	$= K_{oc} * f_{oc}$ for organics	U.S. EPA. 1996a (pg. 31)
K_{oc}	soil organic carbon/water partition coefficient (L/kg)	analyte-specific	EPI Suite
f_{oc}	fraction organic carbon in soil (g/g)	0.002	U.S. EPA. 1996a (pg. 31)
d_a	aquifer thickness (m)	site-specific	U.S. EPA. 1996a (pg. 31)
d_s	depth of source (m)	site-specific	U.S. EPA. 1996a (pg. 31)
d	mixing zone depth (m)	site-specific	U.S. EPA. 1996a (pg. 31)
Particulate Emission Factor Variables			
PEF	Particulate Emission Factor - Minneapolis (m^3/kg)	1.36×10^9 (region-specific)	Determined in this calculator
Q/C	Inverse of the Mean Concentration at the Center of a 0.5-Acre-Square Source (g/m^2 -s per kg/m^3)	93.77 (region-specific)	Determined in this calculator
V	Fraction of Vegetative Cover (unitless)	0.5	U.S. EPA 1996a (pg. 23)
U_m	Mean Annual Wind Speed (m/s)	4.69	U.S. EPA 1996a (pg. 23)
U_t	Equivalent Threshold Value of Wind Speed at 7m (m/s)	11.32	U.S. EPA 1996a (pg. 23)
F(x)	Function Dependent on U_m/U_t (unitless)	0.194	U.S. EPA 1996a (pg. 23)
A	Dispersion constant unitless	PEF and region-specific	U.S. EPA 2002 (pg. D-6 to D-8)
A_s	Areal extent of the site or contamination (acres)	0.5 (range 0.5 to 500)	U.S. EPA 2002 (pg. D-2)

B	Dispersion constant unitless	PEF and region-specific	U.S. EPA 2002 (pg. D-6 to D-8)
C	Dispersion constant unitless	PEF and region-specific	U.S. EPA 2002 (pg. D-6 to D-8)
Volatilization Factor and Soil Saturation Limit Variables			
VF	Volatilization Factor - Los Angeles (m^3/kg)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
Q/C_w	Inverse of the Mean Concentration at the Center of a 0.5-Acre-Square Source (g/m^2 -s per kg/m^3)	68.81	U.S. EPA. 1996b (pg. 24)
D_A	Apparent Diffusivity (cm^2/s)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
T	Exposure interval (s)	9.5×10^8	U.S. EPA. 1996b (pg. 24)
ρ_b	Dry soil bulk density (g/cm^3)	1.5	U.S. EPA. 1996b (pg. 24)
θ_a	Air-filled soil porosity (L_{air}/L_{soil}) ($n - \theta_w$)	0.28	U.S. EPA. 1996b (pg. 24)
n	Total soil porosity (L_{pore}/L_{soil}) ($1 - (\rho_b/\rho_s)$)	0.43	U.S. EPA. 1996b (pg. 24)
θ_w	Water-filled soil porosity (L_{water}/L_{soil})	0.15	U.S. EPA. 1996b (pg. 24)
ρ_s	Soil particle density (g/cm^3)	2.65	U.S. EPA. 1996b (pg. 24)
S	Water Solubility Limit (mg/L)	Contaminant-specific	<u>EPI Suite</u>
D_{ia}	Diffusivity in air (cm^2/s)	Contaminant-specific	U.S. EPA. 2001
H'	Dimensionless Henry's Law Constant	Contaminant-specific	<u>EPI Suite</u>
D_{iw}	Diffusivity in water (cm^2/s)	Contaminant-specific	U.S. EPA. 2001
K_d	Soil-water partition coefficient (L/Kg) ($K_{oc} \times f_{oc}$)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
K_{oc}	Soil organic carbon-water partition coefficient (L/Kg)	Contaminant-specific	<u>EPI Suite</u>
f_{oc}	Organic carbon content of soil (g/g)	0.006	U.S. EPA. 1996b (pg. 24)

U.S. EPA (Environmental Protection Agency). 1987. Processes, Coefficients, and Models for Simulation Toxic Organics and Heavy Metals in Surface Waters. EPA/600/3-87/015. Office of Research and Development, Athens, GA.

U.S. EPA 1989. Risk assessment guidance for Superfund. Volume I: Human health evaluation manual (Part A). Interim Final. Office of Emergency and Remedial Response. EPA/540/1-89/002.

U.S. EPA 1991a. Human health evaluation manual, supplemental guidance: "Standard default

exposure factors". OSWER Directive 9285.6-03.
http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/usersguide.htm

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U.S. EPA 1991b. Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part B, Development of Risk-Based Preliminary Remediation Goals). Office of Emergency and Remedial Response. EPA/540/R-92/003. December 1991

U.S. EPA. 1996a. Soil Screening Guidance: User's Guide. Office of Emergency and Remedial Response. Washington, DC. OSWER No. 9355.4-23
<http://www.epa.gov/superfund/health/conmedia/soil/index.htm#user>

U.S. EPA. 1996b. Soil Screening Guidance: Technical Background Document. Office of Emergency and Remedial Response. Washington, DC. OSWER No. 9355.4-17A
<http://www.epa.gov/superfund/health/conmedia/soil/introtbd.htm>

U.S. EPA. 1997a. Exposure Factors Handbook. Office of Research and Development, Washington, DC. EPA/600/P-95/002Fa.

U.S. EPA 2000. Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds. Part I: Estimating Exposure to Dioxin-Like Compounds. Volume 3--Properties, Environmental Levels, and Background Exposures. Draft Final Report. EPA/600/P- 00/001. Office of Research and Development, Washington, DC. September.

U.S. EPA, 2001. WATER9. Version 1.0.0. Office of Air Quality Planning and Standards, Research Triangle Park, NC. Web site at
<http://www.epa.gov/ttn/chief/software/water/index.html>.

U.S. EPA 2002. Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites. OSWER 9355.4-24. December 2002.
<http://www.epa.gov/superfund/health/conmedia/soil/index.htm>

U.S. EPA 2004. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Final. OSWER 9285.7-02EP. July 2004. Document and website
<http://www.epa.gov/oswer/riskassessment/ragse/index.htm>

U.S. EPA 2009. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment) Final. OSWER 9285.7-82. January 2009. Document, memo and website
<http://www.epa.gov/oswer/riskassessment/ragsf/index.htm>

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APPENDIX 3

RELEVANT PORTIONS OF
*USER'S GUIDE FOR THE JOHNSON AND
ETTINGER (1991) MODEL FOR SUBSURFACE
VAPOR INTRUSION INTO BUILDINGS*

SENSITIVITY ANALYSIS OF *JOHNSON AND
ETTINGER (1991) MODEL*

**USER'S GUIDE FOR
EVALUATING SUBSURFACE VAPOR INTRUSION
INTO BUILDINGS**

Prepared By

Environmental Quality Management, Inc.
Cedar Terrace Office Park, Suite 250
3325 Durham-Chapel Hill Boulevard
Durham, North Carolina 27707-2646

Prepared For

Industrial Economics Incorporated
2667 Massachusetts Avenue
Cambridge, Massachusetts 02140

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For Submittal to

Janine Dinan, Work Assignment Manager

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF EMERGENCY AND REMEDIAL RESPONSE
ARIEL RIOS BUILDING, 5202G
1200 PENNSYLVANIA AVENUE, NW
WASHINGTON, D.C. 20460

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DISCLAIMER

This document presents technical and policy recommendations based on current understanding of the phenomenon of subsurface vapor intrusion. This guidance does not impose any requirements or obligations on the U.S. Environmental Protection Agency (EPA) or on the owner/operators of sites that may be contaminated with volatile and toxic compounds. The sources of authority and requirements for addressing subsurface vapor intrusion are the applicable and relevant statutes and regulations. This guidance addresses the assumptions and limitations that need to be considered in the evaluation of the vapor intrusion pathway. This guidance provides instructions on the use of the vapor transport model that originally was developed by P. Johnson and R. Ettinger in 1991 and subsequently modified by EPA in 1998, 2001, and again in November 2002. On November 29, 2002 EPA published Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Federal Register: November 29, 2002 Volume 67, Number 230 Page 71169-71172). This document is intended to be a companion for that guidance. Users of this guidance are reminded that the science and policies concerning vapor intrusion are complex and evolving.

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EPA	Helen Dawson Janine Dinan Jayne Michauo Debbie Newberry David Riley Henry Schuver
IEC	Adena Greenbaum Henry Roman Eric Ruder
EQ	Dave Dunbar Josh Dunbar Tena Pipkin Tom Robertson
Golder Associates	Mr. Ian Hers

WHAT'S NEW IN THIS VERSION!

This revised version of the User's Guide corresponds with the release of Version 3.1 of the Johnson and Ettinger (1991) model (J&E) spreadsheets for estimating subsurface vapor intrusion into buildings. Several things have changed within the models since Version 2 was released in December 2000 and since the original version was released in September 1998. The following represent the major changes in Version 3.1 to be consistent with Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Quality from Groundwater and Soils dated November 25, 2002 as referenced below:

1. Table 1 lists the chemicals that are commonly found at contaminated sites. This list has been expanded from the list of chemicals included in Version 2 of the model. We have also applied certain criteria to determine whether it is appropriate to run the model for these contaminants. Only those contaminants for which all of the toxicological or physical chemical properties needed to make an assessment of the indoor inhalation risk are included in the spreadsheets. A chemical is considered to be sufficiently toxic if the vapor concentration of the pure component poses an incremental life time cancer risk greater than 1×10^{-6} or the noncancer hazard index is greater than 1. A chemical is considered to be sufficiently volatile if its Henry's law constant is 1×10^{-5} atm-m³/mole or greater. The final chemical list for Version 3 includes 108 chemicals.
2. **Chemical Property Data** - The source of chemical data used in the calculation is primarily EPA's Superfund Chemical Data Matrix (SCDM) database. EPA's WATER9 database is used for chemicals not included in the SCDM database. Appendix B contains other data sources. Henry's Law value for cumene is incorrect in the above listed reference. The correct value was determined by using EPA's system performs automated reasoning in chemistry algorithms found in "Prediction of Chemical Reactivity Parameters and Physical Properties of Organic Compounds from Molecular Structure Using SPARE." EPA-2003.
3. **Toxicity Values** – EPA's Integrated Risk Information System (IRIS) is the generally preferred source of carcinogenic unit risks and non-carcinogenic reference concentrations (RfCs) for inhalation exposure.¹ The following two sources were consulted, in order of preference, when IRIS values were not available: provisional toxicity values recommended by EPA's National Center for Environmental Assessment (NCEA) and EPA's Health Effects Assessment Summary Tables (HEAST). If no inhalation toxicity data could be obtained from IRIS, NCEA, or HEAST, extrapolated unit risks and/or RfCs using toxicity data for oral exposure (cancer slope factors and/or reference doses, respectively) from these same sources

¹ U.S. EPA. 2002. Integrated Risk Information System (IRIS). <http://www.epa.gov/iriswebp/iris/index.html>. November.

using the same preference order were used.² Note that for most compounds, extrapolation from oral data introduces considerable uncertainty into the resulting inhalation value. Values obtained from inhalation studies or from pharmacokinetic modeling applied to oral doses will be less uncertain than those calculated using the equations noted in footnote 2.

IRIS currently does not include carcinogenicity data for trichloroethylene (TCE), a volatile contaminant frequently encountered at hazardous waste sites. The original carcinogenicity assessment for TCE, which was based on a health risk assessment conducted in the late 1980's, was withdrawn from IRIS in 1994. The Superfund Technical Support Center has continued to recommend use of the cancer slope factor from the withdrawn assessment, until a reassessment of the carcinogenicity of TCE is completed. In 2001, the Agency published a draft of the TCE toxicity assessment for public comment.³ Using this guidance, TCE target concentrations for the draft vapor intrusion guidance were calculated using a cancer slope factor identified in that document, which is available on the NCEA web site. This slope factor was selected because it is based on state-of-the-art methodology. However, because this document is still undergoing review, the slope factor and the target concentrations calculated for TCE are subject to change and should be considered "provisional" values.

Toxicity databases such as IRIS are routinely updated as new information becomes available; the data included in the lookup tables are current as of December 2003. Users of these models are strongly encouraged to research the latest toxicity values for contaminants of interest from the sources noted above. In the next year, IRIS reassessments are expected for several contaminants commonly found in subsurface contamination whose inhalation toxicity values are currently based on extrapolation.

4. Assumption and Limitations

The Johnson and Ettinger (J&E) Model 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 assumptions of the J&E Model as implemented in EPA's spreadsheet version are listed in Section 2.11, Section 5, and

² The oral-to-inhalation extrapolations assume an adult inhalation rate (IR) of 20 m³/day and an adult body weight (BW) of 70 kg. Unit risks (URs) were extrapolated from cancer slope factors (CSFs) using the following equation:

$$\text{UR } (\mu\text{g}/\text{m}^3)^{-1} = \text{CSF } (\text{mg}/\text{kg}/\text{d})^{-1} * \text{IR } (\text{m}^3/\text{d}) * (1/\text{BW})(\text{kg}^{-1}) * (10^{-3} \text{ mg}/\mu\text{g})$$

Reference concentrations (RfCs) were extrapolated from reference doses (RfDs) using the following equation:

$$\text{RfC } (\text{mg}/\text{m}^3) = \text{RfD } (\text{mg}/\text{kg}/\text{d}) * (1/\text{IR}) (\text{m}^3/\text{d})^{-1} (\text{BW } (\text{kg})$$

³ US EPA, Trichloroethylene Health Risk Assessment: Synthesis and Characterization – External Review Draft, Office of Research and Development, EPA/600/P-01-002A, August, 2001.

Table 12 along with an assessment of the likelihood that the assumptions can be verified through field evaluation.

5. Soil Parameters

A list of generally reasonable, yet conservative, model input parameters for selected soil and sampling related parameters are provided in Tables 7 and 8. These tables also provide the practical range, typical or mean value (if applicable), and most conservative value for these parameters. For building parameters with low uncertainty and sensitivity, only a single “fixed” value corresponding to the mean or typical value is provided in Table 9. Soil-dependent properties are provided in Table 10 for soils classified according to the US Soil Conservation Soil (SCS) system. If site soils are not classified according to the US SCS, Table 11 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. These input parameters were developed considering soil-physics science, available studies of building characteristics, and expert opinion. Consequently, the input parameters listed in Tables 7 and 8 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. The soil water filled porosity (θ_w) is dependent on the soil type and the default value was removed from the model set up. Users must define soil type or input a value for the porosity.

6. Building Parameters

Building Air Exchange Rate (Default Value = 0.25 hr⁻¹)

Results from 22 studies for which building air exchange data are available were summarized in Hers et al. (2001). When all the data were analyzed, the 10th, 50th, and 90th percentile values were 0.21, 0.51, and 1.48 air exchanges per hour (AEH). Air exchange rates varied depending on season and climatic region. For example, for the winter season and coldest climatic area (Region 1, Great Lakes area and extreme northeast US), the 10th, 50th, and 90th percentile values were 0.11, 0.27, and 0.71 AEH. In contrast, for the winter season and warmest climatic area [Region 4 (southern California, Texas, Florida, Georgia)], the 10th, 50th, and 90th percentile values were 0.24, 0.48, and 1.13 AEH. For this guidance, a default value of 0.25 for air exchange rate was selected to represent the lower end of these distributions. The previous version of the guidance included a default value of 0.45 exchanges per hour.

Building Area and Subsurface Foundation Area (Default Value = 10 m by 10 m)

A Michigan study indicates that a 111.5 m² area approximately corresponds to the 10th percentile floor space area for residential single family dwellings, based on statistics compiled by the U.S. Department of Commerce (DOC) and U.S. Housing and Urban Development (HUD). The previous median value was 9.61 m x 9.61 m.

Building Mixing Height (Default Value = 2.44 m for slab-on-grade scenario; = 3.66 m for basement scenario)

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 the building height, the 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 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 will be less for houses using electrical baseboard heaters. It is likely that mixing height is, to some degree, correlated to the building air exchange rate.

There are little data available that provide for direct inference of mixing height. There are few sites, with a small number of houses where indoor air concentrations were above background, and where both measurements at ground level and the second floor were made (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 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. Less mixing would be expected for an apartment because there are less cross-floor connections than for a house. The default 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.

Crack Width (0.1 cm) and Crack Ratio (Default Value = 0.0002 for basement house; = 0.0038 for slab-on-grade house)

The crack width and crack ratio are related. 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 and crack width are related as follows:

$$\text{Crack Ratio} = \frac{4(\text{Crack Width} / \sqrt{\text{Subsurface Foundation Area}})}{\text{Subsurface Foundation Area}}$$

There is little information 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 Nazaroff (1992), Revzan et al. (1991), and Nazaroff et al. (1985) range from approximately 0.0001 to 0.001. Another possible approach is to measure crack openings although this, in practice, is difficult to do. Figley and Snodgrass (1992) present data from ten houses where edge crack measurements were made. At the eight houses where cracks were observed, the cracks' 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 is 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) range from 0.0001 to 0.0000001. The VOLASOIL model values correspond to values for a "good" and "bad" foundation, respectively. The crack ratio used by J&E (1991) for illustrative purposes ranged from 0.001 to 0.01. The selected default values fall within the ranges observed.

Q_{soil} (Default Value = 5 L/min)

The method used to estimate the vapor flowrate into a building (Q_{soil}) is an analytical solution for two-dimensional soil gas flow to a small horizontal drain (Nazaroff 1992) ("Perimeter Crack Model"). Use of this model can be problematic in that Q_{soil} values are sensitive to soil-air permeability and consequently a wide range in flows can be predicted.

An alternate empirical approach was selected to determine the Q_{soil} value. This new approach is based on trace tests (i.e., mass balance approach). When soil gas advection is the primary mechanism for tracer intrusion into a building, the Q_{soil} value is estimated by measuring the concentrations of a chemical tracer in indoor air, outdoor air, and in soil vapor below a building, and measuring the building ventilation rate (Hers et al. 2000a; Fischer et al. 1996; Garbesi et al. 1993; Rezvan et al. 1991; Barbese and Sectro 1989). The Q_{soil} values measured using this technique were compared to predicted rates using the Perimeter Crack model, for sites with coarse-grained soils. The Perimeter Crack model predictions are both higher and lower than the measured values, but overall are within one order of magnitude of the measured values. Although the Q_{soil} predicted by the models and measured using field tracer tests are uncertain, the results suggest that a "typical" range for houses on coarse-grained soils is on the order of 1 to 10 L/min. A disadvantage with the tracer

test approach is that there are only limited data, and there do not appear to be any tracer studies for field sites with fine-grained soils.

Because the advective flow zone is relatively limited in extent, the soil type adjacent to the building foundation is of importance. In many cases, coarse-grained imported fill is placed below foundations, and either coarse-grained fill, or disturbed, loose fill is placed adjacent to the foundation walls. Therefore, a conservative approach for the purposes of this guidance is to assume that soil gas flow will be controlled by coarse-grained soil, and not to rely on the possible reduction in flow that would be caused by fine-grained soils near the house foundation. For these reasons, a soil gas flow rate of 5 L/min (midpoint between 1 and 10 L/min) was chosen as the input value.

7. Convenience Changes

- Default values for soil bulk densities have been added to the lookup tables for the various soil types.
- Default values for soil water-filled porosity have been updated within the lookup tables for soil properties for the various soil types.
- The chemical data list has been expanded to include 108 chemicals. Chemical physical properties were reviewed and updated where applicable to provide the user with more accurate values.
- All of the lookup functions within the models were modified to include an exact match parameter, rather than a closest match. The models would previously return data for CAS Numbers not in the lookup tables. Although the DATENTER sheet informed the user that this CAS Number was not found, it would return values on the CHEMPROPS sheet that was the closest match. This caused some confusion and therefore was changed.
- CAS number and soil type pick lists were added to the cells within the models where the user is required to provide data in a specific format. The pick lists were added to assist the user from entering data that are not an acceptable parameter.
- All models were modified to require the user to specify the soil type of each stratum. In addition, a button was added that allows the user to automatically retrieve the default values for the soil type selected. These additions were added as a convenience to the user and soil selection can be ignored should site-specific data be available.
- All models were modified to include an input for the average vapor flow rate into the building (Q_{soil}) in liters/minute (L/min). This value can be left blank and the model will calculate the value of Q_{soil} as was done in previous versions.

- All models were also modified to include a button that will reset the default value on the DATENTER sheet. This button will allow the user to clear all values and reset the default values or reset only those values that have a default value. The user is also allowed to specify whether the values should be reset for the basement or slab-on-grade scenario.

SECTION 1

INTRODUCTION TO THE VAPOR INTRUSION MODEL THEORY AND APPLICATION

Volatilization of contaminants located in subsurface soils or in groundwater, and the subsequent mass transport of these vapors into indoor spaces constitutes a potential inhalation exposure pathway, which may need to be evaluated when preparing risk assessments. Likewise, this potential indoor inhalation exposure pathway may need evaluation when estimating a risk-based soil or groundwater concentration below which associated adverse health effects are unlikely.

Johnson and Ettinger (J&E) (1991) introduced a screening-level model that incorporates both convective and diffusive mechanisms for estimating the transport of contaminant vapors emanating from either subsurface soils or groundwater into indoor spaces located directly above the source of contamination. In their article, J&E 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.

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. The model is constructed as both a steady-state solution to vapor transport (infinite or non-diminishing source) and as a quasi-steady-state solution (finite or diminishing source). Inputs to the model include chemical properties of the contaminant, saturated and unsaturated zone soil properties, and structural properties of the building.

This manual provides documentation and instructions for using the vapor intrusion model as provided in the accompanying spreadsheets.

Model results (both screening and advanced) are provided as either a risk-based soil or groundwater concentration, or as an estimate of the actual incremental risks associated with a user-defined initial concentration. That is to say that the model will reverse-calculate an “acceptable” soil or groundwater concentration given a user-defined risk level (i.e., target risk level or target hazard quotient), or the model may be used to forward-calculate an incremental cancer risk or hazard quotient based on an initial soil or groundwater concentration.

The infinite source models for soil contamination and groundwater contamination should be used as first-tier screening tools. In these models, all but the most sensitive model parameters have

been set equal to central tendency or upper bound values. Values for the most sensitive parameters may be user-defined.

More rigorous estimates may be obtained using site-specific data and the finite source model for soil contamination. Because the source of groundwater contamination may be located upgradient of the enclosed structure for which the indoor inhalation pathway is to be assessed, the advanced model for contaminated groundwater is based on an infinite source of contamination, however, site-specific values for all other model parameters may be user-defined.

In addition to the finite and infinite source models referred to above, two models that allow the user to input empirical soil gas concentration and sampling depth information directly into the spreadsheets. These models will subsequently estimate the resulting steady-state indoor air concentrations and associated health risks.

Because of the paucity of empirical data available for either bench-scale or field-scale verification of the accuracy of these models, as well as for other vapor intrusion models, the user is advised to consider the variation in input parameters and to explore and quantify the impacts of assumptions on the uncertainty of model results. At a minimum, a range of results should be generated based on variation of the most sensitive model parameters.

SECTION 2

MODEL THEORY

Chemical fate and transport within soils and between the soil column and enclosed spaces are determined by a number of physical and chemical processes. This section presents the theoretical framework on which the J&E Model is based, taking into account the most significant of these processes. In addition, this section also presents the theoretical basis for estimating values for some of the most sensitive model parameters when empirical field data are lacking. The fundamental theoretical development of this model was performed by J&E (1991).

2.1 MODEL SETTING

Consider a contaminant vapor source (C_{source}) located some distance (L_T) below the floor of an enclosed building constructed with a basement or constructed slab-on-grade. The source of contamination is either a soil-incorporated volatile contaminant or a volatile contaminant in solution with groundwater below the top of the water table.

Figure 1 is a simplified conceptual diagram of the scenario where the source of contamination is incorporated in soil and buried some distance below the enclosed space floor. At the top boundary of contamination, molecular diffusion moves the volatilized contaminant toward the soil surface until it reaches the zone of influence of the building. Here convective air movement within the soil column transports the vapors through cracks between the foundation and the basement slab floor. This convective sweep effect is induced by a negative pressure within the structure caused by a combination of wind effects and stack effects due to building heating and mechanical ventilation.

Figure 2 illustrates the scenario where the source of contamination is below the top of the water table. Here the contaminant must diffuse through a capillary zone immediately above the water table and through the subsequent unsaturated or vadose zone before convection transports the vapors into the structure.

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, groundwater concentrations, and/or possibly near source soil vapor concentrations. The number of samples and measurements needed to establish this information varies by site, and it is not possible to provide a hard and fast rule.

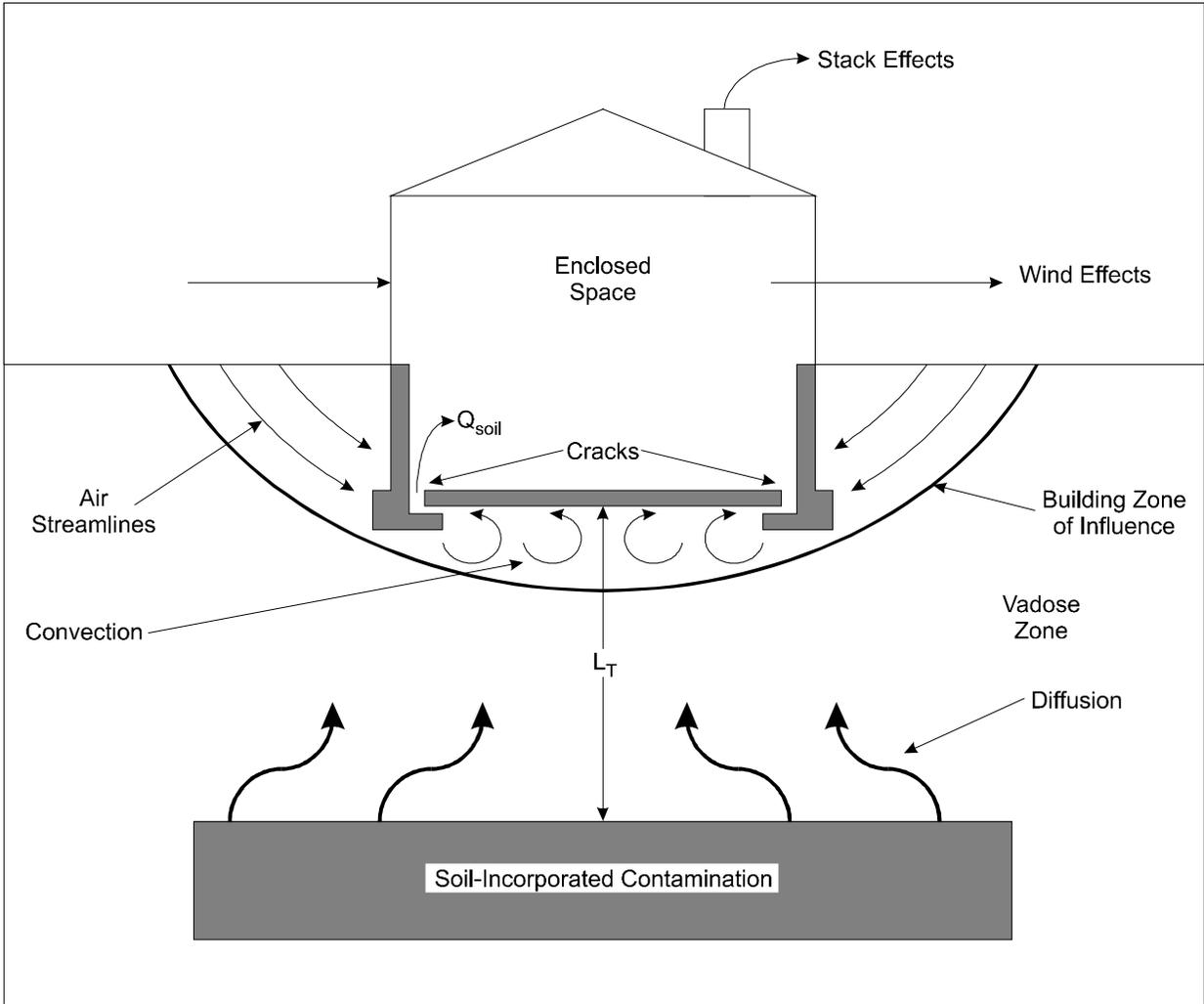


Figure 1. Pathway for Subsurface Vapor Intrusion into Indoor Air

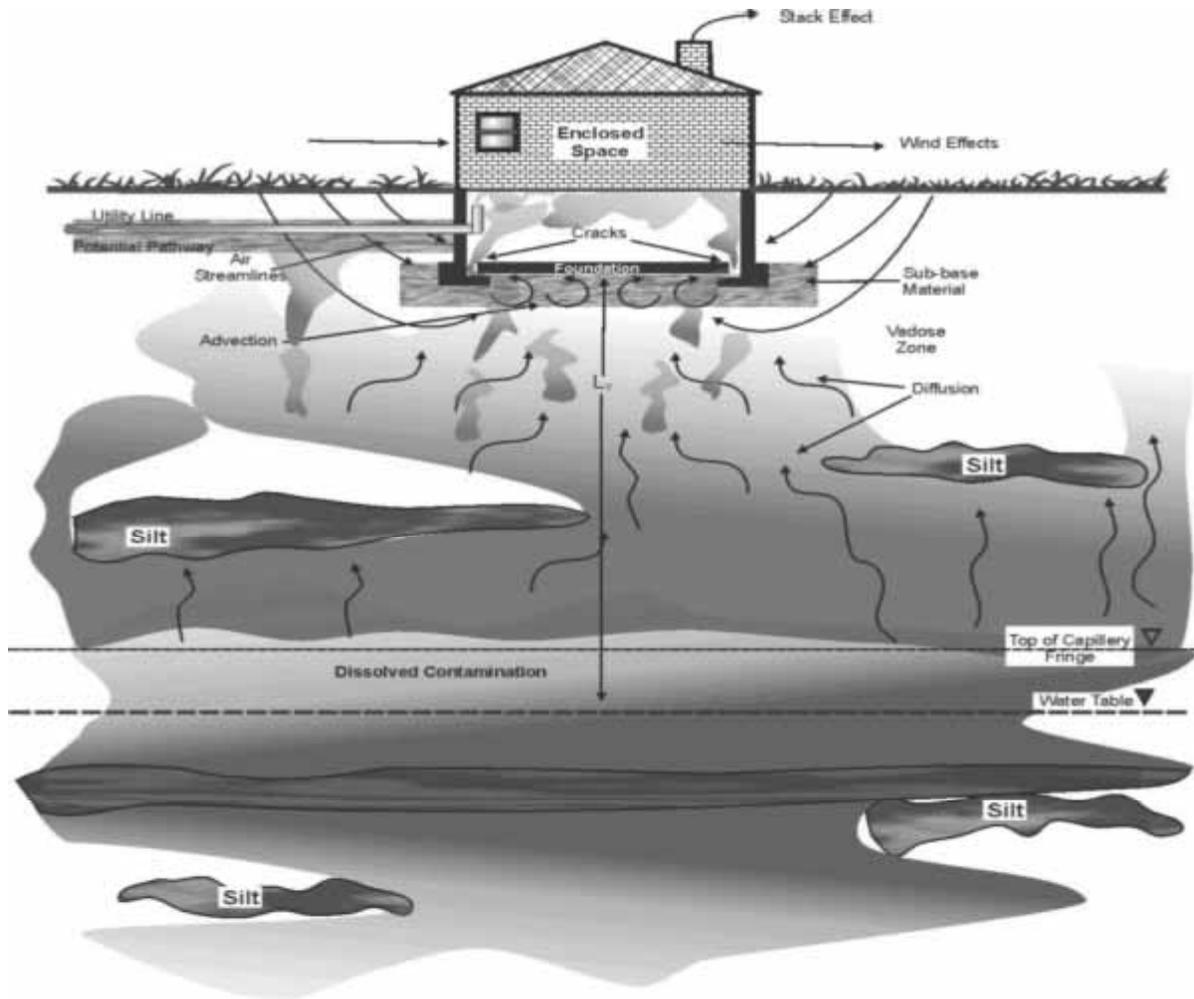


Figure 2. Vapor Pathway into Buildings

Based on the conceptual site model, the user can select the appropriate spreadsheet corresponding to the vapor source at the site and determine whether to use the screening level spreadsheet (which accommodates only one soil type above the capillary fringe) or the more advanced version (which allows up to three layers above the capillary fringe). As most of the inputs to the J&E Model are not collected during a typical site characterization, conservative inputs are typically estimated or inferred from available data and other non-site specific sources of information.

Table 1 lists 114 chemicals that may be found at hazardous waste sites and it indicates whether the chemical is sufficiently toxic and volatile to result in a potentially unacceptable indoor inhalation risk. It also provides a column for checking off the chemicals found or reasonably suspected to be present in the subsurface at a site. Under this approach, a chemical is considered sufficiently toxic if the vapor concentration of the pure component poses an incremental lifetime cancer risk greater than 10^{-6} or results in a non-cancer hazard index greater than one. A chemical is considered sufficiently volatile if its Henry's Law Constant is 1×10^{-5} atm-m³/mol or greater (EPA, 1991). It is assumed that if a chemical does not meet both of these criteria, it need not be further considered as part of the evaluation. Table 1 also identifies six chemicals that meet the toxicity and volatility criteria but are not included in the vapor intrusion models because one or more of the needed physical or chemical properties has not been found in the literature.

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 depending upon the magnitude of the source-building separation (L_T).

2.2 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.

In the case of soil contamination, the initial concentration (C_R) does not contain a residual-phase (e.g., nonaqueous-phase liquid or solid); and in the case of contaminated groundwater, the initial contaminant concentration (C_W) is less than the aqueous solubility limit (i.e., in solution with water).

Given these initial conditions, C_{source} for soil contamination may be estimated from Johnson et al. (1990) as:

$$C_{source} = \frac{H'_{TS} C_R \rho_b}{\theta_w + K_d \rho_b + H'_{TS} \theta_a} \quad (1)$$

where C_{source} = Vapor concentration at the source of contamination, g/cm³-v

H'_{TS} = Henry's law constant at the system (soil) temperature, dimensionless

TABLE 1. SCREENING LIST OF CHEMICALS

CAS No.	Chemical	Is Chemical Sufficiently Toxic? ¹	Is Chemical Sufficiently Volatile? ²	Check Here if Known or Reasonably Suspected to be Present ³
83329	Acenaphthene	YES	YES	
75070	Acetaldehyde	YES	YES	
67641	Acetone	YES	YES	
75058	Acetronitrile	YES	YES	
98862	Acetophenone	YES	YES	
107028	Acrolein	YES	YES	
107131	Acrylonitrile	YES	YES	
309002	Aldrin	YES	YES	
319846	Alpha-HCH (alpha-BHC)	YES	YES	
62533	Aniline	YES	NO	NA
120127	Anthracene	NO	YES	NA
56553	Benz(a)anthracene	YES	NO	NA
100527	Benzaldehyde	YES	YES	
71432	Benzene	YES	YES	
50328	Benzo(a)pyrene	YES	NO	NA
205992	Benzo(b)fluoranthene	YES	YES	
207089	Benzo(k)fluoranthene	NO	NO	NA
65850	Benzoic Acid	NO	NO	NA
100516	Benzyl alcohol	YES	NO	NA
100447	Benzylchloride	YES	YES	
91587	Beta-Chloronaphthalene ³	YES	YES	
319857	Beta-HCH(beta-BHC)	YES	NO	NA
92524	Biphenyl	YES	YES	
111444	Bis(2-chloroethyl)ether	YES	YES	
108601	Bis(2-chloroisopropyl)ether ³	YES	YES	
117817	Bis(2-ethylhexyl)phthalate	NO	NO	NA
542881	Bis(chloromethyl)ether ³	YES	YES	
75274	Bromodichloromethane	YES	YES	
75252	Bromoform	YES	YES	
106990	1,3-Butadiene	YES	YES	
71363	Butanol	YES	NO	NA
85687	Butyl benzyl phthalate	NO	NO	NA
86748	Carbazole	YES	NO	NA
75150	Carbon disulfide	YES	YES	
56235	Carbon tetrachloride	YES	YES	
57749	Chlordane	YES	YES	

(continued)

CAS No.	Chemical	Is Chemical Sufficiently Toxic? ¹	Is Chemical Sufficiently Volatile? ²	Check Here if Known or Reasonably Suspected to be Present ³
126998	2-Chloro-1,3-butadiene(chloroprene)	YES	YES	
108907	Chlorobenzend	YES	YES	
109693	1-Chlorobutane	YES	YES	
124481	Chlorodibromomethane	YES	YES	
75456	Chlorodifluoromethane	YES	YES	
75003	Chloroethane (ethyl chloride)	YES	YES	
67663	Chloroform	YES	YES	
95578	2-Chlorophenol	YES	YES	
75296	2-Chloropropane	YES	YES	
218019	Chrysene	YES	YES	
156592	Cis-1,2-Dichloroethylene	YES	YES	
123739	Crotonaldehyde(2-butenal)	YES	YES	
998828	Cumene	YES	YES	
72548	DDD	YES	NO	NA
72559	DDE	YES	YES	
50293	DDT	YES	NO	NA
53703	Dibenz(a,h)anthracene	YES	NO	NA
132649	Dibenzofuran	YES	YES	
96128	1,2-Dibromo-3-chloropropane ³	YES	YES	
106934	1,2-Dibromoethane(ethylene dibromide)	YES	YES	
541731	1,3-Dichlorobenzene	YES	YES	
95501	1,2-Dichlorobenzene	YES	YES	
106467	1,4-Dichlorobenzene	YES	YES	
91941	3,3-Dichlorobenzidine	YES	NO	NA
75718	Dichlorodifluoromethane	YES	YES	
75343	1,1-Dichloroethane	YES	YES	
107062	1,2-dichloroethane	YES	YES	
75354	1,1-Dichloroethylene	YES	YES	
120832	2,4-Dichloroephenol	YES	NO	NA
78875	1,2-Dichloropropane	YES	YES	
542756	1,3-Dichloropropene	YES	YES	
60571	Dieldrin	YES	YES	
84662	Diethylphthalate	YES	NO	NA
105679	2,4-Dimethylphenol	YES	NO	NA
131113	Dimethylphthalate	NA	NO	NA
84742	Di-n-butyl phthalate	NO	NO	NA

(continued)

CAS No.	Chemical	Is Chemical Sufficiently Toxic? ¹	Is Chemical Sufficiently Volatile? ²	Check Here if Known or Reasonably Suspected to be Present ³
534521	4,6 Dinitro-2methylphenol (4, 6-dinitro-o-cresol)	YES	NO	NA
51285	2,4-Dinitrophenol	YES	NO	NA
121142	2,4-Dinitrotoluene	YES	NO	NA
606202	2,6-Dinitrotoluene	YES	NO	NA
117840	Di-n-octyl phthalate	NO	YES	NA
115297	Endosulfan	YES	YES	
72208	Endrin	YES	NO	NA
106898	Epichlorohydrin ³	YES	YES	
60297	Ethyl ether	YES	YES	
141786	Ethylacetate	YES	YES	
100414	Ethylbenzene	YES	YES	
75218	Ethylene oxide	YES	YES	
97632	Ethylmethacrylate	YES	YES	
206440	Fluoranthene	NO	YES	NA
86737	Fluorene	YES	YES	
110009	Furane	YES	YES	
58899	Gamma-HCH(Lindane)	YES	YES	
76448	Heptachlor	YES	YES	
1024573	Heptachlor epoxide	YES	NO	NA
87683	Hexachloro-1,3-butadiene	YES	YES	
118741	Hexachlorobenzene	YES	YES	
77474	Hexachlorocyclopentadiene	YES	YES	
67721	Hexachloroethane	YES	YES	
110543	Hexane	YES	YES	
74908	Hydrogene cyanide	YES	YES	
193395	Indeno (1,2,3-cd)pyrene	NO	NO	NA
78831	Isobutanol	YES	YES	
78591	Isophorone	YES	NO	NA
7439976	Mercury (elemental)	YES	YES	
126987	Methacrylonitrile	YES	YES	
72435	Methoxychlor	YES	YES	
79209	Methy acetate	YES	YES	
96333	Methyl acrylate	YES	YES	
74839	Methyl bromide	YES	YES	
74873	Methyl chloride (chloromethane)	YES	YES	
108872	Methylcyclohexane	YES	YES	

(continued)

CAS No.	Chemical	Is Chemical Sufficiently Toxic? ¹	Is Chemical Sufficiently Volatile? ²	Check Here if Known or Reasonably Suspected to be Present ³
74953	Methylene bromide	YES	YES	
75092	Methylene chloride	YES	YES	
78933	Methylethylketone (2-butanone)	YES	YES	
108101	Methylisobutylketone (4-methyl-2-pentanone)	YES	YES	
80626	Methylmethacrylate	YES	YES	
91576	2-Methylnaphthalene	YES	YES	
108394	3-Methylphenol(m-cresol)	YES	NO	NA
95487	2-Methylphenol(o-cresol)	YES	NO	NA
106455	4-Methylphenol (p-cresol)	YES	NO	NA
99081	m-Nitrotoluene	YES	NO	NA
1634044	MTBE	YES	YES	
108383	m-Xylene	YES	YES	
91203	Naphthalene	YES	YES	
104518	n-Butylbenzene	YES	YES	
98953	Nitrobenzene	YES	YES	
100027	4-Nitrophenol	YES	NO	NA
79469	2-Nitropropane	YES	YES	
924163	N-nitroso-di-n-butylamine ³	YES	YES	
621647	N-Nitroso-di-n-propylamine	YES	NO	NA
86306	N-Nitrosodiphenylamine	YES	NO	NA
103651	n-Propylbenzene	YES	YES	
88722	o-Nitrotoluene	YES	YES	
95476	o-Xylene	YES	YES	
106478	p-Chloroaniline	YES	NO	NA
87865	Pentachlorophenol	YES	NO	NA
108952	Phenol	YES	NO	NA
99990	p-Nitrotoluene	YES	NO	NA
106423	p-Xylene	YES	YES	
129000	Pyrene	YES	YES	
110861	Pyridine	YES	NO	NA
135988	Sec-Butylbenzene	YES	YES	
100425	Styrene	YES	YES	
98066	Tert-Butylbenzene	YES	YES	
630206	1,1,1,2-Tetrachloroethane	YES	YES	
79345	1,1,2,2,-Tetrachloroethane	YES	YES	
127184	Tetrachloroethylene	YES	YES	

(continued)

CAS No.	Chemical	Is Chemical Sufficiently Toxic? ¹	Is Chemical Sufficiently Volatile? ²	Check Here if Known or Reasonably Suspected to be Present ³
108883	Toluene	YES	YES	
8001352	Toxaphen	YES	NO	NA
156605	Trans-1,2-Dichloroethylene	YES	YES	
76131	1,1,2-Trichloro-1,2,2-trifluoroethane	YES	YES	
120821	1,2,4-Trichlorobenzene	YES	YES	
79005	1,1,2-Trichloroethane	YES	YES	
71556	1,1,1-Trichloroethane	YES	YES	
79016	Trichloroethylene	YES	YES	
75694	Trichlorofluoromethane	YES	YES	
95954	2,4,5-Trichlorophenol	YES	NO	NA
88062	2,4,6-Trichlorophenol	YES	NO	NA
96184	1,2,3-Trichloropropane	YES	YES	
95636	1,2,4-Trimethylbenzene	YES	YES	
108678	1,3,5-Trimethylbenzene	YES	YES	
108054	Vinyl acetate	YES	YES	
75014	Vinyl chloride (chloroethene)	YES	YES	

¹ A chemical is considered sufficiently toxic if the vapor concentration of the pure component poses an incremental lifetime cancer risk greater than 10^{-6} or a non-cancer hazard index greater than 1.

² A chemical is considered sufficiently volatile if its Henry's law constant is 1×10^{-5} atm-m³/mol or greater.

³ One or more of the physical chemical properties required to run the indoor air vapor intrusion models was not found during a literature search conducted March 2003.

- C_R = Initial soil concentration, g/g
 ρ_b = Soil dry bulk density, g/cm³
 θ_w = Soil water-filled porosity, cm³/cm³
 K_d = Soil-water partition coefficient, cm³/g (= K_{oc} x f_{oc})
 θ_a = Soil air-filled porosity, cm³/cm³
 K_{oc} = Soil organic carbon partition coefficient, cm³/g
 f_{oc} = Soil organic carbon weight fraction.

If the initial soil concentration includes a residual phase, the user is referred to the NAPL-SCREEN or NAPL-ADV models as discussed in Appendix A. These models estimate indoor air concentrations and associated risks for up to 10 user-defined contaminants that comprise a residual phase mixture in soils.

C_{source} for groundwater contamination is estimated assuming that the vapor and aqueous-phases are in local equilibrium according to Henry's law such that:

$$C_{source} = H'_{TS} C_w \quad (2)$$

where C_{source} = Vapor concentration at the source of contamination, g/cm³-v

H'_{TS} = Henry's law constant at the system (groundwater) temperature, dimensionless

C_w = Groundwater concentration, g/cm³-w.

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

$$H'_{TS} = \frac{\exp\left[-\frac{\Delta H_{v,TS}}{R_c} \left(\frac{1}{T_S} - \frac{1}{T_R}\right)\right] H_R}{RT_S} \quad (3)$$

where H'_{TS} = Henry's law constant at the system temperature, dimensionless

$\Delta H_{v,TS}$ = 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-m³/mol
 R_C = Gas constant (= 1.9872 cal/mol - °K)
 R = Gas constant (= 8.205 E-05 atm-m³/mol-°K).

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

$$\Delta H_{v,TS} = \Delta H_{v,b} \left[\frac{(1-T_S/T_C)}{(1-T_B/T_C)} \right]^n \quad (4)$$

- where
- $\Delta H_{v,TS}$ = 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 2 gives the value of n as a function of the ratio T_B/T_C .

TABLE 2. VALUES OF EXPONENT n AS A FUNCTION OF T_B/T_C

T_B/T_C	N
< 0.57	0.30
0.57 - 0.71	0.74 (T_B/T_C) - 0.116
> 0.71	0.41

2.3 DIFFUSION THROUGH THE CAPILLARY ZONE

Directly above the water table, a saturated capillary zone exists whereby groundwater is held within the soil pores at less than atmospheric pressure (Freeze and Cherry, 1979). Between drainage and wetting conditions, the saturated water content 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. Therefore, to allow for the calculation of the effective diffusion coefficient by lumping 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:

$$\theta_{w,cz} = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha_1 h)^N\right]^M} \quad (5)$$

- 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 $d\theta_w/dh$ 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 = $1 - (1/N)$.

With a calculated value of $\theta_{w,cz}$ within the capillary zone at the air-entry pressure head, the air-filled porosity within the capillary zone ($\theta_{a,cz}$) corresponding to the minimum value at which gas diffusion is relevant is calculated as the total porosity (n) minus $\theta_{w,cz}$.

Hers (2002) computed the SCS class average values of the water filled porosity and the height of the capillary zone SCS soil textural classifications. Table 3 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 Models. With the class average values presented in Table 3, a general estimate can be made of the values of $\theta_{w,cz}$ and $\theta_{a,cz}$ for each soil textural classification.

The total concentration effective diffusion coefficient across the capillary zone (D_{cz}^{eff}) may then be calculated using the Millington and Quirk (1961) model as:

$$D_{cz}^{eff} = D_a \left(\theta_{a,cz}^{3.33} / n_{cz}^2 \right) + \left(D_w / H'_{TS} \right) \left(\theta_{w,cz}^{3.33} / n_{cz}^2 \right) \quad (6)$$

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, 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'_{TS} = Henry's law constant at the system temperature, dimensionless

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

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

$$E = A(C_{source} - C_{g0})D_{cz}^{eff} / L_{cz} \quad (7)$$

where

E = Rate of mass transfer, g/s

A = Cross-sectional area through which vapors pass, cm^2

C_{source} = Vapor concentration within the capillary zone, g/cm^3-v

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

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

L_{cz} = Thickness of capillary zone, cm .

TABLE 3. 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

The value of C_{source} is calculated using Equation 2; the value of A is assumed to be 1 cm^2 ; and the value of $D_{\text{cz}}^{\text{eff}}$ is calculated by Equation 6. What remains is a way to estimate a value for L_{cz} .

Lohman (1972) and Fetter (1994) estimated the rise of the capillary zone above the water table using the phenomenon of capillary such that 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:

$$L_{\text{cz}} = \frac{2 \alpha_2 \text{COS } \lambda}{\rho_w g R} \quad (8)$$

where

- L_{cz} = Mean rise of the capillary zone, cm
- α_2 = Surface tension of water, g/s (= 73)
- λ = Angle of the water meniscus with the capillary tube, degrees (assumed to be zero)
- ρ_w = Density of water, g/cm³ (= 0.999)
- g = Acceleration due to gravity, cm/s² (= 980)
- R = Mean interparticle pore radius, cm

and;

$$R = 0.2D \quad (9)$$

where

- R = Mean interparticle pore radius, cm
- D = Mean particle diameter, cm.

Assuming that the default values of the parameters given in Equation 8 are for groundwater between 5° and 25°C , Equation 8 reduces to:

$$L_{\text{cz}} = \frac{0.15}{R} \quad (10)$$

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 3). Table 4 shows the centroid compositions and mean particle sizes of the 12 SCS soil textural classes.

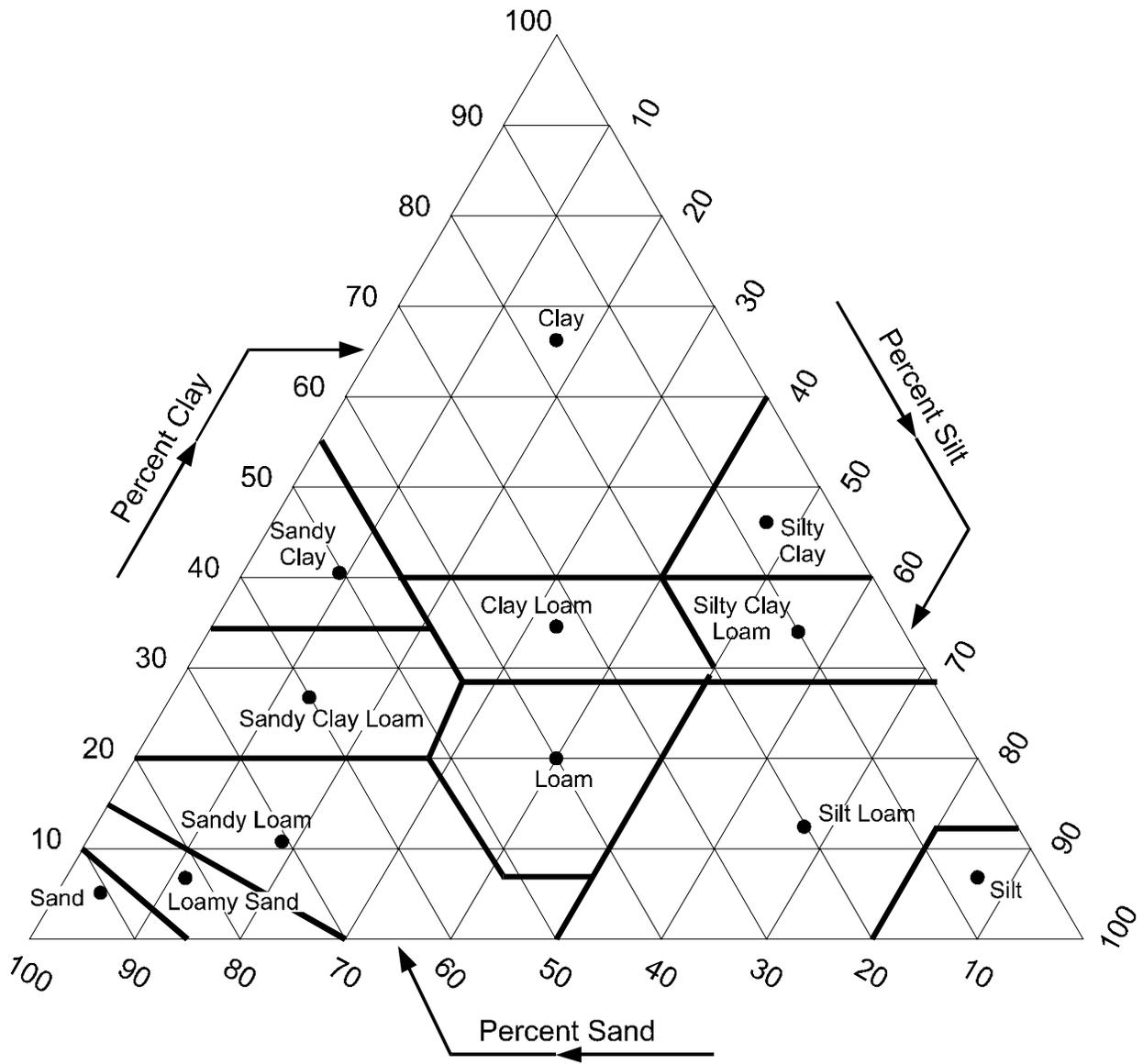


Figure 3. U.S. Soil Conservation Service Classification Chart Showing Centroid Compositions (Solid Circles)

TABLE 4. 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	1.63
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 4, the mean thickness of the capillary zone may then be estimated using Equations 9 and 10.

2.4 DIFFUSION THROUGH THE UNSATURATED ZONE

The effective diffusion coefficient within the unsaturated zone may also be estimated using the same form as Equation 6:

$$D_i^{eff} = D_a \left(\theta_{a,i}^{3.33} / n_i^2 \right) + (D_w / H'_{TS}) \left(\theta_{w,i}^{3.33} / n_i^2 \right) \quad (11)$$

where

- D_i^{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 of layer i, cm^3/cm^3
- D_w = Diffusivity in water, cm^2/s
- $\theta_{w,i}$ = Soil water-filled porosity of layer i, cm^3/cm^3
- H'_{TS} = Henry's law constant at the system temperature, dimensionless

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

$$D_T^{eff} = \frac{L_T}{\sum_{i=0}^n L_i / D_i^{eff}} \quad (12)$$

where

- D_T^{eff} = Total overall effective diffusion coefficient, cm^2/s
- L_i = Thickness of soil layer i, cm
- D_i^{eff} = Effective diffusion coefficient across soil layer i, cm^2/s
- L_T = Distance between the source of contamination and the bottom of the enclosed space floor, cm.

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 12 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 12, but all layers must be located between the source of contamination and the enclosed space floor.

2.5 THE INFINITE SOURCE SOLUTION TO CONVECTIVE AND DIFFUSIVE TRANSPORT

Under the assumption that mass transfer is steady-state, J&E (1991) give the solution for the attenuation coefficient (α) as:

$$\alpha = \frac{\left[\left(\frac{D_T^{\text{eff}} A_B}{Q_{\text{building}} L_T} \right) x \exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D^{\text{crack}} A_{\text{crack}}} \right) \right]}{\left[\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D^{\text{crack}} A_{\text{crack}}} \right) + \left(\frac{D_T^{\text{eff}} A_B}{Q_{\text{building}} L_T} \right) + \left(\frac{D_T^{\text{eff}} A_B}{Q_{\text{soil}} L_T} \right) \left[\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D^{\text{crack}} A_{\text{crack}}} \right) - 1 \right] \right]} \quad (13)$$

where	α	= Steady-state attenuation coefficient, unitless
	D_T^{eff}	= Total overall effective diffusion coefficient, cm^2/s
	A_B	= Area of the enclosed space below grade, cm^2
	Q_{building}	= 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).

The total overall effective diffusion coefficient is calculated by Equation 12. The value of A_B includes the area of the floor in contact with the underlying soil and the total wall area below grade. The building ventilation rate (Q_{building}) may be calculated as:

$$Q_{\text{building}} = (L_B W_B H_B ER) / 3,600 \text{ s} / h \quad (14)$$

where	Q_{building}	= Building ventilation rate, cm^3/s
	L_B	= Length of building, cm
	W_B	= Width of building, cm
	H_B	= Height of building, cm

ER = Air exchange rate, (1/h).

The building dimensions in Equation 14 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.

The volumetric flow rate of soil gas entering the building (Q_{soil}) is calculated by the analytical solution of Nazaroff (1988) such that:

$$Q_{soil} = \frac{2 \pi \Delta P k_v X_{crack}}{\mu \ln(2 Z_{crack} / r_{crack})} \quad (15)$$

where Q_{soil} = Volumetric flow rate of soil gas entering the building, cm^3/s

π = 3.14159

ΔP = Pressure differential between the soil surface and the enclosed space, $g/cm-s^2$

k_v = Soil vapor permeability, cm^2

X_{crack} = Floor-wall seam perimeter, cm

μ = Viscosity of air, $g/cm-s$

Z_{crack} = Crack depth below grade, cm

r_{crack} = Equivalent crack radius, cm.

Equation 15 is an analytical solution to vapor transport solely by pressure-driven air flow to an idealized cylinder buried some distance (Z_{crack}) below grade; the length of the cylinder is taken to be equal to the building floor-wall seam perimeter (X_{crack}). The cylinder, therefore, represents that portion of the building below grade through which vapors pass. The equivalent radius of the floor-wall seam crack (r_{crack}) is given in J&E (1991) as:

$$r_{crack} = \eta (A_B / X_{crack}) \quad (16)$$

where r_{crack} = Equivalent crack radius, cm

η = A_{crack}/A_B , ($0 \leq \eta \leq 1$)

A_B = Area of the enclosed space below grade, cm^2

X_{crack} = Floor-wall seam perimeter, cm.

The variable r_{crack} is actually the product of the fixed crack-to-total area ratio (η) and the hydraulic radius of the idealized cylinder, which is equal to the total area (A_B) divided by that portion of the cylinder perimeter in contact with the soil gas (X_{crack}). Therefore, if the dimensions of the enclosed space below grade (A_B) and/or the floor-wall seam perimeter (X_{crack}) vary, and the crack-to-total area ratio (η) remains constant, the value of r_{crack} must also vary. The total area of cracks (A_{crack}) is the product of η and A_B .

Equation 15 requires that the soil column properties within the zone of influence of the building (e.g., porosities, bulk density, etc.) be homogeneous, that the soil be isotropic with respect to vapor permeability, and that the pressure within the building be less than atmospheric.

Equation 13 contains the exponent of the following dimensionless group:

$$\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}} A_{\text{crack}}} \right) \cdot \quad (17)$$

This dimensionless group represents the equivalent Peclet number for transport through the building foundation. As the value of this group approaches infinity, the value of α approaches:

$$\frac{\left(\frac{D_T^{\text{eff}} A_B}{Q_{\text{building}} L_T} \right)}{\left(\frac{D_T^{\text{eff}} A_B}{Q_{\text{soil}} L_T} \right) + 1} \cdot \quad (18)$$

In the accompanying spreadsheets, if the exponent of Equation 17 is too great to be calculated, the value of α is set equal to Equation 18.

With a calculated value of α , the steady-state vapor-phase concentration of the contaminant in the building (C_{building}) is calculated as:

$$C_{\text{building}} = \alpha C_{\text{source}} \cdot \quad (19)$$

2.6 THE FINITE SOURCE SOLUTION TO CONVECTIVE AND DIFFUSIVE TRANSPORT

If the thickness of soil contamination is known, the finite source solution of J&E (1991) can be employed such that the time-averaged attenuation coefficient ($\langle\alpha\rangle$) may be calculated as:

$$\langle\alpha\rangle = \frac{\rho_b C_R \Delta H_c A_B}{Q_{building} C_{source} \tau} \left(\frac{L_T^0}{\Delta H_c} \right) \left[(\beta^2 + 2 \Psi \tau)^{1/2} - \beta \right] \quad (20)$$

- where
- $\langle\alpha\rangle$ = Time-averaged finite source attenuation coefficient, unitless
 - ρ_b = Soil dry bulk density at the source of contamination, g/cm³
 - C_R = Initial soil concentration, g/g
 - ΔH_c = Initial thickness of contamination, cm
 - A_B = Area of enclosed space below grade, cm²
 - $Q_{building}$ = Building ventilation rate, cm³/s
 - C_{source} = Vapor concentration at the source of contamination, g/cm^{3-v}
 - τ = Exposure interval, s
 - L_T^0 = Source-building separation at time = 0, cm

and;

$$\beta = \left(\frac{D_T^{eff} A_B}{L_T^0 Q_{soil}} \right) \left[1 - \exp \left(- \frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}} \right) \right] + 1 \quad (21)$$

and;

$$\Psi = \frac{D_T^{eff} C_{source}}{(L_T^0)^2 \rho_b C_R} \quad (22)$$

Implicit in Equation 20 is the assumption that source depletion occurs from the top boundary of the contaminated zone as contaminant volatilizes and moves upward toward the soil surface. This creates a hypothetical "dry zone" (δ) that grows with time; conversely, the "wet zone" of contamination retreats proportionally. When the thickness of the depletion zone (δ) is equal to the initial thickness of contamination (ΔH_c), the source is totally depleted. The unitless expression $(L_T^0/\Delta H_c)[(\beta^2 + 2\Psi\tau)^{1/2} - \beta]$ in Equation 20 represents the cumulative fraction of the depletion zone at the end of the exposure interval τ . Multiplying this expression by the remainder of Equation 20 results in the time-averaged finite source attenuation coefficient ($\langle\alpha\rangle$).

With a calculated value for $\langle\alpha\rangle$, the time-averaged vapor concentration in the building ($C_{building}$) is:

$$C_{building} = \langle\alpha\rangle C_{source} \quad (23)$$

For extended exposure intervals (e.g., 30 years), the time for source depletion may be less than the exposure interval. The time for source depletion (τ_D) may be calculated by:

$$\tau_D = \frac{[\Delta H_c / L_T^0 + \beta]^2 - \beta^2}{2\Psi} \quad (24)$$

If the exposure interval (τ) is greater than the time for source depletion (τ_D), the time-averaged building vapor concentration may be calculated by a mass balance such that:

$$C_{building} = \frac{\rho_b C_R \Delta H_c A_B}{Q_{building} \tau} \quad (25)$$

where $C_{building}$ = Time-averaged vapor concentration in the building, g/cm³-v

ρ_b = Soil dry bulk density at the source of contamination, g/cm³

C_R = Initial soil concentration, g/g

ΔH_c = Initial thickness of contamination, cm

A_B = Area of enclosed space below grade, cm²

$Q_{building}$ = Building ventilation rate, cm³/s

τ = Exposure interval, s.

2.7 THE SOIL GAS MODELS

Use of the J&E Model has typically relied on a theoretical partitioning of the total volume soil concentration into the sorbed, aqueous, and vapor phases. The model has also relied on a theoretical approximation of vapor transport by diffusion and convection from the source of emissions to the building floor in contact with the soil. Use of measured soil gas concentrations directly beneath the building floor instead of theoretical vapor concentrations and vapor transport has obvious advantages that would help to reduce the uncertainty in the indoor air concentration estimates made by the model.

The soil gas models (SG-SCREEN and SG-ADV) are designed to allow the user to input measured soil gas concentration and sampling depth information directly into the spreadsheets. In the new models, the value of the user-defined soil gas concentration is assigned as the value of C_{source} in Equation 19. The steady-state (infinite source) attenuation coefficient (α) in Equation 19 is calculated using Equation 13. The steady-state solution for the attenuation coefficient is used 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. The soil gas models estimate the steady-state indoor air concentration over the exposure duration. For a detailed discussion of using the soil gas models as well as soil gas sampling, see Section 4 of this document.

2.8 SOIL VAPOR PERMEABILITY

Soil vapor permeability (k_v) is one of the most sensitive model parameters associated with convective transport of vapors within the zone of influence of the building. Soil vapor permeability is typically measured from field pneumatic tests. If field data are lacking, however, an estimate of the value of k_v can be made with limited data.

Soil intrinsic permeability is a property of the medium alone that varies with the size and shape of connected soil pore openings. Intrinsic permeability (k_i) can be estimated from the soil saturated hydraulic conductivity:

$$k_i = \frac{K_s \mu_w}{\rho_w g} \quad (26)$$

where

- k_i = Soil intrinsic permeability, cm^2
- K_s = Soil saturated hydraulic conductivity, cm/s
- μ_w = Dynamic viscosity of water, g/cm-s (= 0.01307 at 10°C)
- ρ_w = Density of water, g/cm^3 (= 0.999)

g = Acceleration due to gravity, cm/s^2 (= 980.665).

Schaap and Leij (1998) computed the SCS class average values of the saturated hydraulic conductivity (K_s) for each of the 12 SCS soil textural classifications (Table 5). With these values, a general estimate of the value of k_i can be made by soil type. As an alternative, in situ measurements of the site-specific saturated hydraulic conductivity can be made and the results input into Equation 26 to compute the value of the soil intrinsic permeability.

Effective permeability is the permeability of the porous medium to a fluid when more than one fluid is present; it is a function of the degree of saturation. The relative air permeability of soil (k_{rg}) is the effective air permeability divided by the intrinsic permeability and therefore takes into account the effects of the degree of water saturation on air permeability.

TABLE 5. CLASS AVERAGE VALUES OF SATURATED HYDRAULIC CONDUCTIVITY FOR THE 12 SCS SOIL TEXTURAL CLASSIFICATIONS

Soil texture , USDA	Class average saturated hydraulic conductivity, cm/h
Sand	26.78
Loamy sand	4.38
Sandy loam	1.60
Sandy clay loam	0.55
Sandy clay	0.47
Loam	0.50
Clay loam	0.34
Silt loam	0.76
Clay	0.61
Silty clay loam	0.46
Silt	1.82
Silty clay	0.40

Parker et al. (1987) extended the relative air permeability model of van Genuchten (1980) to allow estimation of the relative permeabilities of air and water in a two- or three-phase system:

$$k_{rg} = (1 - S_{te})^{1/2} (1 - S_{te}^{1/M})^{2M} \quad (27)$$

where k_{rg} = Relative air permeability, unitless ($0 \leq k_{rg} \leq 1$)

S_{te} = Effective total fluid saturation, unitless

M = van Genuchten shape parameter, unitless.

Given a two-phase system (i.e., air and water), the effective total fluid saturation (S_{te}) is calculated as:

$$S_{te} = \frac{(\theta_w - \theta_r)}{(n - \theta_r)} \quad (28)$$

where S_{te} = Effective total fluid saturation, unitless

θ_w = Soil water-filled porosity, cm^3/cm^3

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

n = Soil total porosity, cm^3/cm^3 .

Class average values for the parameters θ_r and M by SCS soil type may be obtained from Table 3.

The effective air permeability (k_v) is then the product of the intrinsic permeability (k_i) and the relative air permeability (k_{rg}) at the soil water-filled porosity θ_w .

2.9 CALCULATION OF A RISK-BASED SOIL OR GROUNDWATER CONCENTRATION

Both the infinite source model estimate of the steady-state building concentration and the finite source model estimate of the time-averaged building concentration represent the exposure point concentration used to assess potential risks. Calculation of a risk-based media concentration for a carcinogenic contaminant takes the form:

$$C_c = \frac{TR \times AT_c \times 365 \text{ days / yr}}{URF \times EF \times ED \times C_{building}} \quad (29)$$

where C_c = Risk-based media concentration for carcinogens, $\mu\text{g}/\text{kg}$ -soil, or $\mu\text{g}/\text{L}$ -water

TR = Target risk level, unitless

AT_c = Averaging time for carcinogens, yr

URF = Unit risk factor, $(\mu\text{g}/\text{m}^3)^{-1}$

EF = Exposure frequency, days/yr

ED = Exposure duration, yr

C_{building} = Vapor concentration in the building, $\mu\text{g}/\text{m}^3$ per $\mu\text{g}/\text{kg}$ -soil,
or $\mu\text{g}/\text{m}^3$ per $\mu\text{g}/\text{L}$ -water.

In the case of a noncarcinogenic contaminant, the risk-based media concentration is calculated by:

$$C_{\text{NC}} = \frac{\text{THQ} \times \text{AT}_{\text{NC}} \times 365 \text{ days / yr}}{\text{EF} \times \text{ED} \times \frac{1}{\text{RfC}} \times C_{\text{building}}} \quad (30)$$

where

C_{NC}	= Risk-based media concentration for noncarcinogens, $\mu\text{g}/\text{kg}$ -soil, or $\mu\text{g}/\text{L}$ -water
THQ	= Target hazard quotient, unitless
AT_{NC}	= Averaging time for noncarcinogens, yr
EF	= Exposure frequency, days/yr
ED	= Exposure duration, yr
RfC	= Reference concentration, mg/m^3
C_{building}	= Vapor concentration in the building, mg/m^3 per $\mu\text{g}/\text{kg}$ -soil, or mg/m^3 per $\mu\text{g}/\text{L}$ -water.

The spreadsheets calculate risk-based media concentrations based on a unity initial concentration. That is, soil risk-based concentrations are calculated with an initial hypothetical soil concentration of 1 $\mu\text{g}/\text{kg}$ -soil, while for groundwater the initial hypothetical concentration is 1 $\mu\text{g}/\text{L}$ -water.

For this reason, the values of C_{source} and C_{building} shown on the INTERCALCS worksheet when reverse-calculating a risk-based media concentration do not represent actual values. For these calculations, the following message will appear on the RESULTS worksheet:

"MESSAGE: The values of C_{source} and C_{building} on the INTERCALCS worksheet are based on unity and do not represent actual values."

When forward-calculating risks from a user-defined initial soil or groundwater concentration, the values of C_{source} and C_{building} on the INTERCALCS worksheet are correct.

2.10 CALCULATION OF INCREMENTAL RISKS

Forward-calculation of incremental risks begins with an actual initial media concentration (i.e., $\mu\text{g}/\text{kg}$ -soil or $\mu\text{g}/\text{L}$ -water). For carcinogenic contaminants, the risk level is calculated as:

$$Risk = \frac{URF \times EF \times ED \times C_{building}}{AT_C \times 365 \text{ days} / \text{yr}} \quad (31)$$

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

$$HQ = \frac{EF \times ED \times \frac{1}{RfC} \times C_{building}}{AT_{NC} \times 365 \text{ days} / \text{yr}} \quad (32)$$

2.11 MAJOR MODEL ASSUMPTIONS/LIMITATIONS

The following represent the major assumptions/limitations of the J&E Model.

1. Contaminant vapors enter the structure primarily through cracks and openings in the walls and foundation.
2. Convective transport occurs primarily within the building zone of influence and vapor velocities decrease rapidly with increasing distance from the structure.
3. Diffusion dominates vapor transport between the source of contamination and the building zone of influence.
4. All vapors originating from below the building will enter the building unless the floors and walls are perfect vapor barriers.
5. All soil properties in any horizontal plane are homogeneous.
6. The contaminant is homogeneously distributed within the zone of contamination.
7. The areal extent of contamination is greater than that of the building floor in contact with the soil.
8. 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.
9. The model does not account for transformation processes (e.g., biodegradation, hydrolysis, etc.).

10. The soil layer in contact with the structure floor and walls is isotropic with respect to permeability.
11. Both the building ventilation rate and the difference in dynamic pressure between the interior of the structure and the soil surface are constant values.

Use of the J&E Model as a first-tier screening tool to identify sites needing further assessment requires careful evaluation of the assumptions listed in the previous section to determine whether any conditions exist that would render the J&E Model inappropriate for the site. If the model is deemed applicable at the site, 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 will be exceeded at the site. Precise prediction of concentration levels is not possible with this approach.

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, groundwater concentrations, and/or possibly near source soil vapor concentrations. The number of samples and measurements needed to establish this information varies by site and it's not possible to provide a hard and fast rule. Bulk soil concentrations should not be used unless appropriately preserved during sampling.

Based on the conceptual site model (CSM), the user can select the appropriate spreadsheet corresponding to the vapor source at the site and determine whether to use the screening level spreadsheet (which allows only one soil type above the capillary fringe) or the more advanced version (which allows up to three layers above the capillary fringe). 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.

The uncertainty in determining key model parameters and sensitivity of the J&E Model to those key model parameters is qualitatively described in Table 6. As shown in the table, building-related parameters will moderate to high uncertainty and model sensitivity include: Q_{soil} , building crack ratio, building air-exchange rate, and building mixing height. Building-related parameters with low uncertainty and sensitivity include: foundation area, depth to base of foundation, and foundation slab thickness. Of the soil-dependent properties, the soil moisture parameters clearly are of critical importance for the attenuation value calculations.

TABLE 6. UNCERTAINTY AND SENSITIVITY OF KEY PARAMETERS FOR THE VAPOR INTRUSION MODEL

Input Parameter	Parameter Uncertainty Or Variability	Shallower Contamination Building Underpressurized	Parameter Sensitivity		Deeper Contamination Building Not Underpressurized
			Deeper Contamination Building Underpressurized	Shallower Contamination Building Not Underpressurized	
Soil Total Porosity (n)	Low	Low	Low	Low	Low
Soil Water-filled Porosity (θ_w)	Moderate to High	Low to Moderate	Moderate to High	Moderate to High	Moderate to High
Capillary Zone Water-filled Porosity ($\theta_{n,cz}$)	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Thickness of Capillary Zone (L_{cz})	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Soft Dry Bulk Density (ρ_b)	Low	Low	Low	Low	Low
Average Vapor Flowrate into a Building (Q_{soil})	High	Moderate to High	Low to Moderate	N/A	N/A
Soil Vapor Permeability(K_v)	High	Moderate to High	Low to Moderate	N/A	N/A
Soil to Building Pressure Differential (ΔP)	Moderate	Moderate	Low to Moderate	N/A	N/A
Henry's Law Constant (for single chemical) (H)	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Diffusivity in Air (D_A)	Low	Low	Low	Low	Low
Indoor Air Exchange Rate (ER)	Moderate	Moderate	Moderate	Moderate	Moderate
Enclosed Space Height (H_B)	Moderate	Moderate	Moderate	Moderate	Moderate
Area of Enclosed Space Below Grade (A_B)	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Depth Below Grade to Bottom of Enclosed Space (L_F)	Low	Low	Low	Low	Low
Crack-to-Total Area Ratio (η)	High	Low	Low	Moderate to High	Low to Moderate
Enclosed Space Floor Thickness (L_{crack})	Low	Low	Low	Low	Low

SECTION 3

SOIL AND GROUNDWATER MODEL APPLICATION

This section provides step-by-step instructions on how to implement the soil and groundwater contamination versions of the J&E Model using the spreadsheets. This section also discusses application of the soil gas versions of the model. The user provides data and selects certain input options, and views model results via a series of worksheets. Error messages are provided within both the data entry worksheet and the results worksheet to warn the user that entered data are missing or outside of permitted limits.

The J&E Model as constructed within the accompanying spreadsheets requires a range of input variables depending on whether a screening-level or advanced model is chosen. Table 7 provides a list of all major input variables, the range of practical values for each variable, the default value for each variable, and the relative model sensitivity and uncertainty of each variable. Table 7 also includes references for each value or range of values.

Table 8 indicates the results of an increase in the value of each input parameter. The results are shown as either an increase or a decrease in the building concentration (C_{building}) of the pollutant. An increase in the building concentration will result in an increase in the risk when forward-calculating from an initial soil or groundwater concentration. When reverse-calculating to a risk-based “acceptable” soil or groundwater concentration, an increase in the hypothetical unit building concentration will result in a lower “acceptable” soil or groundwater concentration.

A list of reasonably conservative model input parameters for building-related parameters is provided in Table 9, which also provides the practical range, typical or mean value (if applicable), and most conservative value for these parameters. For building parameters with low uncertainty and sensitivity, only a single “fixed” value corresponding to the mean or typical value is provided in Table 9. Soil-dependent properties are provided in Table 10 for soils classified according to the US SCS system. If site soils are not classified according to the US SCS, Table 11 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 7. RANGE OF VALUES FOR SELECTED INPUT PARAMETERS

Input parameter	Practical range of values	Default value
Soil water-filled porosity (θ_w)	0.04 – 0.33 cm ³ /cm ^{3a}	Soil dependent see Table 10
Soil vapor permeability (k_v)	10 ⁻⁶ – 10 ⁻¹² cm ^{2b,c}	10 ⁻⁸ cm ^{2d}
Soil-building pressure differential (ΔP)	0 – 20 Pa ³	4 Pa ^f
Media initial concentration (C_R, C_w)	User-defined	NA
Depth to bottom of soil contamination (L_b)	User-defined	NA
Depth to top of concentration (L_T)	User-defined	NA
Floor-wall seam gap (w)	0.05 – 1.0 cm ^e	0.1 cm ^e
Soil organic carbon fraction (f_{oc})	0.001 – 0.006 ^a	0.002 ^a
Indoor air exchange rate (ER)	0.18 – 1.26 (H ⁻¹) ^g	0.25 (h ⁻¹) ^{g,h}
Soil total porosity (n)	0.34 – 0.53 cm ³ /cm ^{3a}	0.43 cm ³ /cm ^{3a}
Soil dry bulk density (ρ_b)	1.25 – 1.75 g/cm ^{3a}	1.5 g/cm ^{3a}

^aU.S. EPA (1996a and b).

^bJohnson and Ettinger (1991).

^cNazaroff (1988).

^dBased on transition point between diffusion and convection dominated transport from Johnson and Ettinger (1991).

^eEaton and Scott (1984); Loureiro et al. (1990).

^fLoureiro et al. (1990); Grimsrud et al. (1983).

^gKoontz and Rector (1995).

^hParker et al. (1990).

ⁱU.S. DOE (1995).

TABLE 8. EFFECT ON BUILDING CONCENTRATION FROM AN INCREASE IN INPUT PARAMETER VALUES

Input parameter	Change in parameter value	Effect on building concentration
Soil water-filled porosity (θ_w)	Increase	Decrease
Soil vapor permeability (k_v)	Increase	Increase
Soil-building pressure differential (ΔP)	Increase	Increase
Media initial concentration (C_R, C_w) ^a	Increase	Increase
Depth to bottom of soil contamination (L_b) ^b	Increase	Increase
Depth to top of concentration (L_T)	Increase	Decrease
Floor-wall seam gap (w)	Increase	Increase
Soil organic carbon fraction (f_{oc})	Increase	Decrease
Indoor air exchange rate (ER)	Increase	Decrease
Building volume ^c ($L_B \times W_B \times H_B$)	Increase	Decrease
Soil total porosity (n)	Increase	Increase
Soil dry bulk density (ρ_b)	Increase	Decrease

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

^b Applicable only to advanced model for soil contamination.

^c Used with building air exchange rate to calculate building ventilation rate.

TABLE 9. BUILDING-RELATED PARAMETERS FOR THE VAPOR INTRUSION MODEL

Input Parameter	Units	Fixed or Variable	Typical or Mean Value	Range	Conservative Value	Default Value
Total Porosity	cm ³ /cm ³	Fixed	Specific to soil texture, see Table 10			
Unsaturated Zone Water-filled Porosity	cm ³ /cm ³	Variable	Specific to soil texture, see Table 10			
Capillary Transition zone Water-filled Porosity	cm ³ /cm ³	Fixed	Specific to soil texture, see Table 10			
Capillary Transition Zone height	cm ³ /cm ³	Fixed	Specific to soil texture, see Table 10			
Q _{soil}	L/min	Variable	Specific to soil texture, see Table 10			
Soil air permeability	m ²	Variable	Specific to soil texture, see Table 10			
Building Depressurization	Pa	Variable	4	0-15	15	N/A
Henry's law constant (for single chemical)	-	Fixed	Specific to chemical, see Appendix B			
Free-Air Diffusion Coefficient (single chemical)	-	Fixed	Specific to chemical, see Appendix B			
Building Air exchange Rate	hr ⁻¹	Variable	0.5	0.1-1.5	0.1	0.25
Building Mixing height – Basement scenario	m	Variable	3.66	2.44-4.88	2.44	3.66
Building Mixing height – Slab-on-grade scenario	m	Variable	2.44	2.13-3.05	2.13	2.44
Building Footprint Area – Basement Scenario	m ²	Variable	120	80-200+	80	100
Building Footprint Area – Slab-on-Grade Scenario	m ²	Variable	120	80-200+	80	100
Subsurface Foundation area – Basement Scenario	m ²	Variable	208	152-313+	152	180
Subsurface Foundation area – Slab-on-Grade Scenario	m ²	Fixed	127	85-208+	85	106
Depth to Base of Foundation – Basement Scenario	m	Fixed	2	N/A	N/A	2
Depth to Base of Foundation – Slab-on-Grade Scenario	m	Fixed	0.15	N/A	N/A	0.15
Perimeter Crack Width	mm	Variable	1	0.5-5	5	1
Building Crack ratio – Slab-on-Grade Scenario	dimensionless	Variable	0.00038	0.00019-0.0019	0.0019	3.77 x 10 ⁻⁴
Building Crack ratio – Basement Scenario	dimensionless	Variable	0.0002	0.0001-0.001	0.001	2.2 x 10 ⁻⁴
Crack Dust Water-Filled Porosity	cm ³ /cm ³	Fixed	Dry	N/A	N/A	Dry
Building Foundation Slab Thickness	m	Fixed	0.1	N/A	N/A	0.1

TABLE 10. SOIL-DEPENDENT PROPERTIES FOR THE VAPOR INTRUSION MODEL - FIRST TIER ASSESSMENT

U.S. Soil Conservation Service (SCS) Soil Texture	Saturated		Unsaturated Zone				Capillary Transition Zone		
	Water Content Total Porosity θ_s (cm ³ /cm ³)	Residual Water Content θ_r (cm ³ /cm ³)	Water-Filled Porosity				Saturated Water Content Total Porosity θ_s (cm ³ /cm ³)	$\theta_{w, cap}$ @ air-entry	Height Cap Zone Fetter (94) (cm)
			Mean or Typical ($FC_{1/3bar} + \theta_r$)/2 $\theta_{w, unsat}$ (cm ³ /cm ³)	Range $\theta_{w, unsat}$ (cm ³ /cm ³)	Conservative $\theta_{w, unsat}$ (cm ³ /cm ³)	Modeled $\theta_{w, unsat}$ (cm ³ /cm ³)			
Clay	0.459	0.098	0.215	0.098-0.33	0.098	0.215	0.459	0.412	81.5
Clay Loam	0.442	0.079	0.168	0.079-0.26	0.079	0.168	0.442	0.375	46.9
Loam	0.399	0.061	0.148	0.061-0.24	0.061	0.148	0.399	0.332	37.5
Loamy Sand	0.39	0.049	0.076	0.049-0.1	0.049	0.076	0.39	0.303	18.8
Silt	0.489	0.05	0.167	0.05-0.28	0.050	0.167	0.489	0.382	163.0
Silt Loam	0.439	0.065	0.180	0.065-0.3	0.065	0.180	0.439	0.349	68.2
Silty Clay	0.481	0.111	0.216	0.11-0.32	0.111	0.216	0.481	0.424	192.0
Silty Clay Loam	0.482	0.09	0.198	0.09-0.31	0.090	0.198	0.482	0.399	133.9
Sand	0.375	0.053	0.054	0.053-0.055	0.053	0.054	0.375	0.253	17.0
Sandy Clay	0.385	0.117	0.197	0.117-0.28	0.117	0.197	0.385	0.355	30.0
Sandy Clay Loam	0.384	0.063	0.146	0.063-0.23	0.063	0.146	0.384	0.333	25.9
Sandy Loam	0.387	0.039	0.103	0.039-0.17	0.039	0.103	0.387	0.320	25.0
Loamy Sand	0.39	0.049	0.076	0.049-0.1	0.049	0.076	0.39	0.303	18.8

TABLE 11. GUIDANCE 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 international-expert opinion. Consequently, the input parameters listed in Tables 9 and 10 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. Justification for the building-related and soil-dependent parameters values selected as default values for the J&E Model is described below.

3.1 JUSTIFICATION OF DEFAULT SOIL-DEPENDENT PROPERTIES

The default soil-dependent parameters recommended for a first tier assessment (Table 10) represent mean or typical values, rather than the most conservative value, in order to avoid overly conservative estimates of attenuation factors. Note, however, that the range of values for some

soil properties can be very large, particularly in the case of moisture content and hydraulic conductivity. Consequently, selecting a soil type and corresponding typical soil property value may not accurately or conservatively represent a given site. Note also that Table 9 does 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. Consequently, in cases where the vadose zone is characterized by very coarse materials, the J&E Model may not provide a conservative estimate of attenuation factor.

As discussed above, the J&E Model is sensitive to the value of soil moisture content. Unfortunately, there is little information available 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 10 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.

3.2 JUSTIFICATION OF DEFAULT BUILDING-RELATED PROPERTIES

Building Air Exchange Rate (Default Value = 0.25 AEH)

The results of 22 studies for which building air exchange rates are reported in Hers et al. (2001). Ventilation rates vary widely from approximately 0.1 AEH for energy efficient “air-tight” houses (built in cold climates) (Fellin and Otson, 1996) to over 2 AEH (AHRAE (1985); upper range). In general, ventilation rates will be higher in summer months when natural ventilation rates are highest. Murray and Burmaster (1995) conducted one of the most comprehensive studies of U.S. residential air exchange rates (sample size of 2844 houses). The data set was analyzed on a seasonal basis and according to climatic region. When all the data were analyzed, the 10th, 50th and 90th percentile values were 0.21, 0.51 and 1.48 AEH. Air exchange rates varied depending on season and climatic region. For example, for the winter season and coldest climatic area (Region 1, e.g., Great Lakes area and extreme northeast U.S.), the 10th, 50th, and 90th percentile values were 0.11, 0.27 and 0.71 AEH, respectively.. In contrast, for the winter season and warmest climatic area [Region 4 (southern California, Texas, Florida, Georgia)], the 10th, 50th, and 90th percentile values were 0.24, 0.48 and 1.13 AEH, respectively. Although building air exchange rates would be higher during the summer months, vapor intrusion during winter months (when house depressurization is expected to be most significant) would be of greatest concern. For this guidance, a default value of 0.25 for air exchange rate was selected to represent the lower end of these distributions.

Crack Width and Crack Ratio (Default Value = 0.0002 for basement house; = 0.0038 for slab-on-grade house)

The crack width and crack ratio are related. 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 and crack width are related as follows:

$$\text{Crack Ratio} = \text{Crack Width} \times 4 \times (\text{Subsurface Foundation Area})^{0.5} / \text{Subsurface Foundation Area}$$

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 Nazaroff (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 this, in practice, is difficult to do. Figley and Snodgrass (1992) 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) 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 J&E (1991) for illustrative purposes ranged from 0.001 to 0.01. The selected default values fall within the ranges observed.

Building Area and Subsurface Foundation Area (Default Value = 10 m by 10 m)

The default building area is based on the following information:

- Default values used in the Superfund User’s Guide (9.61 m by 9.61 m or 92.4 m²)
- Default values used by the State of Michigan, 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 m²).

The Michigan guidance document indicates that the 111.5 m² 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 typical, upper, and lower ranges presented in Table 9 are subjectively chosen values. The subsurface foundation area is a function of the building area, and depth to the base of the foundation, which is fixed.

Building Mixing Height (Default Value = 2.44 m for slab-on-grade scenario; = 3.66 m for basement scenario)

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 provides for direct inference of mixing height. There are few sites, with a small number of houses where indoor air 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. Jeff Kurtz, EMSI, personal communication, June 2002). Less mixing would be expected for an apartment because there are less 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.

Q_{soil} (Default Value = 5 L/min)

The method often used with the J&E Model for estimating the soil gas advection rate (Q_{soil}) through the building envelope is an analytical solution for two-dimensional soil gas flow to a small horizontal drain (Nazaroff 1992) (“Perimeter Crack Model”). Use of this model can be problematic in that Q_{soil} values are sensitive to soil-air permeability and consequently a wide range in flows can be predicted.

An alternate empirical approach is to select a Q_{soil} value on the basis of tracer tests (i.e., mass balance approach). When soil gas advection is the primary mechanism for tracer intrusion into a building, the Q_{soil} can be estimated by measuring the concentrations of a chemical tracer in indoor air, in outdoor air, and in soil vapor below a building, and by measuring the building ventilation rate (Hers et al. 2000a; Fischer et al. 1996; Garbesi et al. 1993; Rezvan et al. 1991; Garbesi and Sextro, 1989). For sites with coarse-grained soils (Table 10). The Q_{soil} values measured using this technique are compared to predicted rates using the Perimeter Crack model. The Perimeter Crack model predictions are both higher and lower than the measured values, but overall are within one order of magnitude of the measured values. Although the Q_{soil} values predicted by the models and measured

using field tracer tests are uncertain, the results suggest that a “typical” range for houses on coarse-grained soils is on the order of 1 to 10 L/min. A disadvantage with the tracer test approach is that only limited data are available and there do not appear to be any tracer studies for field sites with fine-grained soils.

It is also important to recognize that the advective zone of influence for soil gas flow is limited to soil immediately adjacent to the building foundation. Some data on pressure coupling provide insight on the extent of the advective flow zone. For example, Garbesi *et al.* (1993) report a pressure coupling between the soil and experimental basement (*i.e.*, relative to that between the basement and atmosphere) equal to 96 percent directly below the slab, between 29 percent and 44 percent at 1 m below the basement floor slab, and between 0.7 percent and 27 percent at a horizontal distance of 2 m from the basement wall. At the Chatterton site (research site investigated by the author), the pressure coupling immediately below the building floor slab ranged from 90 to 95 percent and at a depth of 0.5 m was on the order of 50 percent. These results indicate that the advective zone of influence will likely be limited to a zone within 1 to 2 m of the building foundation.

Because the advective flow zone is relatively limited in extent, the soil type adjacent to the building foundation is of importance. In many cases, coarse-grained imported fill is placed below foundations, and either coarse-grained fill, or disturbed, loose fill is placed adjacent to the foundation walls. Therefore, a conservative approach for the purposes of this guidance is to assume that soil gas flow will be controlled by coarse-grained soil, and not rely on the possible reduction in flow that would be caused by fine-grained soils near to the house foundation. For these reasons, a soil gas flow rate of 5 L/min (midpoint between 1 and 10 L/min) was chosen as the input value.

3.3 RUNNING THE MODELS

Eight different models are provided in MICROSOFT EXCEL formats.

1. Models for Soil Contamination:
SL-SCREEN-Feb 04.XLS
SL-ADV-Feb 04.XLS
2. Models for Groundwater Contamination:
GW-SCREEN-Feb 04.XLS
GW-ADV-Feb 04.XLS
3. Model for Soil Gas Contamination
SG-SCREEN-Feb 04.xls
SG-ADV-Feb 04.xls
4. Models for Non Aqueous Phase Liquids
NAPL-SCREEN-Feb 04.xls

Both the screening-level models and the advanced models allow the user to calculate a risk-based media concentration or incremental risks from an actual starting concentration in soil or in groundwater. Data entry within the screening-level models is limited to the most sensitive model parameters and incorporates only one soil stratum above the contamination. The advanced models provide the user with the ability to enter data for all of the model parameters and also incorporate up to three individual soil strata above the contamination for which soil properties may be varied.

To run any of the models, simply open the appropriate model file within MICROSOFT EXCEL. Each model is constructed of the following worksheets:

1. DATENTER (Data Entry Sheet)
2. CHEMPROPS (Chemical Properties Sheet)
3. INTERCALCS (Intermediate Calculations Sheet)
4. RESULTS (Results Sheet)
5. VLOOKUP (Lookup Tables).

The following is an explanation of what is contained in each worksheet, how to enter data, how to interpret model results, and how to add/revise the chemical properties data found in the VLOOKUP Tables. As examples, Appendix C contains all the worksheets for the advanced soil contamination model SL-ADV.

3.4 THE DATA ENTRY SHEET (DATENTER)

Figure 4 is an example of a data entry sheet. In this case, it shows the data entry sheet for the screening-level model for contaminated groundwater (GW-SCREEN). Figure 5 is an example of an advanced model data entry sheet (GW-ADV). Note that the screening-level model sheet requires entry of considerably less data than does the advanced sheet. To enter data, simply position the cursor within the appropriate box and type the value; all other cells are protected.

Error Messages

In the case of the screening-level models, all error messages will appear in red type below the applicable row of data entry boxes. For the advanced models, error messages may appear on the data entry sheet or in the lower portion of the results sheet. Error messages will occur if required entry data are missing or if data are out of range or do not conform to model conventions. The error message will tell the user what kind of error has occurred.

GW-SCREEN
Version 3.1; 02/04

Reset to
Defaults

CALCULATE RISK-BASED GROUNDWATER CONCENTRATION (enter "X" in "YES" box)

YES X
OR

CALCULATE INCREMENTAL RISKS FROM ACTUAL GROUNDWATER CONCENTRATION
(enter "X" in "YES" box and initial groundwater conc. below)

YES

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_w ($\mu\text{g/L}$)	Chemical
56235		Carbon tetrachloride

MORE
↓

ENTER Depth below grade to bottom of enclosed space floor, L_f (cm)	ENTER Depth below grade to water table, L_{WT} (cm)	ENTER SCS soil type directly above water table	ENTER Average soil/ groundwater temperature, T_s ($^{\circ}\text{C}$)	ENTER Average vapor flow rate into bldg. (Leave blank to calculate) Q_{soil} (L/m)
200	400	SC	10	5

MORE
↓

ENTER Vadose zone SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined vadose zone soil vapor permeability, k_v (cm^2)	ENTER Vadose zone SCS soil type Lookup Soil Parameters	ENTER Vadose zone soil dry bulk density, ρ_b^v (g/cm^3)	ENTER Vadose zone soil total porosity, n^v (unitless)	ENTER Vadose zone soil water-filled porosity, θ_w^v (cm^3/cm^3)
SC			SC	1.63	0.385	0.197

MORE
↓

ENTER Target risk for carcinogens, TR (unitless)	ENTER Target hazard quotient for noncarcinogens, THQ (unitless)	ENTER Averaging time for carcinogens, AT_C (yrs)	ENTER Averaging time for noncarcinogens, AT_{NC} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)
1.0E-06	1	70	30	30	350
Used to calculate risk-based groundwater concentration.					

Figure 4. GW-SCREEN Data Entry Sheet

Figure 6 is an example of an error message appearing on the data entry sheet. Figure 7 illustrates error messages appearing within the message and error summary section on the results sheet (advanced models only).

Entering Data

Each data entry sheet requires the user to input values for model variables. Data required for the soil contamination scenario will differ from that required for the groundwater contamination scenario. In addition, data required for the screening-level models will differ from that required for the advanced models.

Model Variables--

The following is a list of all data entry variables required for evaluating either a risk-based media concentration or the incremental risks due to actual contamination. A description for which model(s) the variable is appropriate is given in parenthesis after the name of the variable. In addition, notes on how the variable is used in the calculations and how to determine appropriate values of the variable are given below the variable name. A quick determination of which variables are required for a specific model can be made by reviewing the data entry sheet for the model chosen. Example data entry sheets for each model can be found in Appendix D.

1. *Calculate Risk-Based Concentration or Calculate Incremental Risks from Actual Concentration* (All Soil and Groundwater Models)

The model will calculate either a risk-based soil or groundwater concentration or incremental risks but cannot calculate both simultaneously. Enter an "X" in only one box.

2. *Chemical CAS No.* (All Models)

Enter the appropriate CAS number for the chemical you wish to evaluate; do not enter dashes. The CAS number entered must exactly match that of the chemical, or the error message "CAS No. not found" will appear in the "Chemical" box. Once the correct CAS number is entered, the name of the chemical will automatically appear in the "Chemical" box. A total of 108 chemicals and their associated properties are included with each model; see Section 3.7 for instructions on adding/revising chemicals.

GW-SCREEN
Version 3.1; 02/04

Reset to
Defaults

CALCULATE RISK-BASED GROUNDWATER CONCENTRATION (enter "X" in "YES" box)

YES

OR

CALCULATE INCREMENTAL RISKS FROM ACTUAL GROUNDWATER CONCENTRATION
(enter "X" in "YES" box and initial groundwater conc. below)

YES

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_w ($\mu\text{g/L}$)	Cannot calculate risk-based concentration and incremental risk simultaneously.
56235		Carbon tetrachloride

Figure 6. Example Error Message on Data Entry Sheet

RISK-BASED SOIL CONCENTRATION CALCULATIONS:

INCREMENTAL RISK CALCULATIONS:

Indoor exposure soil conc., carcinogen ($\mu\text{g/kg}$)	Indoor exposure soil conc., noncarcinogen ($\mu\text{g/kg}$)	Risk-based indoor exposure soil conc., ($\mu\text{g/kg}$)	Soil saturation conc., C_{sat} ($\mu\text{g/kg}$)	Final indoor exposure soil conc., ($\mu\text{g/kg}$)	Incremental risk from vapor intrusion to indoor air, carcinogen (unitless)	Hazard quotient from vapor intrusion to indoor air, noncarcinogen (unitless)
NA	NA	NA	3.09E+05	NA	8.0E-08	7.9E-04

MESSAGE AND ERROR SUMMARY BELOW: (DO NOT USE RESULTS IF ERRORS ARE PRESENT)

SCROLL
DOWN
TO "END"

ERROR: Combined thickness of strata A + B + C must be = depth below grade to top of contamination.

Figure 7. Example Error Message on Results Sheet

3. *Initial Soil or Groundwater Concentration* (All Soil and Groundwater Models) (L_w)

Enter a value only if incremental risks are to be calculated. Be sure to enter the concentration in units of $\mu\text{g}/\text{kg}$ (wet weight basis soil) or $\mu\text{g}/\text{L}$ (groundwater). Typically, this value represents the average concentration within the zone of contamination. 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.

4. *Average Soil/Groundwater Temperature* (All Models) (T_s)

The soil/groundwater temperature is used to correct the Henry's law constant to the specified temperature. Figure 8 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.

5. *Depth Below Grade to Bottom of Enclosed Space Floor* (All Models) (L_F)

Enter the depth to the bottom of the floor in contact with the soil. The default value for slab-on-grade and basement construction is 15 cm and 200 cm, respectively.

6. *Depth Below Grade to Top of Contamination* (Soil Models Only) (L_T)

Enter the depth to the top of soil contamination. If the contamination begins at the soil surface, enter the depth below grade to the bottom of the enclosed space floor. The depth to the top of contamination must be greater than or equal to the depth to the bottom of the floor.

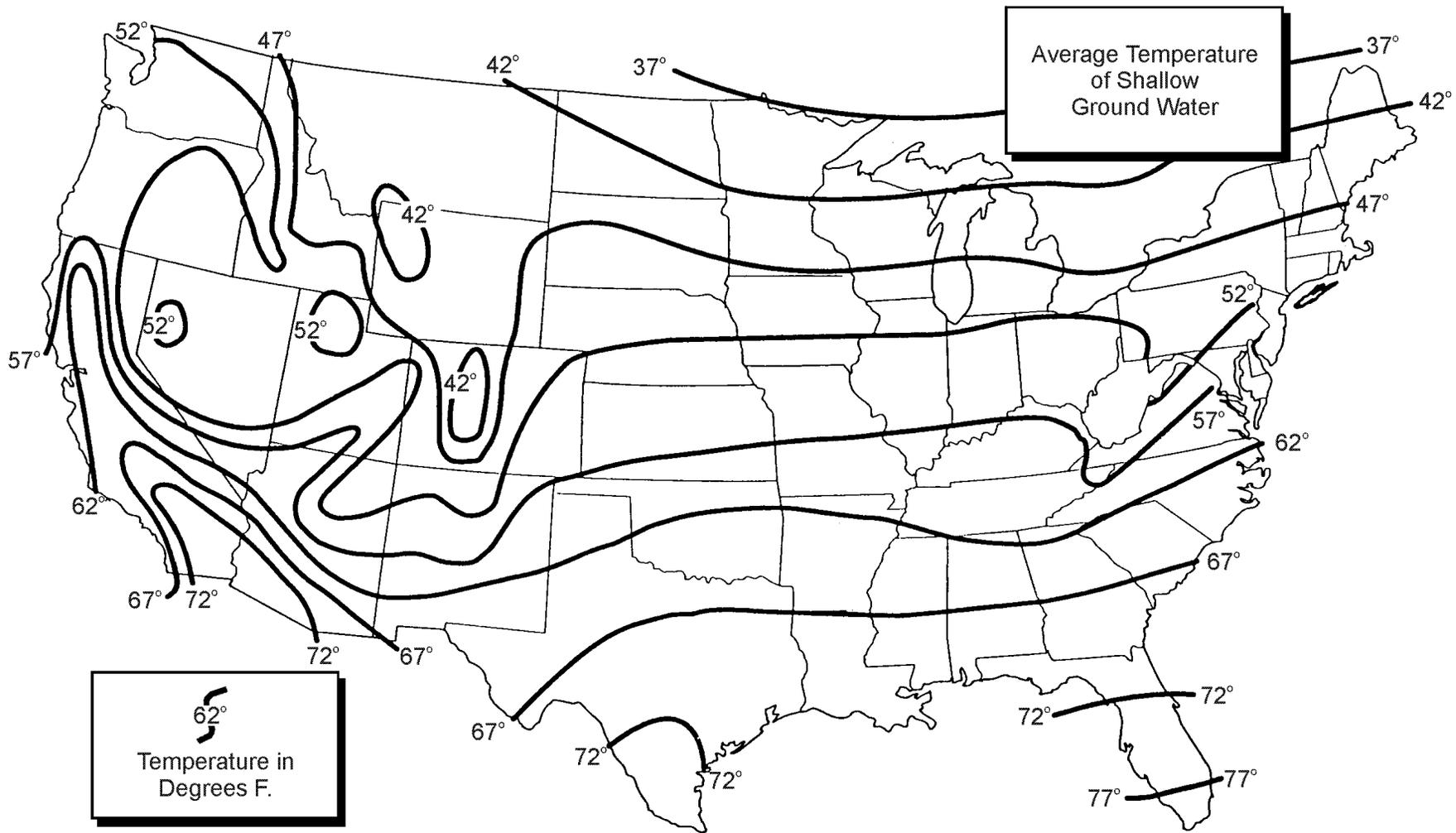


Figure 8. Average Shallow Groundwater Temperature in the United States

7. *Depth Below Grade to Water Table (Groundwater Models Only) (L_{wt})*

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.

8. *Depth Below Grade to Bottom of Contamination (Advanced Soil Model Only) (L_B)*

This value is used to calculate the thickness of soil contamination. A value greater than zero and greater than the depth to the top of contamination will automatically invoke the finite source model. If the thickness of contamination is unknown, two options are available:

1. Entering a value of zero will automatically invoke the infinite source model.
2. Enter the depth to the top of the water table. This will invoke the finite source model under the assumption that contamination extends from the top of contamination previously entered down to the top of the water table.

9. *Thickness of Soil Stratum "X" (Advanced Models Only) (h_x , $x = A, B, \text{ or } C$)*

In the advanced models, 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 contamination, or to the soil gas sampling depth, as appropriate. If soil strata B and/or C are not to be considered, a value of zero must be entered for each stratum not included in the analysis.

10. *Soil Stratum A SCS Soil Type (Advanced Models Only) (SES – soil)*

Enter one of the following SCS soil type abbreviations:

<u>Abbreviation</u>	<u>SCS Soil Type</u>
C	Clay
CL	Clay loam
L	Loam
LS	Loamy sand
S	Sand
SC	Sandy clay
SCL	Sandy clay loam
SI	Silt
SIC	Silty clay
SICL	Silty clay loam
SIL	Silty loam
SL	Sandy loam

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. 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 7.

The SCS soil type along with the Stratum A soil water-filled porosity is used to estimate the soil vapor permeability of Stratum A which is in contact with the floor and walls of the enclosed space below grade. Alternatively, the user may define a soil vapor permeability (see Variable No. 11).

11. *User-Defined Stratum A Soil Vapor Permeability (Advanced Models Only)(K_v)*

As an alternative to estimating the soil vapor permeability of soil Stratum A, the user may define the soil vapor permeability. As a general guide, the following represent the practical range of vapor permeabilities:

<u>Soil type</u>	<u>Soil vapor permeability, cm²</u>
Medium sand	1.0 x 10 ⁻⁷ to 1.0 x 10 ⁻⁶
Fine sand	1.0 x 10 ⁻⁸ to 1.0 x 10 ⁻⁷
Silty sand	1.0 x 10 ⁻⁹ to 1.0 x 10 ⁻⁸
Clayey silts	1.0 x 10 ⁻¹⁰ to 1.0 x 10 ⁻⁹

12. *Vadose Zone SCS Soil Type (Screening Models Only) (SCS – soil)*

Because the screening-level models accommodate only one soil stratum above the top of contamination or soil gas sampling depth, enter the SCS soil type from the list given in Variable No. 10.

13. *User-Defined Vadose Zone Soil Vapor Permeability (Screening Models Only) (K_v)*

For the same reason cited in No. 12 above, the user may alternatively define a soil vapor permeability. Use the list of values given in Variable No. 11 as a general guide.

14. *Soil Stratum Directly Above the Water Table (Advanced Groundwater Models Only) (A, B, or C)*

Enter either A, B, or C as the soil stratum directly above the water table. This value must be the letter of the deepest stratum for which a thickness value has been specified under Variable No. 9.

15. *SCS Soil Type Directly Above Water Table (Groundwater Models Only) (SCS – soil)*

Enter the correct SCS soil type from the list given in Variable No. 10 for the soil type directly above the water table. The soil type entered is used to estimate the rise (thickness) of the capillary zone.

16. *Stratum "X" Soil Dry Bulk Density* (Advanced Models Only) (P_x , $x = A, B, \text{ or } C$)

Identify the soil type for each strata and accept the default value or enter a site-specific value for the average soil dry bulk density. Dry bulk density is used in a number of intermediate calculations and is normally determined by field measurements (ASTM D 2937 Method).

17. *Stratum "X" Soil Total Porosity* (Advanced Models Only) (n^x , $x = A, B, \text{ or } C$)

Total soil porosity (n) is determined as:

$$n = 1 - \rho_b / \rho_s$$

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).

18. *Stratum "X" Soil Water-Filled Porosity* (Advanced Models Only) (θ_w^x , $X = a, b, \text{ or } c$)

Enter the average long-term volumetric soil moisture content; this is typically a depth-averaged value for the appropriate soil stratum. A long-term average value is typically not readily available. Do not use values based on episodic measurements unless they are representative of long-term conditions. Table 10 provides a soil-specific range of typical value for specified soils. The user must define soil type or input site-specific values.

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 3 and 4 (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 internet website at <http://www.ussl.ars.usda.gov/MODELS/HYDRUS.HTM>. One and two-dimensional commercial versions of HYDRUS (Windows versions) are available at the International Ground Water Modeling Center website at <http://www.mines.edu/research/igwmc/software/>. 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.ussl.ars.usda.gov/MODELS/rosetta/rosetta.htm>. The van Genuchten hydraulic properties can then be input into HYDRUS to estimate soil moisture content.

19. *Stratum "X" Soil Organic Carbon Fraction* (Advanced Soil Models Only) (f_{oc}^X , X = A, B, or c)

Enter the depth-averaged soil organic carbon fraction for the stratum specified. Soil organic carbon is measured by burning off soil carbon in a controlled-temperature oven. This parameter, along with the chemical's organic carbon partition coefficient (K_{oc}), is used to determine the soil-water partition coefficient (K_d).

20. *Vadose Zone Soil Dry Bulk Density* (Screening Models Only) (ρ^A)

Because the screening-level models accommodate only one soil stratum above the top of contamination, identify the soil type and accept the default values or enter the depth-averaged soil dry bulk density. The universal default value is 1.5 g/cm³, which is consistent with U.S. EPA (1996a and b) for subsurface soils.

21. *Vadose Zone Soil Total Porosity* (Screening Models Only) (m^A)

Because the screening-level models accommodate only one soil stratum above the top of contamination, enter the depth-averaged soil total porosity. The default value is 0.43, which is consistent with U.S. EPA (1996a and b) for subsurface soils.

22. *Vadose Zone Soil Water-Filled Porosity* (Screening Models Only) (θ_w^A)

Because the screening-level models accommodate only one soil stratum above the top of contamination, enter the depth-averaged soil water-filled porosity. The default value is 0.30, which is consistent with U.S. EPA (1996a and b) for subsurface soils.

23. *Vadose Zone Soil Organic Carbon Fraction* (Soil Screening Model Only) (f_{oc}^A)

Because the screening-level models accommodate only one soil stratum above the top of contamination, enter the depth-averaged soil organic carbon fraction. The default value is 0.002, which is consistent with U.S. EPA (1996a and b) for subsurface soils.

24. *Enclosed Space Floor Thickness* (Advanced Models Only) (L_{crack})

Enter the thickness of the floor slab. All models operate under the assumption that the floor in contact with the underlying soil is composed of impermeable concrete

whether constructed as a basement floor or slab-on-grade. The default value is 10 cm, which is consistent with J&E (1991).

25. *Soil-Building Pressure Differential* (Advanced Models Only) (ΔP)

Because of wind effects on the structure, stack effects due to heating of the interior air, and unbalanced mechanical ventilation, a negative pressure with respect to the soil surface is generated within the structure. This pressure differential (ΔP) induces a flow of soil gas through the soil matrix and into the structure through cracks, gaps, and openings in the foundation. The effective range of values of ΔP is 0-20 pascals (Pa) (Loureiro et al., 1990; Eaton and Scott, 1984). Individual average values for wind effects and stack effects are approximately 2 Pa (Nazaroff et al., 1985; Put and Meijer, 1989). Typical values for the combined effects of wind pressures and heating are 4 to 5 Pa (Loureiro et al., 1990; Grimsrud et al., 1983). A conservative default value of ΔP was therefore chosen to be 4 Pa (40 g/cm-s²).

For more information on estimating site-specific values of ΔP , the user is referred to Nazaroff et al. (1987) and Grimsrud et al. (1983).

26. *Enclosed Space Floor Length* (Advanced Models Only) (L_B)

The default value is 1000 cm (see Variable No. 28).

27. *Enclosed Space Floor Width* (Advanced Models Only) (W_B)

The default value is 1000 cm (see Variable No. 28).

28. *Enclosed Space Height* (Advanced Models Only) (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 for a single story house without a basement.

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 is 3.66 m. This value represents a two-fold reduction in vapor concentrations between the floors.

29. *Floor-Wall Seam Crack Width* (Advanced Models Only) (W)

The conceptual model used in the spreadsheets follows that of Loureiro et al. (1990) and Nazaroff (1988) and is illustrated in Figure 9. The model is based on a single-

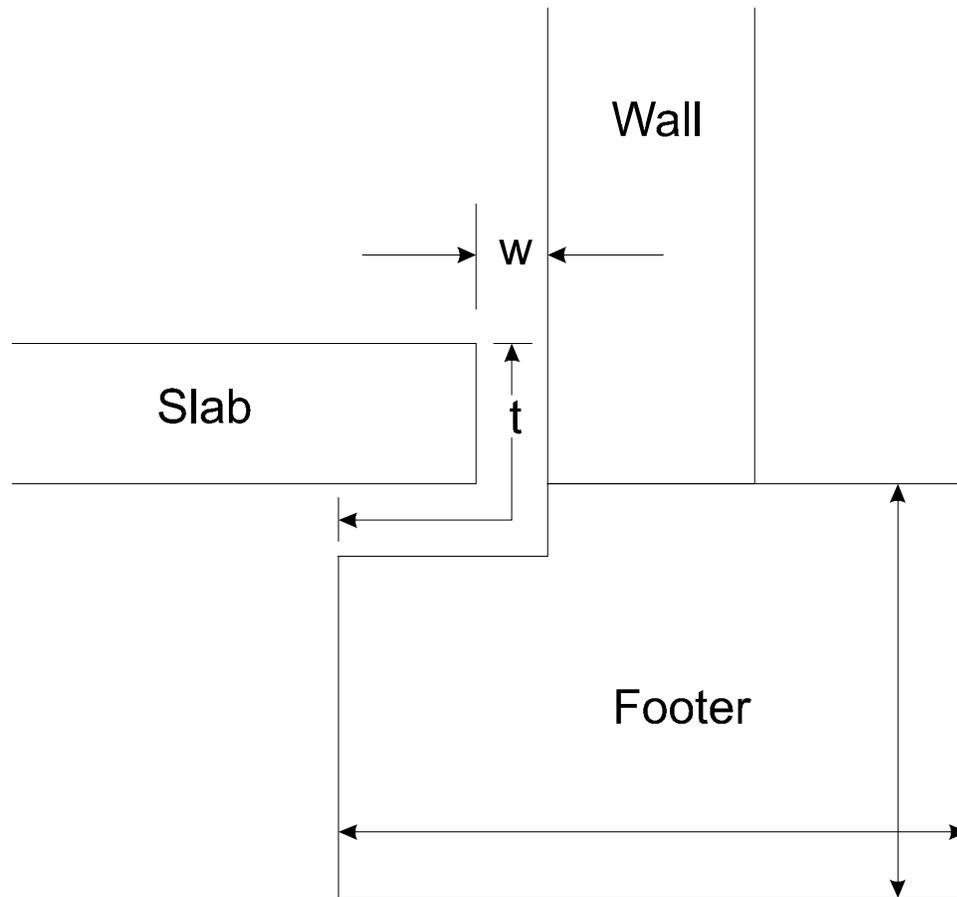


Figure 9. Floor Slab and Foundation

family house with a poured concrete basement floor and wall foundations, or constructed slab-on-grade in similar fashion. A gap is assumed to exist at the junction between the floor and the foundation along the perimeter of the floor. The gap exists as a result of building design or concrete shrinkage. This gap is assumed to be the only opening in the understructure of the house and therefore the only route for soil gas entry.

Eaton and Scott (1984) reported typical open areas of approximately 300 cm^2 for the joints between walls and floor slabs of residential structures in Canada. Therefore, given the default floor length and width of 1000 cm , a gap width (w) of 0.1 cm equates to a total gap area of 900 cm^2 , which is reasonable given the findings of Eaton and Scott. This value of the gap width is also consistent with the typical value reported in Loureiro et al. (1990). The default value of the floor-wall seam crack width was therefore set equal to 0.1 cm .

30. *Indoor Air Exchange Rate (Advanced Models Only) (ER)*

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 0.25/h. This value is consistent with the 10th percentile of houses in all regions of the U.S., as reported in Koontz and Rector (1995). This value is also consistent with the range of the control group of 331 houses in a study conducted by Parker et al. (1990) to compare data with that of 292 houses with energy-efficient features in the Pacific Northwest.

31. *Averaging Time for Carcinogens (All Models) (AT_c)*

Enter the averaging time in units of years. The default value is 70 years.

32. *Averaging Time for Noncarcinogens (All Models) (AT_{nc})*

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 (1996a and b) is 30 years.

33. *Exposure Duration (All Models) (ED)*

Enter the exposure duration in units of years. The default value for residential exposure from U.S. EPA (1996a and b) is 30 years.

34. *Exposure Frequency (All Models) (EF)*

Enter the exposure frequency in units of days/yr. The default value for residential exposure from U.S. EPA (1996a and b) is 350 days/yr.

35. *Target Risk for Carcinogens (All Soil and Groundwater Models) (TR)*

If a risk-based media concentration is to be calculated, enter the target risk-level. The default value is 1×10^{-6} .

36. *Target Hazard quotient for Noncarcinogens (All Soil and Groundwater Models) (THQ)*

If a risk-based media concentration is to be calculated, enter the target hazard quotient. The default value is 1.

The remaining four worksheets include the results sheet (RESULTS) and three ancillary sheets. The ancillary sheets include the chemical properties sheet (CHEMPROPS), the intermediate calculations sheet (INTERCALCS), and the lookup tables (VLOOKUP).

3.5 THE RESULTS SHEET (RESULTS)

Once all data are entered in the data entry sheet, the model results may be viewed on the RESULTS sheet. For the soil and groundwater models, calculations are presented as either a risk-based soil or groundwater concentration, or the incremental risks associated with an initial soil or groundwater concentration. In the case of the advanced models, the user should check the message and error summary below the results section to ensure that no error messages appear. If one or more error messages appear, re-enter the appropriate data.

The RESULTS worksheet shows the indoor exposure soil or groundwater concentration for either a carcinogen or noncarcinogen as appropriate. When a contaminant is both a carcinogen and a noncarcinogen, the risk-based indoor exposure concentration is set equal to the lower of these two values. In addition, the soil saturation concentration (C_{sat}) or the aqueous solubility limit (S) is also displayed for the soil and groundwater models, respectively.

The equilibrium vapor concentration at the source of contamination is limited by the value of C_{sat} for soil contamination and by the value of S for groundwater contamination, as appropriate. For a single contaminant, the vapor concentration directly above the source of soil contamination cannot be greater than that associated with the soil saturation concentration; for groundwater contamination, the vapor concentration cannot be greater than that associated with the solubility limit. As a result, subsurface soil concentrations greater than C_{sat} and groundwater concentrations greater than S will not produce higher vapor concentrations. Therefore, if the indoor vapor concentration predicted from a soil concentration greater than or equal to the value of C_{sat} and it 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. The same is true for an indoor vapor concentration predicted from a groundwater concentration greater than or equal to the value of S. That does not necessarily mean, however, that the subsurface contamination will not be of concern from a groundwater protection standpoint, (ingestion) and the potential for free-phase contamination (e.g., NAPL) must also be addressed.

For subsurface soils, the physical state of a contaminant at the soil temperature plays a significant role. When a contaminant is a liquid (or gas) at the soil temperature, the upper limit of the soil screening level is set at C_{sat} . This tends to reduce the potential for NAPL to exist within the vadose zone. The case is different for a subsurface contaminant that is a solid at the soil temperature. In this case, the screening level is not limited by C_{sat} because of the reduced possibility of leaching to the water table. If the model estimates a risk-based screening level greater than C_{sat} for a solid in soils, the model will display the final soil concentration as "NOC" or Not of Concern for the vapor intrusion pathway.

In the case of groundwater contamination, the physical state of the contaminant is not an issue in that the contamination has already reached the water table. Because the equilibrium vapor concentration at the source of emissions cannot be higher than that associated with the solubility limit, the vapor concentration is calculated at the solubility limit if the user enters a groundwater concentration greater than the value of S when forward-calculating risk. When reverse-calculating a risk-based groundwater concentration, the model will display the final groundwater concentration as "NOC" for the vapor intrusion pathway if the model calculates a risk-based level greater than or equal to the value of S. It should be noted, however, that if the soil properties or other conditions specified in the DATENTER worksheet are changed, the final risk-based soil or groundwater concentration must be remodeled.

It should also be understood that if a contaminant is labeled "Not of Concern" for the vapor intrusion pathway, all other relevant exposure pathways must be considered for both contaminated soils and groundwater.

3.6 THE CHEMICAL PROPERTIES SHEET (CHEMPROPS)

The chemical properties sheet provides a summary of the chemical and toxicological properties of the chemical selected for analysis. These data are retrieved from the VLOOKUP sheet by CAS number. All data in the chemical properties sheet are protected.

3.7 THE INTERMEDIATE CALCULATIONS SHEET (INTERCAL)

The intermediate calculations sheet provides solutions to intermediate variables. Review of the values of the intermediate variables may be helpful in an analysis of the cause-and-effect relationships between input values and model results. All data in the intermediate calculations sheet are protected.

3.8 THE LOOKUP TABLES (VLOOKUP)

The VLOOKUP sheet contains two lookup tables from which individual data are retrieved for a number of model calculations. The first table is the Soil Properties Lookup Table. This table contains 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 Leij, Stevens, et al (1994).

3.9 ADDING, DELETING, OR REVISING CHEMICALS

Data for any chemical may be edited, new chemicals added, or existing chemicals deleted from the Chemical Properties Lookup Table within the VLOOKUP worksheet. To begin an editing

session, the user must unprotect (unseal) the worksheet (the password is "ABC" in capital letters); editing of individual elements or addition and deletion of chemicals may then proceed. Space has been allocated for up to 260 chemicals in the lookup table. Row number 284 is the last row that may be used to add new chemicals. After the editing session is complete, the user must sort all the data in the lookup table (except the column headers) in ascending order by CAS number. After sorting is complete, the worksheet should again be protected (sealed).

SECTION 4

SOIL GAS MODEL APPLICATION

Two additional models have been added to allow the user to input measured soil gas concentration and sampling depth data directly into the spreadsheet. These models eliminate the need for theoretical partitioning of a total volume soil concentration or a groundwater concentration into discrete phases. This section provides instructions for using the soil gas models.

4.1 RUNNING THE MODELS

Two models are provided as MICROSOFT EXCEL spreadsheets. The screening-level model is titled SG-SCREEN.xls (EXCEL). The advanced model is titled SG-ADV.xls.

Both the screening-level and advanced models allow the user to calculate steady-state indoor air concentrations and incremental risks from user-defined soil gas concentration data. The models do not allow for reverse-calculation of a risk-based soil or groundwater concentration. As with the soil and groundwater screening-level models, the SG-SCREEN model operates under the assumption that the soil column properties are homogeneous and isotropic from the soil surface to an infinite depth. In addition, the SG-SCREEN model uses the same default values for the building properties as the SL-SCREEN and GW-SCREEN models. The advanced model allows the user to specify up to three different soil strata from the bottom of the building floor in contact with the soil to the soil gas sampling depth. Finally, the advanced model allows the user to specify values for all of the model variables.

To run the models, simply open the appropriate file within either MICROSOFT EXCEL worksheet. Each model is constructed of the following worksheets:

1. DATENTER (Data Entry Sheet)
2. CHEMPROPS (Chemical Properties Sheet)
3. INTERCALCS (Intermediate Calculations Sheet)
4. RESULTS (Results Sheet)
5. VLOOKUP (Lookup Tables)

Each worksheet follows the form of the worksheets in the soil and groundwater models. See Section 4.2 for a description of each worksheet.

The DATENTER worksheet of each of the soil gas models is different than those of the soil and groundwater models. Figure 10 shows the DATA ENTER worksheet of the SG-ADV model. Note that there is no option for running the model to calculate a risk-based media concentration. As with the other models, the user enters the CAS number of the chemical of interest. This automatically retrieves the chemical and toxicological data for that chemical. The CAS number must match one of the chemicals listed in the VLOOKUP worksheet, or the message "CAS No. not found" will appear in the "Chemical" box. The user also has the opportunity to add new chemicals to the data base. Next, the user must enter a value for the soil gas concentration of the chemical of interest. The user may enter this value in units of $\mu\text{g}/\text{m}^3$ or parts-per-million by volume (ppmv). If the soil gas concentration is entered in units of ppmv, the concentration is converted to units of $\mu\text{g}/\text{m}^3$ by:

$$C_g' = \frac{C_g \times MW}{R \times T_S} \quad (33)$$

where

- C_g' = Soil gas concentration, $\mu\text{g}/\text{m}^3$
- C_g = Soil gas concentration, ppmv
- MW = Molecular weight, g/mol
- R = Gas constant (= $8.205 \text{ E-}05 \text{ atm}\cdot\text{m}^3/\text{mol}\cdot^\circ\text{K}$)
- T_S = System (soil) temperature, $^\circ\text{K}$.

In the soil gas models, the steady-state indoor air concentration is calculated by Equation 19 (i.e., $C_{\text{building}} = \alpha C_{\text{source}}$). The value of the vapor concentration at the source of emissions (C_{source}) is assigned the value of the user-defined soil gas concentration. The value of the steady-state attenuation coefficient (α) in Equation 19 is calculated by Equation 13. 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.

The SG-SCREEN model operates under the assumption of homogeneously distributed soil properties and isotropic conditions with respect to soil vapor permeability from the soil surface to an infinite depth. The SG-ADV model, on the other hand, allows the user to specify up to three different soil strata between the building floor in contact with the soil and the soil gas sampling depth. Soil properties within these three strata may be varied to allow for different diffusion resistances to vapor transport.

4.2 SOIL GAS SAMPLING

In order to use the soil gas models, soil gas concentrations must be measured at one or more depths below ground surface (bgs). The user is advised to take samples directly under building slabs

SG-ADV
Version 3.1: 02/04

Reset to Defaults

Soil Gas Concentration Data	
ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Soil gas conc., C _g (ppmv)
OR	ENTER Soil gas conc., C _g (µg/m ³)
71432	2.00E+01
Chemical Benzene	

MORE ↓

ENTER Depth below grade to bottom of enclosed space floor, L _f (cm)	ENTER Soil gas sampling depth below grade, L _s (cm)	ENTER Average soil temperature, T _s (°C)	ENTER Thickness of soil stratum A, h _A (cm) (Enter value or 0)	ENTER Thickness of soil stratum B, h _B (cm) (Enter value or 0)	ENTER Thickness of soil stratum C, h _C (cm) (Enter value or 0)	ENTER Soil stratum A SCS soil type used to estimate soil vapor permeability, k _v (cm ²)
200	400	10	100	100	100	L

MORE ↓

ENTER Stratum A SCS soil type Lookup Soil Parameters	ENTER Stratum A soil total porosity, n ^A (unitless)	ENTER Stratum A soil dry bulk density, ρ _d ^A (g/cm ³)	ENTER Stratum A soil water-filled porosity, g _w ^A (cm ³ /cm ³)	ENTER Stratum B SCS soil type Lookup Soil Parameters	ENTER Stratum B soil dry bulk density, ρ _d ^B (g/cm ³)	ENTER Stratum B soil total porosity, n ^B (unitless)	ENTER Stratum B soil water-filled porosity, g _w ^B (cm ³ /cm ³)	ENTER Stratum C SCS soil type Lookup Soil Parameters	ENTER Stratum C soil dry bulk density, ρ _d ^C (g/cm ³)	ENTER Stratum C soil total porosity, n ^C (unitless)	ENTER Stratum C soil water-filled porosity, g _w ^C (cm ³ /cm ³)
1.5	0.43	1.5	0.15	1.5	1.5	0.43	0.25	1.7	0.38	0.3	

MORE ↓

ENTER Enclosed space floor thickness, L _{enc} (cm)	ENTER Soil-bldg pressure differential, ΔP (g/cm-s ²)	ENTER Enclosed space floor length, L _e (cm)	ENTER Enclosed space height, H _b (cm)	ENTER Floor-wall seam crack width, w (cm)	ENTER Indoor air exchange rate, ER (1/h)	ENTER Average vapor flow rate into bldg, Q _{av} Leave blank to calculate (L/m)
10	40	1000	366	0.1	0.25	5

END

ENTER Averaging time for carcinogens, AT _c (yrs)	ENTER Averaging time for noncarcinogens, AT _{nc} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)
70	30	30	350

Figure 10. SG-ADV Data Entry Worksheet

or basement floors when possible. This can be accomplished by drilling through the floor and sampling through the drilled hole. Alternatively, an angle-boring rig can be used to sample beneath the floor from outside the footprint of the building. When sampling directly beneath the floor is not possible, enough samples adjacent to the structure should be taken to adequately estimate an average concentration based on reasonable spatial and temporal scales.

Soil gas measurements can be made using several techniques; however, active whole-air sampling methods and active or passive sorbent sampling methods are usually employed. Typically, a whole-air sampling method is used whereby a non-reactive sampling probe is inserted into the soil to a prescribed depth. This can be accomplished manually using a "slam bar," or a percussion power drill, or the probe can be inserted into the ground using a device such as a Geoprobe.[®] The Geoprobe[®] device is attached to the rear of a specially customized vehicle. In the field, the rear of the vehicle is placed over the sample location and hydraulically raised on its base. The weight of the vehicle is then used to push the sampling probe into the soil. A built-in hammer mechanism allows the probe to be driven to predetermined depths up to 50 feet depending on the type of soil encountered. Soil gas samples can be withdrawn directly from the probe rods, or flexible tubing can be connected to the probe tips at depth for sample withdrawal.

Whole-air sampling is typically accomplished using an evacuated Summa or equivalent canister, or by evacuation to a Tedlar bag. Normal operation includes the use of an in-line flow controller and a sintered stainless steel filter to minimize particles becoming entrained in the sample atmosphere. For a 6-liter Summa canister, a normal sampling flow rate for a 24-hr integrated sample might be on the order of 1.5 ml/min; however, higher sampling rates can be used for grab samples. The sampling rate chosen, however, must not be so high as to allow for ambient air leakage between the annulus of the probe and the surrounding soils. Depending on the target compounds, excessive air leakage can dilute the sample (in some cases below the analytical detection limits).

One way to check for leakage is to test an aliquot of the sample gas for either nitrogen or oxygen content before the sample is routed to the canister or Tedlar bag. To test for nitrogen in real- or near real-time requires a portable gas chromatograph/mass spectrometer (GC/MS). A portable oxygen meter, however, can be used to test for sample oxygen content in real-time with a typical accuracy of one-half of one percent. If air leakage is detected by the presence of excessive nitrogen or oxygen, the seal around the sample probe at the soil surface as well as all sampling equipment connections and fittings should be checked. Finally, the flow rate may need to be reduced to decrease or eliminate the air leakage.

The collection and concentration of soil gas contaminants can be greatly affected by the components of the sampling system. It is imperative to use materials that are inert to the contaminants of concern. Areas of sample collection that need particular attention are:

- The seal at the soil surface around the sample probe
- Use of a probe constructed of stainless steel or other inert material
- Minimization of the use of porous or synthetic materials (i.e., PTFE, rubber, or most plastics) that may adsorb soil gas and cause cross-contamination

- Purging of the sample probe and collection system before sampling
- Leak-check of sampling equipment to reduce air infiltration
- Keeping the length of all sample transfer lines as short as possible to minimize condensation of extracted gas in the lines.

The choice of analytical methods for whole-air soil gas sampling depends on the contaminants of concern. Concentrations of volatile organic compounds (VOCs) in the soil gas are typically determined using EPA Method TO-14 or TO-15. In the case of semi-volatile compounds, an active sorbent sampling methodology can be used. In this case, a low-volume sampling pump is normally used to withdraw the soil gas, which is then routed to a polyurethane foam (PUF) plug. Vapor concentrations of semi-volatile contaminants sorbed to the PUF are then determined using EPA Method TO-10. The active soil gas sampling equipment can be assembled to allow for both canister sampling for volatiles and PUF sampling for semi-volatiles.

Passive sorbent sampling involves burial of solid sorbent sampling devices called cartridges or cassettes to a depth of normally 5 feet or less. The cassettes may be configured with one or more sorbents depending on the list of target analytes, and are typically left in-ground for 72 to 120 hours or longer. During this time period, the vapor-phase soil gas contaminants pass through the cassette and are adsorbed as the soil gas moves toward the soil surface by diffusion and/or convection. Analytical methods for sorbent sampling depend on the target analytes and the sorbent used and may include EPA Method TO-10 or a modified EPA Method TO-1. Vapor-phase concentrations for some solid sorbent sampling systems are determined using the total mass of each contaminant recovered, the time in-ground, the cross-sectional area of the cassette, the diffusivity of the compound in air, and a quasi-empirical adsorption rate constant.

Recent EPA technology verification reports produced by the EPA National Exposure Research Laboratory (EPA 1998, 1998a) concluded, at least for two such systems, that the sorbent methodologies accurately accounted for the presence of most of the soil gas contaminants in the studies. Further, the reports concluded that the sorbent systems showed detection of contaminants at low concentrations not reported using an active whole-air sampling system. For one system, however, it was noted that as the vapor concentrations reported for the whole-air sampling system increased by 1 to 4 orders-of-magnitude, the associated concentrations reported for the sorbent system increased only marginally. Perhaps the best use of such passive sorbent sampling methods is to help confirm which contaminants are present in the soil gas and not necessarily contaminant concentrations.

An excellent discussion of soil gas measurement methods and limitations can be found in the ASTM Standard Guide for Soil Gas Monitoring in the Vadose Zone D5314-92e1. ASTM Standard Guides are available from the ASTM website at:

<http://www.astm.org>.

In addition, soil gas measurement method summaries can be found in the EPA Standard Operating Procedures for Soil Gas Sampling (SOP No. 2042) developed by the EPA Environmental Response

Team (ERT) in Edison, New Jersey. This document can be downloaded from the ERT Compendium of Standard Operating Procedures at the following website:

http://www.ert.org/media_resrcs/media_resrcs.asp.

Data Quality and Data Quality Objectives

The results of soil gas sampling must meet the applicable requirements for data quality and satisfy the data quality objectives of the study for which they are intended. Data quality objectives are qualitative and quantitative statements derived from the data quality objectives process that clarify study objectives, define the appropriate type of data, and specify the tolerable levels of potential decision errors that will be used to support site decisions. Data quality objectives are formulated in the first phase of a sampling project.

In the second phase of the project, a Quality Assurance Project Plan (QAPP) translates these requirements into measurement performance specifications and quality assurance/quality control procedures to provide the data necessary to satisfy the user's needs. The QAPP is the critical planning document for any environmental data collection operation because it documents how quality assurance and quality control activities will be implemented during the life of the project. Development of the data quality objectives and the QAPP for soil gas sampling should follow the guidance provided by EPA's Quality Assurance Division of the Office of Research and Development. Guidance documents concerning the development and integration of the data quality objectives and the QAPP can be obtained from the EPA website at:

http://epa.gov/ncercqa/qa/qa_docs.html.

In addition to the above guidance, the EPA Regional Office and/or other appropriate regulatory agency should be consulted concerning specific sampling requirements.

4.3 ASSUMPTIONS AND LIMITATIONS OF THE SOIL GAS MODEL

As discussed previously, the soil gas models operate 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 2.11 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 equilibria 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.

SECTION 5

ASSUMPTIONS AND LIMITATIONS OF THE J&E MODEL

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.

EPA is suggesting that the J&E Model be used at Resource Conservation and Recovery Act (RCRA) Corrective Action Sites, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)/Superfund Sites, and voluntary cleanup sites. EPA is not recommending that the J&E Model be used for sites contaminated with petroleum products if the products were derived from Underground Storage Tanks. The J&E Model does not account for contaminant attenuation (biodegradation, hydrolysis, sorption, and oxidation/reduction). Attenuation is potentially a significant concern for these type of sites. EPA is recommending that investigators use OSWER Directive 9610.17: Use of Risk Based Decision-Making in UST Corrective Action Programs to evaluate these types of sites.

The J&E Model as implemented by EPA assumes homogeneous soil layers with isotropic properties that characterize the subsurface. The first tier spreadsheet versions allow only one layer; the advanced spreadsheet versions allow up to three layers. Sources of contaminants that can be modeled include dissolved, sorbed, or vapor sources where the concentrations are below the aqueous solubility limit, the soil saturation concentration, and/or the pure component vapor concentration. The contaminants are assumed to be homogeneously distributed at the source. All but one of the spreadsheets assumes an infinite source. The exception is the advanced model for a bulk soil source, which allows for a finite source. For the groundwater and bulk soil models, the vapor concentration at the source is calculated assuming equilibrium partitioning. 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. Neither sorption nor biodegradation is accounted for in the transport of vapor from the source to the base of the building.

The assumptions described above and in Table 12 suggest a number of conditions that preclude the use of the Non-NAPL Models as implemented by EPA. These conditions include:

TABLE 12. ASSUMPTIONS AND LIMITATIONS OF THE 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 evaluation 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		
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		
Soil is homogeneous within any horizontal plane	Stratigraphy can be described by horizontal layers (not tilted layers)	Observe pattern of layers and unconformities Note: In simplified J&E Model layering is not considered
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, others?	Not likely

(continued)

Assumption	Implication	Field Evaluation
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.
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.	Observations of fractured rock, fractured clay, karst, macropores, preferential flow channels.
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
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
Contaminant vapors enter structures primarily through cracks and openings in the walls and foundation	Flow through the wall and foundation material itself neglected	Observe numbers of cracks and openings. Assessment of contribution from construction materials themselves not likely

- 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.
- Very small building air exchange rates (e.g., $< 0.25/h$)
- Buildings with crawlspace structures or other significant openings to the subsurface (e.g., earthen floors, stone buildings, etc.). The EPA spreadsheet only allows for either slab on grade or basement construction.
- 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.

The vapor equilibrium models employed to estimate the vapor concentration at the source of soil contamination is applicable only if "low" concentrations of the compound(s) are sorbed to organic carbon in the soil, dissolved in soil moisture, and present as vapor within the air-filled soil pores (i.e., a three-phase system). The vapor equilibrium models do not account for a residual phase NAPLs. If residual phase contaminants are present in the soil column, the user is referred to either the NAPL-SCREEN or NAPL-ADV model (Appendix A), as appropriate.

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 soil concentration is greater than the soil saturation concentration (C_{sat}) or if the groundwater concentration is greater than the solubility limit (S), the equilibrium vapor concentration will be calculated at the value of C_{sat} or S as appropriate.

The user is also reminded that when estimating a risk-based soil concentration, the model will compare the calculated soil concentration with the soil saturation concentration above which a residual phase is likely to occur. The soil saturation concentration (C_{sat}) is calculated as in U.S. EPA (1996a and b). If the risk-based concentration is greater than the saturation concentration and the contaminant is a liquid or gas at the soil temperature, the final soil concentration will be set equal to the soil saturation concentration. This tends to eliminate the possibility of allowing a liquid residual phase to exist within the soil column, which may leach to the water table. If the risk-based soil concentration is greater than C_{sat} and the contaminant is a solid, the contaminant is not of concern for the vapor intrusion pathway.

Likewise, the groundwater models 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 both the soil saturation concentration and the aqueous solubility limit do not consider the effects of multiple contaminants. The estimated values, therefore, may be artificially high such that a residual phase may actually exist at somewhat lower concentrations.

The procedures used to estimate the soil vapor permeability of the soil stratum in contact with the building floor and walls assume isotropic soils and steady-state soil moisture content. In addition, the calculations do not account for preferential vapor pathways due to soil fractures, vegetation root pathways, or the effects of a gravel layer below the floor slab or backfill. These items may act to increase the vapor permeability of in situ soils.

If in situ pneumatic tests are used to measure site vapor permeability, care must be taken to ensure adequate sampling to reduce the possibility of missing important soil structure effects due to anisotropy.

Single-point in situ pneumatic tests are typically conducted by measuring the pressure in a probe as a metered flow of air is passed through the probe and into the soil. Garbesi et al. (1996), however, demonstrated that soil vapor permeability increases with the sampling length scale. Using a dual-probe dynamic pressure sampling apparatus, Garbesi et al. (1996) demonstrated that the average soil vapor permeability typically increases up to a constant value as the distance between the source probe and detector probe increases. On a length scale typical of a house (3 to 10 m), use of the dual-probe sampling technique found that the soil permeability was approximately 10 to 20 times higher than that measured by the single-point method. Although arguably the most accurate means of determining in situ soil vapor permeability, the techniques of Garbesi et al. (1996) are complex and require specialized equipment.

Another method for determining the intrinsic permeability of soil is to conduct empirical measurements of the saturated hydraulic conductivity (K_s). These data are then input into Equation

26. The resulting value of k_i is then multiplied by the relative air permeability (k_{rg}) calculated by Equation 27 to yield the effective air permeability of the soil.

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 models do 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 models do 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 lumping 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).

Lumping 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 contain higher contaminant concentrations) is redistributed in the vadose zone resulting in temporary elevations in soil gas concentrations.

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).

As with the estimation procedure for soil vapor permeability, 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.

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.

5.1 SOURCE VAPOR CONCENTRATION

As applied in the accompanying spreadsheets, the vapor equilibrium model employed to estimate the vapor concentration at the source of soil contamination is applicable in the limit of "low" concentrations where compounds are sorbed to organic carbon in the soil, dissolved in soil moisture, and present as vapor within the air-filled soil pores (i.e., a three-phase system). The model does not account for a residual phase (e.g., NAPL). If residual phase contaminants are present in the soil column, the user is referred to either the NAPL-SCREEN or NAPL-ADV model, as appropriate.

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 soil concentration is greater than the soil saturation concentration (C_{sat}) or if the groundwater concentration is greater than the solubility limit (S), the equilibrium vapor concentration will be calculated at the value of C_{sat} or S as appropriate.

The user is also reminded that when estimating a risk-based soil concentration, the model will compare the calculated soil concentration with the soil saturation concentration above which a residual phase is likely to occur. The soil saturation concentration (C_{sat}) is calculated as in U.S. EPA (1996a and b). If the risk-based concentration is greater than the saturation concentration and the contaminant is a liquid or gas at the soil temperature, the final soil concentration will be set equal to the soil saturation concentration. This tends to eliminate the possibility of allowing a liquid residual phase to exist within the soil column, which may leach to the water table. If the risk-based soil concentration is greater than C_{sat} and the contaminant is a solid, the contaminant is not of concern for the vapor intrusion pathway.

Likewise, the groundwater models 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 both the soil saturation concentration and the aqueous solubility limit do not consider the effects of multiple contaminants. The estimated values, therefore, may be artificially high such that a residual phase may actually exist at somewhat lower concentrations.

5.2 SOIL VAPOR PERMEABILITY

The procedures used to estimate the soil vapor permeability of the soil stratum in contact with the building floor and walls assumes isotropic soils and steady-state soil moisture content. In addition, the calculations do not account for preferential vapor pathways due to soil fractures, vegetation root pathways, or the effects of a gravel layer below the floor slab or backfill which may act to increase the vapor permeability with respect to in situ soils.

If in situ pneumatic tests are used to measure site vapor permeability, care must be taken to ensure adequate sampling to reduce the possibility of missing important soil structure effects due to anisotropy.

Single point in situ pneumatic tests are typically conducted by measuring the pressure in a probe as a metered flow of air is passed through the probe and into the soil. Garbesi et al. (1996), however, demonstrated that soil vapor permeability increases with the sampling length scale. Using a dual-probe dynamic pressure sampling apparatus, Garbesi et al. (1996) demonstrated that the average soil vapor permeability typically increases up to a constant value as the distance between the source probe and detector probe increases. On a length scale typical of a house (3 to 10 m) use of the dual-probe sampling technique found that the soil permeability was approximately 10 to 20 times higher than that measured by the single point method. Although arguably the most accurate means of determining in situ soil vapor permeability, the techniques of Garbesi et al. (1996) are complex and require specialized equipment.

Another method for determining the intrinsic permeability of soil is to conduct empirical measurements of the saturated hydraulic conductivity (K_s). These data are then input into Equation 26. The resulting value of k_i is then multiplied by the relative air permeability (k_{rg}) calculated by Equation 27 to yield the effective air permeability of the soil.

5.3 RISE OF AND DIFFUSION ACROSS THE CAPILLARY ZONE

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

models do 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 models do 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 might rise to levels above the floor in some cases.

Diffusion across the capillary zone is estimated based on lumping 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 a 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).

Lumping 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 over estimation 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 which had previously been part of the saturated zone (and hence contain higher contaminant concentrations) is redistributed in the vadose zone resulting in temporary elevations in soil gas concentrations.

5.4 DIFFUSIVE AND CONVECTIVE TRANSPORT INTO THE STRUCTURE

The following is a discussion of the major assumptions and limitations of the J&E Model for diffusive and convective vapor transport into buildings.

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).

As with the estimation procedure for soil vapor permeability, 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).

SECTION 6

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 default values for input variables will result in higher indoor air concentrations and thus higher incremental risks or lower risk-based media 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. A combination of modeling and sampling methods is also possible to reduce the uncertainty of the calculated indoor air concentrations. Typically this involves field methods for measuring soil gas very near or below an actual structure. It should be understood, however, 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 is typically due to a vapor pooling 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 Model as well as for calibrating the Model 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. Appendix E contains bibliography and references.

APPENDIX A

USER'S GUIDE FOR NON-AQUEOUS PHASE LIQUIDS

Purpose

The NAPL-SCREEN and NAPL-ADV models are designed to forward calculate incremental cancer risks or noncarcinogenic hazard quotients due to subsurface soil vapor intrusion into buildings. The models are specifically designed to handle nonaqueous phase liquids or solids in soils. The user may specify up to 10 soil contaminants, the concentrations of which form a residual phase mixture. A residual phase mixture occurs when the sorbed phase, aqueous phase, and vapor phase of each chemical have reached saturation in soil. Concentrations above this saturation limit for all of the specified chemicals of a mixture will result in a fourth or residual phase (i.e., nonaqueous phase liquid or solid).

Other vapor intrusion models (SL-SCREEN, SL-ADV, SG-SCREEN, SG-ADV, GW-SCREEN, and GW-ADV) handled only a single contaminant and only when the soil concentration was at or below the soil saturation limit (i.e., a three-phase system). Use of these models when a residual phase is present, results in an overprediction of the soil vapor concentration and subsequently the building vapor concentration.

Residual Phase Theory

The three-phase system models estimate the equilibrium soil vapor concentration at the emission source (C_{source}) using the procedures from Johnson et al. (1990):

$$C_{source} = \frac{H'_{TS} C_R \rho_b}{\theta_w + K_d \rho_b + H'_{TS} \theta_a} \quad (1)$$

where:	C_{source}	=	Vapor concentration at the source of contamination, g/cm ³
	H'_{TS}	=	Henry's law constant at the soil temperature, dimensionless
	C_R	=	Initial soil concentration, g/g
	ρ_b	=	Soil dry bulk density, g/cm ³
	θ_w	=	Soil water-filled porosity, cm ³ /cm ³
	K_d	=	Soil-water partition coefficient, cm ³ /g (= $K_{oc} \times f_{oc}$)
	θ_a	=	Soil air-filled porosity, cm ³ /cm ³
	K_{oc}	=	Soil organic carbon partition coefficient, cm ³ /g
	f_{oc}	=	Soil organic carbon weight fraction.

In Equation 1, the equilibrium vapor concentration is proportional to the soil concentration up to the soil saturation limit. When a residual phase is present, however, the vapor concentration is independent of the soil concentration but proportional to the mole fraction of the individual component of the residual phase mixture. In this case, the equilibrium vapor concentration must be calculated numerically for a series of time-steps. For each time-step, the mass of each constituent that is volatilized is calculated using Raoult's law and the appropriate mole fraction. At the end of each time-step, the total mass lost is subtracted from the initial mass and the mole fractions are recomputed for the next time-step.

The NAPL-SCREEN and NAPL-ADV models use the procedures of Johnson et al. (2001) to calculate the equilibrium vapor concentration at the source of emissions for each time-step. Within each model, the user-defined initial soil concentration of each component in the mixture is checked to see if a residual phase is present. This is done by calculating the product of the activity coefficient of component i in water (α_i) and the mole fraction of i dissolved in soil moisture (y_i) such that:

$$\alpha_i y_i = \frac{M_i}{\left[\left(P_i^v(T_S) \theta_a V / RT_S \right) + \left(M^{H_2O} / \alpha_i \right) + \left(K_{d,i} M_{soil} / \alpha_i MW_{H_2O} \right) \delta(M^{H_2O}) \right]} \quad (2)$$

where:

M_i	=	Initial moles of component i in soil, moles
$P_i^v(T_S)$	=	Vapor pressure of i at the average soil temperature, atm
θ_a	=	Soil air-filled porosity, cm ³ /cm ³
V	=	Volume of contaminated soil, cm ³
R	=	Ideal gas constant, 82.05 atm-cm ³ /mol-°K
T_S	=	Average soil temperature, °K
$M_2^{H_2O}$	=	Total moles in soil moisture dissolved phase, moles
α_i	=	Activity coefficient of i in water, unitless
$K_{d,i}$	=	Soil-water partition coefficient of i , cm ³ /g
M_{soil}	=	Total mass of contaminated soil, g
MW_{H_2O}	=	Molecular weight of water, 18 g/mol
$\delta(M_2^{H_2O})$	=	1 if $M_2^{H_2O} > 0$, and
$\delta(M_2^{H_2O})$	=	0 if $M_2^{H_2O} = 0$.

If the sum of all the values of $\alpha_i y_i$ for all of the components of the mixture is less than 1, the mixture does not contain a residual phase and the models are not applicable. In such cases, the SL-SCREEN or SL-ADV model can be used to estimate the building concentration.

Once it has been determined that a residual phase does exist, the mole fraction of each component (x_i) is determined by iteratively solving Equations 3 and 4 subject to the constraint that the sum of all the mole fractions equals unity ($\sum x_i = 1$):

$$x_i = \frac{M_i}{\left[\left(P_i^v(T_S) \theta_a V / RT_S \right) + M^{HC} + \left(M^{H_2O} / \alpha_i \right) + \left(K_{d,i} M_{soil} / \alpha_i MW_{H_2O} \right) \delta(M^{H_2O}) \right]} \quad (3)$$

and,

$$x_i = \frac{M_i^{HC}}{M^{HC}} \quad (4)$$

where M_i^{HC} is the number of moles of component i in residual phase and M^{HC} is the total number of moles of all components in residual phase. The solution is simplified by assuming that $M_2^{H_2O}$ is approximately equal to the number of moles of water in the soil moisture. With the mole fraction of each component at the initial time-step, the equilibrium vapor concentration at the source of emissions is calculated by Raoult's law:

$$C_{source} = \frac{x_i P_i^v(T_S) MW_i}{RT_S} \quad (5)$$

where MW_i is the molecular weight of component i (g/mol).

At the beginning of each succeeding time-step, the number of moles of each chemical remaining in the soil from the previous time-step are again checked to see if a residual phase is present using Equation 2. When a residual phase is no longer present, the equilibrium vapor concentration at the source of emissions is calculated by:

$$C_{source} = \frac{\alpha_i y_i P_i^v(T_S) MW_i}{RT_S} \quad (6)$$

Ancillary Calculations

The activity coefficient of component i in water (α_i) is estimated from its solubility. Because hydrocarbons are typically sparingly soluble in water, the following generalization has been applied to compounds that are liquid or solid at the average soil temperature:

$$\alpha_i = (1/y_i) = (55.55 \text{ moles/L}) MW_i / S_i \quad (7)$$

where S_i is the solubility of component i (g/L). For gases at the average soil temperature, the corresponding relationship is:

$$\alpha_i = (1/y_i) \left(1 \text{ atm} / P_i^v(T_S) \right) = (55.55 \text{ moles/L}) \left(MW_i (1 \text{ atm}) / S_i P_i^v(T_S) \right) \quad (8)$$

Assuming that the vapor behaves as an ideal gas with a relatively constant enthalpy of vaporization between 70°F and the average soil temperature, the Clausius-Clapeyron equation can be used to estimate the vapor pressure at the desired temperature:

$$P^v(T_S) = P^v(T_R) \times \exp \left[\left(\frac{T_B \times T_R}{(T_B - T_R)} \right) \left(\frac{1}{T_S} - \frac{1}{T_R} \right) \ln \left(\frac{P^v(T_R)}{P_B} \right) \right] \quad (9)$$

where: $P^v(T_S)$ = Vapor pressure at the desired temperature T_S , atm
 $P^v(T_R)$ = Vapor pressure at the reference temperature T_R , atm

T_B	=	Normal boiling point, °K
T_R	=	Vapor pressure reference temperature, °K
T_S	=	The desired temperature, °K
P_B	=	Normal boiling point pressure = 1 atm.

Building Concentration

The vapor concentration within the building or enclosed space ($C_{building}$) is calculated using the steady-state solution of Johnson and Ettinger (1991) such that:

$$C_{building} = \alpha C_{source} \quad (10)$$

The steady-state attenuation coefficient (α) is calculated by:

$$\alpha = \frac{\left[\left(\frac{D_T^{eff} A_B}{Q_{building} L_T} \right) \times \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}} \right) \right]}{\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}} \right) + \left(\frac{D_T^{eff} A_B}{Q_{building} L_T} \right) + \left(\frac{D_T^{eff} A_B}{Q_{soil} L_T} \right) \left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}} \right) - 1 \right] \right]} \quad (11)$$

where:

α	=	Steady-state attenuation coefficient, unitless
D_T^{eff}	=	Total overall effective diffusion coefficient, cm ² /s
A_B	=	Area of the enclosed space below grade, cm ²
$Q_{building}$	=	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.

The reader is referred to Section 2.5 of this Guidance for a more detailed discussion of the derivation of Equation 11 and procedures for determining values for model input parameters. Except for the calculation of the equilibrium vapor concentration at the source of emissions, NAPL-SCREEN is identical to the three-phase model SL-SCREEN and NAPL-ADV is identical to the three-phase model SL-ADV.

The NAPL-SCREEN and NAPL-ADV models explicitly solve for the time-averaged building concentration over the exposure duration using a forward finite-difference numerical approach. For each time-step δt :

$$M_i(t + \delta t) = M_i(t) - \delta t (C_{building} \times Q_{building} / MW_i) \quad (12)$$

where $M_i(t)$ is the number of moles of component i in soil at the previous time and $M_i(t+\delta t)$ is the number of moles at the new time. The time-step interval is variable as a function of the percent of mass lost over the time-step. The user may specify a minimum and maximum percent loss allowed; these values are applied to the single component of the residual phase mixture with the highest mass loss rate during each time-step interval. If the user-specified maximum percent loss is exceeded, the next time-step interval is reduced by half; likewise, if the user-specified minimum percent loss is not achieved, the next time-step interval is increased by a factor of two. The instantaneous building concentration at time = t is calculated using Equation 10 for each time-step. The time-averaged building concentration is estimated using a trapezoidal approximation of the integral.

Model Assumptions and Limitations

The NAPL-SCREEN and NAPL-ADV models operate under the assumption that sufficient time has elapsed since the time of initial soil contamination for steady-state conditions to have been achieved. This means that the subsurface vapor plume has reached the bottom of the enclosed space floor and that the vapor concentration has reached its maximum value. An estimate of the time required to reach near steady-state conditions (τ_{ss}) can be made using the following equations from API (1998):

$$\tau_{ss} \cong \frac{R_v \theta_a L_T^2}{D^{eff}} \quad (13)$$

and,

$$R_v = 1 + \frac{\theta_w}{\theta_a H'_{TS}} + \frac{\rho_b K_d}{\theta_a H'_{TS}} \quad (14)$$

and,

$$D^{eff} = D_a \frac{\theta_a^{10/3}}{n^2} + \left(\frac{D_w}{H'_{TS}} \right) \frac{\theta_w^{10/3}}{n^2} \quad (15)$$

where R_v is the unitless vapor phase retardation factor, L_T is the source-building separation (cm), D^{eff} is the effective diffusion coefficient (cm^2/s), D_a is the diffusivity in air (cm^2/s), D_w is the diffusivity in water (cm^2/s), and n is the soil total porosity (cm^3/cm^3). The NAPL-SCREEN and NAPL-ADV models are applicable only when the elapsed time since initial soil contamination meets or exceeds the value of τ_{ss} (see **Using the Models**).

Emission source depletion is calculated by estimating the rate of vapor loss as a function of time such that the mass lost at each time-step is subtracted from a finite mass of contamination at the source. This requires the model user to estimate the dimensions of the emission source, e.g., the length, width, and thickness of the contaminated zone. The model should only be used, therefore,

when the extent of soil contamination has been sufficiently determined. It should be noted that because the NAPL-SCREEN and NAPL-ADV models are one-dimensional, the areal extent of soil contamination (i.e., length \times width) can be less than but not greater than the areal extent of the building floor in contact with the soil.

Each model treats the contaminated zone directly below the building as a box containing a finite mass of each specified compound. The initial contamination contained within the box is assumed to be homogeneously distributed. After each time-step, the remaining contamination is assumed to be instantaneously redistributed within the box to homogeneous conditions. The diffusion path length from the top of contamination to the bottom of the enclosed space floor therefore remains constant with time. Use of this simplifying assumption means that the degree of NAPL soil saturation is not required in the calculation of the total overall effective diffusion coefficient (D_T^{eff}).

As time proceeds, the concentration of the mixture of compounds within the soil column may reach the soil saturation limit. Below this point, a residual phase will cease to exist and the vapor concentration of each chemical will decrease proportional to its total volume soil concentration. Theoretically, the vapor concentration will decrease asymptotically, approaching but never reaching zero. Because of the nature of the numerical solution to equilibrium vapor concentration, however, compounds with high effective diffusion coefficients (e.g., vinyl chloride) may reach zero soil concentrations while other less volatile contaminants will not. If the initial soil concentrations are significantly higher than their respective values of the soil saturation concentration, a residual phase may persist up to the user-defined exposure duration.

Model assumptions and limitations concerning vapor transport and vapor intrusion into buildings are those specified for the three-phase models.

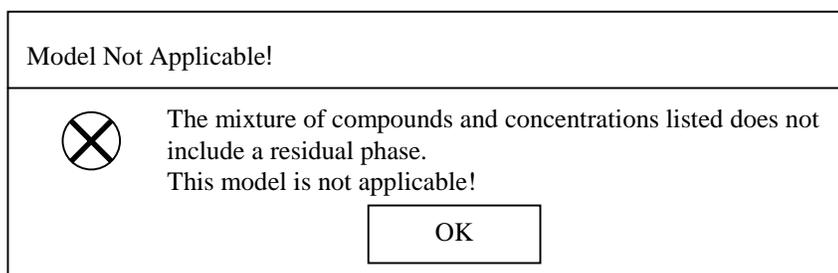
Using the Models

Each model is constructed as a Microsoft[®] Excel workbook containing five worksheets. The DATENTER worksheet is the data entry worksheet and also provides model results. The VLOOKUP worksheet contains the “Chemical Properties Lookup Table” with listed chemicals and associated chemical and toxicological properties. It should be noted that the toxicological properties for many of these chemicals were derived by route-to-route extrapolation. In addition, the VLOOKUP worksheet includes the “Soil Properties Lookup Table” containing values for model intermediate variables used in estimating the soil vapor permeability. The CHEMPROPS worksheet provides a summary of the chemical and toxicological properties of the soil contaminants selected by the user. In addition, the CHEMPROPS worksheet provides calculated values for the soil saturation concentration (C_{sat}) and the time to reach steady-state conditions (τ_{ss}) once all required data are entered into the DATENTER worksheet. The INTERCALCS worksheet contains calculated values of intermediate model variables. Finally, the COMPUTE worksheet contains the numerical solutions for equilibrium vapor concentration and building vapor concentration as a function of time.

Both models use the Microsoft® SOLVER add-in algorithms to simultaneously solve Equations 3 and 4 for each of up to 10 chemicals specified by the user. In order to run NAPL-SCREEN or NAPL-ADV, the SOLVER add-in must be loaded into EXCEL. The user is referred to the EXCEL instructions for loading the SOLVER add-in.

On the DATENTER worksheet, the user may specify up to 10 soil contaminants by CAS number along with associated soil concentrations in units of mg/kg. The CAS number entered must match exactly one of the 93 chemicals listed in the VLOOKUP worksheet or the error message “CAS No. not found” will appear in the “Chemical” box. If the list of chemicals and concentrations entered does not constitute a residual phase, the error message in Figure 1 will appear after starting the model.

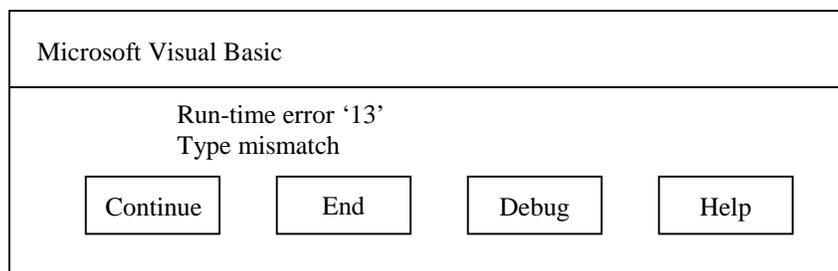
Figure 1. Residual Phase Error Message



If this error message box appears, use either the SL-SCREEN or SL-ADV model to estimate subsurface vapor intrusion into the building.

After starting the model calculations, other error message boxes may appear if data entry values are missing on the DATENTER worksheet or if entered values do not conform to model assumptions. If such an error message box appears, fill-in missing data or re-enter data as appropriate. If entered data values are outside the expected range or if text values are entered where numeric values are expected, the model calculation macro will be suspended and the run-time error message in Figure 2 will appear.

Figure 2. Run-Time Error Message



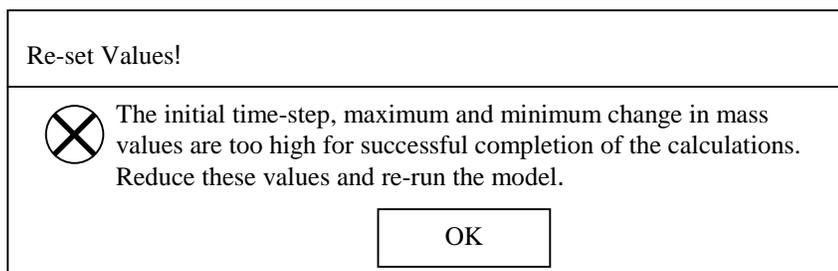
Should this error message appear, click on the “End” button to terminate the macro and return to the DATENTER worksheet. At this point, the user should review all of the entered values and make the appropriate corrections.

In addition to contaminant data, soil properties data, zone of contamination data, and exposure assumptions must also be specified in the DATENTER worksheet. Similar to the SL-SCREEN three-phase model, the NAPL-SCREEN model allows for only one soil stratum between the top of contamination and the bottom of the building floor in contact with the soil. In addition, the NAPL-SCREEN model uses built-in default values for all building variables (e.g., building dimensions, air exchange rate, total crack area, etc.). These default values are for single-family detached residences; therefore, the NAPL-SCREEN model should only be used for the residential exposure scenario.

The NAPL-ADV model, like the SL-ADV model, allows for up to three different soil strata between the top of contamination and the bottom of the building floor. In addition, the NAPL-ADV model allows the user to enter values for all model variables. This allows for the estimation of soil vapor intrusion into buildings other than single-family residences.

For each model, the user must also enter the duration of the first (initial) time-step interval. The maximum and minimum change in mass for each time-step must also be specified. The values of the initial time-step interval, and the maximum and minimum change in mass are important. If these values are too low, the model will calculate very small increments in the mass lost over time which will greatly extend the run-time of the model. In general, if the concentrations of the least volatile chemicals in the mixture are well above their respective values of the soil saturation concentration, a relatively large initial time-step interval, and maximum and minimum change in mass should be specified (e.g., 4 days, 10%, and 5%, respectively). For comparison, the value of the soil saturation concentration (C_{sat}) for each chemical specified by the user may be found in the CHEMPROPS worksheet after all data have been entered on the DATENTER worksheet. If, however, the soil concentrations of the most volatile constituents are very close to their respective saturation limits, large values of the initial time-step interval, and the maximum and minimum change in mass will result in the error message in Figure 3 after starting the model.

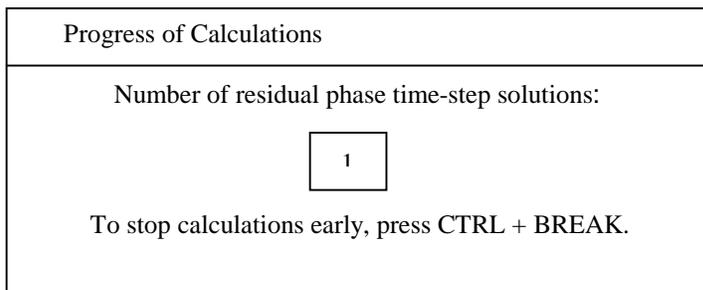
Figure 3. Time-Step and Change in Mass Error Message



Should this error message occur, reduce the value of the initial time-step interval and the values of the maximum and minimum change in mass to smaller values and re-run the model. The error message will be repeated until the values of these variables are sufficiently small.

After all required data are entered into the DATENTER worksheet, the model is run by clicking on the “Execute Model” button which will change from reading “Execute” to “Stand by...”. In addition, the message box in Figure 4 will appear keeping a running count of the number of residual phase time-step solutions achieved by the model.

Figure 4. Progress of Calculations Message Box

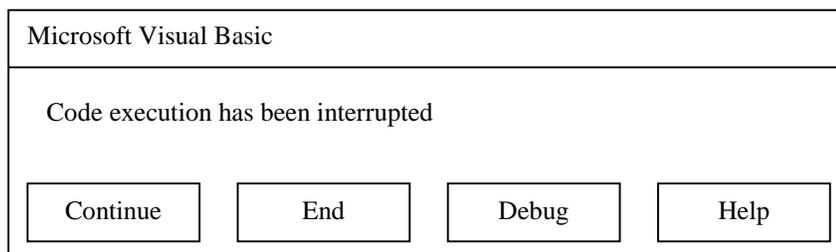


Each SOLVER trial solution can also be seen running in the status bar at the bottom of the screen. When the model is finished calculating, the “Execute Model” button will read “Done” and the Progress of Calculations message box in Figure 4 will disappear. The time-averaged building concentrations, incremental cancer risks, and/or hazard quotients will then be displayed under the “RESULTS” section of the DATENTER worksheet. In addition, an “X” will appear beside the calculated risk or hazard quotient of each contaminant for which a route-to-route extrapolation was employed. It should be noted that a route-to-route extrapolation was used for any chemical without a unit risk factor (URF) or a reference concentration (RfC). Therefore, the user should evaluate the resulting cancer risks and/or hazard quotients of such chemicals. Once a solution has been achieved and the user wishes to save the results, the file should be saved under a new file name. If the user wishes to delete all of the data previously entered on the DATENTER worksheet, this may be accomplished by clicking on the “Clear Data Entry Sheet” button.

Stopping Calculations Early

As mentioned previously, the user-defined values of the initial time-step interval, and the maximum and minimum change in mass should be chosen carefully. If the model run-time is excessive or if the user simply wishes to terminate the calculations, the model may be stopped by pressing CTRL + BREAK. If termination occurs in-between SOLVER solutions, the message box in Figure 5 will appear.

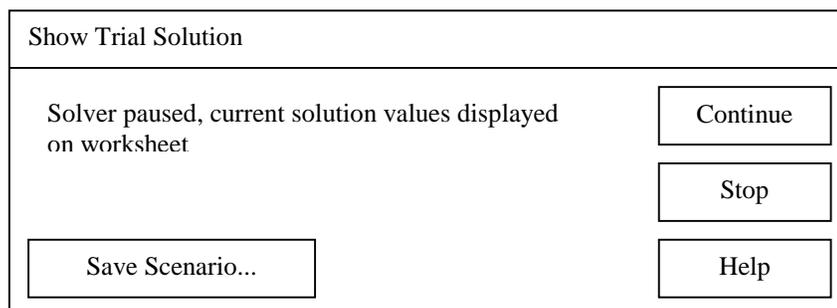
Figure 5. Code Interruption Message Box



If this message box appears, click on the “End” button to terminate the macro.

If the termination occurs during a SOLVER solution, the message box in Figure 6 will appear. If this message box appears, click on the “Stop” button. This will stop the SOLVER solution but not the program macro. Depending on where in the macro code the interruption occurs, the model may continue to operate after clicking on the “Stop” button in Figure 6. If this happens, press CTRL + BREAK again. At this point, the message box in Figure 5 will appear; click on the “End” button to terminate the macro.

Figure 6. Solver Interruption Message Box



At this point, the user may examine the model results up to the point of termination on the COMPUTE worksheet. The values of the “Change in mass”, the “Time-step interval”, and the “Cumulative time” should be examined to determine if changes are necessary in the values of the initial time-step interval, and the maximum and minimum change in mass. After these or any other values are changed on the DATENTER worksheet, the model may be re-run by clicking on the “Execute Model” button.

Step-By-Step Procedures for Running the Models

The following gives the step-by-step procedures for running either the NAPL-SCREEN or the NAPL-ADV model.

1. On the DATENTER worksheet, enter the CAS number of each soil contaminant in the residual phase mixture (do not include dashes in the CAS numbers). After the CAS numbers have been entered, the respective chemical names will appear in the “Chemical” box.
2. On the DATENTER worksheet, enter the soil concentration of each contaminant in units of mg/kg as well as values for all remaining variables except the “Initial time-step”, the “Maximum change in mass”, and the “Minimum change in mass”.
3. On the CHEMPROPS worksheet, note the calculated values of the “Time to steady state” (τ_{ss}) for each contaminant. Calculated values of the time-averaged building concentration and associated risks for contaminants with values of τ_{ss} greater than the actual elapsed time since initial soil contamination will be artificially high.
4. On the CHEMPROPS worksheet, note the calculated values of the “Soil saturation concentration” (C_{sat}) for each contaminant. Use these data to help determine appropriate user-defined values for the initial time-step, and the maximum and minimum change in mass. Typical values for these variables might be 2 days, 7%, and 4%, respectively, but may be considerably higher or lower depending on the number of chemicals in the analysis and the starting soil concentrations (see the discussion on page 8).
5. Click on the “Execute Model” button to begin the model calculations. If data are missing on the DATENTER worksheet, or entered values do not conform to model assumptions, an error message box will appear after the model is started informing the user of the type of error encountered. Enter the appropriate values on the DATENTER worksheet and re-run the model. Once the model has successfully started, note the number of residual phase time-step solutions achieved by the model in the Progress of Calculations message box (Figure 4). Use this information to help establish new values for the initial time-step interval and the maximum and minimum change in mass if the number of time-steps needs to be increased or decreased.
6. When the NAPL-SCREEN model has finished calculating, check column “O” on the COMPUTE worksheet to determine how many time-steps were calculated while a residual phase was present; one time-step is equal to one row (when using the NAPL-ADV model check column “P”). A residual phase is present when the value in column “O” or “P”, as appropriate, is equal to 1.000. In general, a greater number of time-steps means a more accurate estimate of the time-averaged building concentration. If the starting soil concentrations of the most volatile contaminants are very close to their respective values of C_{sat} , a minimum of 5 to 10 time-steps should be calculated by the model. For all other cases, a reasonable number of time-steps is between 40 and 70. To increase the number of time-steps calculated by the model, decrease the values of the initial time-step interval and the maximum and minimum change in mass. The opposite is true when the number of time-steps is to be decreased.

7. If the message box in Figure 1 appears after starting the model, the mixture of compounds and concentrations specified does not include a residual phase. Use the SL-SCREEN or SL-ADV model to calculate indoor air concentrations and risks for each contaminant separately.
8. If the message box in Figure 3 appears after starting the model, reduce the input values of the initial time-step, and maximum and minimum change in mass and re-run the model.
9. If the run-time of the model is excessive, terminate the model macro by pressing CTRL + BREAK (see the discussion under **Stopping Calculations Early** on pages 9 and 10). Examine the calculated values of the “Change in mass”, the “Time-step interval”, and the “Cumulative time” on the COMPUTE worksheet. Re-enter new lower values for the initial time-step interval, and the maximum and minimum change in mass and re-run the model.
10. After successful completion of a model run, note the calculated values of the “Time-averaged building concentration”, “Incremental cancer risk”, and/or “Hazard quotient” in the “RESULTS” section of the DATENTER worksheet. Also note for which contaminants a route-to-route extrapolation was employed. If the model results are to be retained, save the file under a new file name.

Adding, Deleting or Revising Chemical Data

Additional chemicals can be listed in the “Chemical Properties Lookup Table” within the VLOOKUP worksheet. To add, delete or revise chemicals, the VLOOKUP worksheet must be unprotected using the password “ABC” in capital letters. Row number 171 is the last row that may be used to add new chemicals. If new chemicals are added or chemicals deleted, the user must sort all the data in the “Chemical Properties Lookup Table” (except the column headers) in ascending order by CAS number. After sorting is complete, the worksheet should again be protected.

APPENDIX E
BIBLIOGRAPHY AND REFERENCE LIST

- American Petroleum Institute (API). 1998. Assessing the Significance of Subsurface Contaminant Vapor Migration to Enclosed Spaces, Site-Specific Alternatives to Generic Estimates. API Publication No. 4674. Washington, D.C.
- American Petroleum Institute. 2002. Practical Guidance for Assessing the "Groundwater to Indoor Air" Vapor Migration Pathway at Petroleum Hydrocarbon Sites..
- Bonazountas, M., and J. M. Wagner. 1984. "SESOIL,". A Seasonal Soil Compartment Model. Prepared by Arthur D. Little for U.S. EPA, Office of Toxic Substances.
- Brooks, R. H., and A. T. Corey. 1966. Properties of porous media affecting fluid flow. J. Irrig. Drainage Div., ASCE Proc. 72 (IR2), 61-88.
- Burkhard, L. P., D. E. Armstrong, and A. W. Andren. 1985. Henry's law constants for the polychlorinated biphenyls. Environ. Sci. Technology, 19:590-596.
- Carsel, R. F., and R. S. Parrish. 1988. Developing joint probability distributions of soil water retention characteristics. Water Resources Research, 24(5):755-769.
- Clapp, P. B. and G. Homberger. 1978. Empirical Equations for Some Soil Hydraulic Properties. Water Resources Research, Vol. 14 (4) 601-604.
- Cody, R. J. 2002. Groundwater to Indoor Air: Introductory Comments. Technical Support Project, General Meeting. Denver, Colorado.
- Dawson, H. 2002. Groundwater to Indoor Air Vapor Intrusion Issues. TSP General Meeting. Denver, CO.
- Dawson, H. E. 2002. Reliability of screening level approaches for evaluating the vapor intrusion to indoor air pathway. Presented at the 2002 RCRA National Meeting Washington, D.C.
- DiPersio, T., and J. Fitzgerald. 1995. Guidelines for the Design, Installation, and Operation of Sub-Slab Depressurization Systems. Prepared for Massachusetts Department of Environmental Protection, Northeast Regional Office.
- Dunn, I. S., L. R. Anderson, and F. W. Keifer. 1980. Fundamentals of Geotechnical Analysis. John Wiley & Sons, New York, New York.
- Eagleson, P. S. 1978. Climate, Soil, and Vegetation 3. A Simplified Model of Soil Moisture Movement in the Liquid Phase. Water Resources Research, Vol. 14(5):722-730.
- Eaton, R. S., and A. G. Scott. 1984. Understanding radon transport into houses. Radiation Protection Dosimetry, 7:251-253.

Environmental Quality Management, Inc. 2000. User's Guide for the NAPL-SCREEN and NAPL-ADV Models for Subsurface Vapor Intrusion into Building. Prepared for U.S. EPA.

Environmental Quality Management, Inc., User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings. Prepared for U.S. EPA Office of Emergency and Remedial Response. Washington, DC. U.S. EPA, 2000,

Environmental Quality Management, Inc., Supplemental Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathways. Prepared for the USEPA Superfund Program Office of Emergency Response and Remediation. Washington, DC. December 2001

Ettinger, R. 2002. Vapor Intrusion Modeling: Theory and Implications. Indoor Air Session, Technical Support Project Meeting. Denver, CO.

Fetter, C. W. 1994. Applied Hydrogeology, 3rd Ed., Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Fitzpatrick, N. A., and J. J. Fitzgerald. 1996. An evaluation of vapor intrusion into buildings through a study of field data. Presented at the 11th Annual Conference on Contaminated Soils. University of Massachusetts, Amherst.

Fitzpatrick, N. A., and J. J. Fitzgerald. 1997. An evaluation of vapor intrusion into buildings through a study of field data. In: Soil Vapor Transport to Indoor Air Workshop, February 6-7, 1997, Brea, California.

Fischer, M. L., A. J. Bentley, K. A. Dunkin, A. T. Hodgson, W. W. Nazaroff, R. G. Sexto, and J. M. Daisey. 1996. Factors affecting indoor air concentrations of volatile organic compounds at a site of subsurface gasoline contamination. Environ. Sci. Technol., 30(10):2948-2957.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall Inc. : Englewood Cliffs, New Jersey.

Freijer, J. I. 1994. Calibration of jointed tube model for the gas diffusion coefficient in soils. Soil Sci. Soc. Am. J., 58:1067-1076.

Gillham, R. W. 1984. The capillary fringe and its effect on water table response. Journal of Hydrology, 67:307-324.

Grimsrud, D. T., M. H. Sherman, and R. C. Sonderegger. 1983. Calculating infiltration: implications for a construction quality standard. In: Proceedings of the American Society of Heating, Refrigerating and Air-conditioning Engineers Conference, Thermal Performance of Exterior Envelopes of Buildings II., ASHRAE. SP38, pp. 422-452, Atlanta, Georgia.

Hartman, B. 2002. Reevaluating the Upward Vapor Migration Risk Pathway. LUSTLine Bulletin 41.

Hartman, B. 2002. The Upward Migration of Vapors. LUSTLine Bulletin 27.

Hasset, J. J., W. L. Banwart, and R. A. Griffin. 1983. Correlation of Compound Properties with Sorption Characteristics of Non-polar Compounds in Soils and Sediments: Concepts and Limitations in Environment and Solid Wastes: Characterization, Treatment, and Disposal. Butterworth Publishers: London. pp 161-178.

Hawker, D. W., and D. W. Connell. 1988. Octanol-water partition coefficients of polychlorinated biphenyl congeners. Environ. Sci. Technology, 22:382-387.

Hers, I. 2002. Subsurface Vapor Intrusion to Indoor Air Pathway: Model Predictions and Comparisons to Field Data. U.S. EPA RCRA National Meeting.

Hers, I. June 3, 2002 Technical Memorandum to Debbie Newberry, USEPA OSW. Input Parameters for OSWER Wide Guidance for Vapor Intrusion Pathway.

Hofelt, C. Addressing the Vapor Intrusion Pathway in Texas. Texas Natural Resource Conservation Commission, Toxicology and Risk Assessment Section.

Howard, P. H., R. S. Boethling, W. F. Jarvis, W. M. Meylan, and E. M. Michalenko. 1991. Handbook of Environmental Degradation Rates. Lewis Publishers, Chelsea, Michigan. 725 pp.

Hubbard, J. 1999. Region III Soil-to-Groundwater SSLs. Letter to RBC Table Users.

Johnson, P. C. May 2002. Identification of Critical Parameters for the Johnson and Ettinger (1991) Vapor Intrusion Model. American Petroleum Institute Bulletin No. 17, Washington, DC.

Johnson, P. C., R. A. Ettinger, J. Kurtz, R. Bryan, and J. E. Kester. 2002. Migration of Soil Gas Vapors to Indoor Air: Determining Vapor Attenuation Factors Using a Screening-Level Model and Field Data from the CDOT-MTL Denver, Colorado. Technical Task Force Bulletin No. 16, American Petroleum Institute. April.

Johnson, P. C., and R. A. Ettinger. 1991. Heuristic model for predicting the intrusion rate of contaminant vapors in buildings. Environ. Sci. Technol. 25: 1445-1452.

Johnson, P. C., M. B. Hertz, and D. L. Beyers. 1990. Estimates for hydrocarbon vapor emissions resulting from service station remediations and buried gasoline-contaminated soils. In: Petroleum Contaminated Soils, Vol. 3., Lewis Publishers, Chelsea, Michigan

- Jury, W. A. undated. A Users Manual for the Environmental Fate Screening Model Programs. Submitted to California Department of Health Services.
- Jury, W. A., R. Grover, W. F. Spencer, and W. J. Farmer. 1980. Modeling Vapor Losses of Soil Incorporated Triallate. *Soil Sci. Soc. Am. J.*,44:445-450.
- Jury, W. A., W. F. Spencer, and W. J. Farmer. 1983. Behavior Assessment Model for Trace Organics in Soil: I. Model Description. *J. Environ. Qual.*, 12(4):558-564.
- Jury, W. A., W. J. Farmer, and W. F. Spencer. 1984. Behavior Assessment Model for Trace Organics in Soil: II. Chemical Classification and Parameter Sensitivity. *J. Environ. Qual.*,(13):567-572.
- Jury, W. A., W. F. Spencer, and W. J. Farmer. 1984. Behavior Assessment Model for Trace Organics in Soil: III. Application of Screening Model. *J. Environ. Qual.*,13(4):573-579.
- Jury, W. A., W. F. Spencer, and W. J. Farmer. 1984. Behavior Assessment Model for Trace Organics in Soil: IV. Review of Experimental Evidence. *J. Environ. Qual.*, 13(4):580-586.
- Jury, W. A., D. Russo, G. Streile, and H. El Abd. 1990. Evaluation of Volatilization by Organic Chemicals Residing Below the Soil Surface. *Water Resources Res.* 26(1):13-20.
- Kemblowski, M. and P. C. Johnson. 2000. Environmental Monitoring, Modeling, and Management and Bayesian Belief Networks. *Envirosoft 2000*. Bilbao, Spain.
- Koontz, M. D., and H. E. Rector. 1995. Estimation of Distributions for Residential Air Exchange Rates. EPA Contract 68-D9-0166, Work Assignment 3-19. U.S. EPA, Office of Pollution Prevention and Toxics. Washington, DC.
- Kremesec, V. 2002. API Case Examples of the Evaluation of the EI Vapor Pathway Guidance. American Petroleum Institute.
- Kurz, D. W. 2000. Estimating residential indoor air impacts due to groundwater contamination. *Proceedings of the 2000 Conference on Hazardous Waste Research*.
- Larsen, K. 2002. Applying the Hazard Ranking System (HRS) to Vapor Intrusion Sites. 2002 National Site Assessment Conference. Austin, Texas.
- Last, G., and M. Fayer. 1999. Vandose Zone Conceptual Model Technical Approach for SAC Rev. 0. System Assessment Capability Workshop. Richland, Washington.
- Ley, T.W., Stevens, R. G., Topielec, R and Neibling, W. H. Soil Water Monitoring and Measurement. Pacific Northwest Extension Publication 0475, 1994.

Little, J. C., J. M. Daisy, and W. W. Nazaroff. 1992. Transport of subsurface contaminants into buildings: an exposure pathway for volatile organics. *Environ. Sci. Technol.* 26: 2058-2066.

Lohman, S. W. 1972. *Ground-Water Hydraulics*. Geological Survey Professional Paper 708, U.S. Department of the Interior, Washington, DC.

Loureiro, C. O., L. M. Abriola, J. E. Martin, and R. G. Sextro. 1990. Three-dimensional simulation of radon transport into houses with basements under constant negative pressure. *Environ. Sci. Technology*, 24:1338-1348.

Lyman, W. J., W. F. Reehl, and D. H. Rosenblatt. 1990. *Handbook of Chemical Property Estimation Methods*. McGraw Hill: New York, New York.

Ma, Y., M. Kemblowski, and G. E. Urroz. Kinematic Mixing and Chemical Reactions in Heterogeneous Aquifers. Department of Civil and Environmental Engineering, Utah Water Research Laboratory, Utah State University.

Mayer, R., J. Letey, and W. J. Farmer. 1974. Models for Predicting Volatilization of Soil Incorporated Pesticides. *Soil Sci. Soc. America Proc.* (38):563-568.

McCarthy, K. A., and R. L. Johnson. 1993. Transport of volatile organic compounds across the capillary fringe. *Water Resources Research*, 29(6):1675-1683.

McHugh, T. E. 2002. Evaluation of the Groundwater-to-Indoor Air Exposure Pathway. Presentation Materials

Michigan Environmental Science Board. 2001. Evaluation of the Michigan Department of Environmental Quality's Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria.

Millington, R. J., and J. M. Quirk. 1961. Permeability of porous solids. *Trans. Faraday Soc.*, 57:1200-1207.

Nazaroff, W. W. 1988. Predicting the rate of ²²²Rn entry from soil into the basement of a dwelling due to pressure-driven air flow. *Radiation Protection Dosimetry*, 24:199-202.

Nazaroff, W. W., H. Feustel, A. V. Nero, K. L. Revan, D. T. Grimsrud, M. A. Essling, and R. E. Toohey. 1985. Radon transport into a detached one-story house with a basement. *Atmospheric Environment*, 19(1):31-46.

Nazaroff, W. W., S. R. Lewis, S. M. Doyle, B. A. Moed, and A. V. Nero. 1987. Experiments on pollutant transport from soil into residential basements by pressure-driven airflow. *Environ. Sci. Technology*, 21(5):459-466.

- Nelson, D. W., and L. E. Sommers. 1982. Total carbon, organic carbon, and organic matter. In: A. L. Page (ed), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. 2nd Ed., 9(2):539-579, American Society of Agronomy, Madison, Wisconsin.
- New Jersey Department of Environmental Protection. 1999. *Indoor Air Sampling Guide for Volatile Organic Contaminants*.
- Nielson, K. K., and V. C. Rogers. 1990. Radon transport properties of soil classes for estimating indoor radon entry. In: F. T. Cross (ed), *Proceedings of the 29th Hanford Symposium of Health and the Environment. Indoor Radon and Lung Cancer: Reality or Myth? Part 1*. Battelle Press, Richland, Washington.
- Nudelman, N. S., S. M. Rios, and O. Katusich. 2002. Fate of the Oil Residuals in Patagonian Soils Effects of the Environmental Exposure Time. *Contaminated Soil Sediment & Water Magazine* <http://www.aehsmag.com/issues/2002/april_may/patagonian.htm>.
- O'Grady, M. 2002. Indoor Air Pathway-Implications for Site Assessments. EPA 2000 National Site Assessment Conference Homepage. <http://www.epa.gov/superfund/programs/siteasmt/sa_conf/ogrady/ogrady.htm>.
- Park, H. S. 1999. A Method for Assessing Soil Vapor Intrusion from Petroleum Release Sites: Multi-phase/Multi-fraction Partitioning.
- Parker, J. C., R. J. Lenhard, and T. Kuppusamy. 1987. A parametric model for constitutive properties governing multiphase flow in porous media. *Water Resources Research*, 23(4):618-624.
- Parker, G. B., M. McSorley, and J. Harris. 1990. The northwest residential infiltration survey: A field study of ventilation in new houses in the Pacific northwest. In: *Air Change Rate and Air Tightness in Buildings*, ASTM STP 1067, pp:93-103. American Society for Testing and Materials, Philadelphia, Pennsylvania.
- Parsons Engineering Science, Inc. 2000. Methyl Tertiary-Butyl Ether (MTBE) Its Movement and Fate in the Environment and Potential for Natural Attenuation. Presented to The Air Force Center for Environmental Excellence.
- Pennsylvania Department of Environmental Protection. March 2002. Science Advisory Board Meeting Minutes. <<http://www.dep.state.pa.us/dep/subject/advcoun/cleanup/mar2min.htm>>.
- Perry's Chemical Engineers' Handbook, 7th Ed. 1977. McGraw-Hill, New York, New York.
- Radian Corporation. 1989. Short-Term Fate and Persistence of Motor Fuels in Soils. American Petroleum Institute Report DCN 89-204-145-04.

Radian International. 2000. Guide to Optimal Groundwater Monitoring: Interim Final prepared for Naval Facilities Engineering Service Center, Port Hueneme, California.

Roggemans, S., C. L. Bruce, P. C. Johnson, and R. L. Johnson. 2001. Vadose Zone Natural Attenuation of Hydrocarbon Vapors: An Empirical Assessment of Soil Gas Vertical Profile Data. API Soil and Groundwater Technical Task Force Bulletin Number 15. Washington, DC.

Rong, Y. 2002. Laboratory Detection Limits. Contaminated Soil Sediment & Water Magazine April-May <http://www.aehsmag.com/issues/2002/april_may/laboratory_detection.htm>.

Sager, S. L., L. D. Braddy, and C. H. Day. 2002. The Crack Factor in Vapor Intrusion Calculations. Society for Risk Analysis 1997 Annual Meeting Homepage. <<http://www.riskworld.com/Abstract?1997/SRAam97/ab7ab357.htm>>.

San Diego County Department of Environmental Health, Land and Water Quality Division. 1999. User's Guide to the Vapor Risk 2000.

Sariyev, A., et al. 2002. Mathematical Modeling of Soil Hydraulic Properties and Numerical Analyses of Moisture Dynamic. <http://www.toprak.org.tr/isd/can_53.htm>.

Schaap, M. G., F. J. Leij, and M. Th. van Genuchten. 1997. Neural network analysis for hierarchical prediction of soil water retention and saturated hydraulic conductivity. Submitted to Soil Sci. Soc. Am. J. Personal communication from M. Th. van Genuchten, June 23, 1997.

Schroeder, P. R., R. L. Peyton, B. M. McEnroe, and J. W. Sjostrom. 1989. The Hydrologic Evaluation of Landfill Performance (HELP) Model. Prepared for the U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio.

Shan, C., and D. B. Stephens. 1995. An Analytical Solution for Vertical Transport of Volatile Chemicals in the Vadose Zone. J. of Contaminant Hydrology, Vol. 18, pp. 259-277.

Sorini, S. S., J. F. Schabron, and J. F. Rovani, Jr. 2002. Evaluation of VOC Loss from Soil Samples: Extrusion into Empty VOA Vials, Refrigerated Storage, and Methanol Injection in Preparation for Volatile Organic Analysis. Contaminated Soil Sediment & Water Magazine April-May <http://www.aehsmag.com/issues/2002/april_may/vocloss.htm>.

Spencer, W. F., M. M. Cliath, W. A. Jury, and L. Z. Zhang. 1988. Volatilization of Organic Chemicals from Soil as Related to Their Henry's Law Constants. J. Environ. Qual., 17(3):504-509.

Thibodeaux, L. J. 1981. Estimating the Air Emissions of Chemicals from Hazardous Waste Landfills. J. of Haz. Mat. 4:235-244.

- Toy, T. J., A. J. Kuhaida, Jr., and B. E. Munson. 1978. The predictions of mean monthly soil temperature from mean monthly air temperature, *Soil Science*, 126:181-189.
- Truesdale, R. S., M. L. Lowry, and S. N. Wolf. 2002. Draft Procedure and Issues Report: Vapor Intrusion Pathway. Prepared for the Indiana Department of Environmental Management.
- U.S. Department of Energy. 1995 Housing Characteristics, Report No. DOE/EIA-0314(93). Energy Information Administration, Washington, DC.
- U.S. Department of the Navy. Regulatory Basis for Conducting Ecological Risk Assessments. Navy Guidance for Conducting Ecological Risk Assessments.
- U.S. EPA. 2003. Prediction of Chemical Reactivity Parameters and Physical Properties of Organic Compounds from Molecular Substitute Using SPARC.
- U.S. EPA. 2002. EMSOFT Users Guide Office of Research and Development National Center for Environmental Assessment. NCEA –W-0073 R
- U.S. EPA. Office of Solid Waste and Emergency Response (OSWER)
Draft of the Guidance For Evaluating The Vapor Intrusion to Indoor Air Pathway From Groundwater Soils (Subsurface Vapor Intrusion Guidance) November 29, 2002.
- U.S. EPA OAQPS. 2002. Landfill Air Emissions Estimation Model. EPA-OAQPS Landfill Air Emissions Estimation Model Homepage. <<http://www.epa.gov/oar/oaqps/landfill.html>>.
- U.S. EPA. 2002. Region 6. Human Health Medium-Specific Screening Levels. EPA Region 6 - RCRA Human Health Medium Specific Screening Levels.
<http://www.epa.gov/earth1r6/6pd/rcra_c/pd-n/screen.htm>.
- U.S. EPA. 2000. Institutional Controls: A Site Manager's Guide to Identifying, Evaluating and Selecting Institutional Controls at Superfund and RCRA Corrective Action Cleanups. Office of Solid Waste and Emergency Response. EPA 540-F-00-005.
- U.S. EPA. 1998. BIOPLUME III: Natural Attenuation Decision Support System User's Manual Version 1.0. Office of Research and Development. EPA/600/R-98/010.
- U.S. EPA 1996, Soil Screening Guidance: User's Guide. EPA/540/R-96/018. Office of Solid Waste and Emergency Response. Washington, DC.
- U.S. EPA 1996. Soil Screening Guidance: Technical Background Document. EPA/540/R-95/128. Office of Solid Waste and Emergency Response. Washington, DC.
- U.S. EPA 1995, Review of Mathematical Modeling for Evaluating Soil Vapor Extraction Systems. EPA/540/R-95-513. Office of Research and Development, Washington, DC.

U.S. EPA 1992, Assessing Potential Indoor Air Impacts for Superfund Sites. National Technical Guidance Study Series. Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. EPA-451/R-92-002.

U.S. EPA, 1988. Superfund Exposure Assessment Manual. Office of Solid Waste and Emergency Response, Washington, DC. EPA/540/1-88/001.

Van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society Am. Journal*, 44:892-898.

Vereecken, H., J. Maes, J. Feyen, and P. Darius. 1989. Estimating the soil moisture retention characteristic from texture, bulk density, and carbon content. *Soil Sci.*, 148:389-403.

Vereecken, H., J. Maes, and J. Feyen. 1990. Estimating unsaturated hydraulic conductivity from easily measured soil properties. *Soil Sci.*, 149:1-12.

Vogel, T., K. Huang, R. Zhang, and M. Th. van Genuchten. 1996. The HYDRUS Code for Simulating One-Dimensional Water Flow, Solute Transport, and Heat Movement in Variably - Saturated Media, Version 5.0. U.S. Salinity Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Riverside, California. Research Report No. 140.

Waitz, M. F., J. Freijer, P. Kruele, and F. Swartjes. 1996. The VOLASOIL Risk Assessment Model Based on CSOIL for Soils Contaminated with Volatile Compounds. Report No. 715810014. National Institute for Public Health and the Environment. Bilthoven, The Netherlands.

Wenning, R. J. 2002. Focus on Sediments: USEPA Principles for Managing Contaminated Sediment Risks at Hazardous Waste Sites. *Contaminated Soil Sediment & Water Magazine* <http://www.aehsmag.com/issues/2002/april_may/USEPA.htm>.

Evaluation of the Johnson and Ettinger Model for Prediction of Indoor Air Quality

by Ian Hers, Reidar Zapf-Gilje, Paul C. Johnson, and Loretta Li

Abstract

Screening level models are now commonly used to estimate vapor intrusion for subsurface volatile organic compounds (VOCs). Significant uncertainty is associated with processes and models and, to date, there has been only limited field-based evaluation of models for this pathway. To address these limitations, a comprehensive evaluation of the Johnson and Ettinger (J&E) model is provided through sensitivity analysis, comparisons of model-predicted to measured vapor intrusion for 11 petroleum hydrocarbon and chlorinated solvent sites, and review of radon and flux chamber studies. Significant intrusion was measured at five of 12 sites with measured vapor attenuation ratios (α_m 's) (indoor air/source vapor) ranging from $\sim 1 \times 10^{-6}$ to 1×10^{-4} . Higher attenuation ratios were measured for studies using radon, inert tracers, and flux chambers; however, these ratios are conservative owing to boundary conditions and tracer properties that are different than those at most VOC-contaminated sites. Reasonable predictions were obtained using the J&E model with comparisons indicating that model-predicted vapor attenuation ratios (α_p 's) were on the same order, or less than the α_m 's. For several sites, the α_m were approximately two orders of magnitude less than the α_p 's indicating that the J&E model is conservative in these cases. The model comparisons highlight the importance in using appropriate input parameters for the J&E model. The regulatory implications associated with use of the J&E model to derive screening criteria are also discussed.

Introduction

The use of models to predict indoor air quality associated with volatile organic compound (VOC) contamination in soil and ground water is now commonplace (ASTM 1995; Johnson et al. 1998, Hers et al. 2002). Screening models typically used for this pathway are the Johnson and Ettinger (1991) model (henceforth referred to as the J&E model), or variants thereof. Processes controlling the intrusion of VOC vapors into buildings are not well understood, the accuracy of the J&E model is uncertain, and there have been only limited comparisons of model predictions to field data. There are also substantial differences in the way in which the J&E model is used for regulatory purposes.

To address these limitations, this paper presents a comprehensive evaluation of the J&E model based on theoretical considerations and field data from petroleum hydrocarbon and chlorinated solvent sites, and radon and flux chamber studies. Data sources are published studies, consultant or agency reports, and a field-based research program conducted by the authors. Included in the data sets analyzed are several recent groundbreaking investigations at chlorinated solvent sites.

The paper begins with an analysis of methods for estimating input parameters for the J&E model and their effect on model sensitivity and uncertainty. This analysis provides the needed context for the methods employed to interpret the field data used for this study. It is also important because it is

essential that model attributes and potential limitations be understood before using field data to evaluate the predictive capabilities of a model. Field-based methods for the evaluation of vapor attenuation ratio (α), defined as the indoor air concentration divided by the source vapor concentration, are evaluated next. The primary focus is measured vapor attenuation ratios (α_m) from 11 sites with petroleum hydrocarbon and chlorinated solvent contamination. Information from tracer studies using radon or an injected tracer such as sulphur hexafluoride (SF_6), and flux chamber studies are also reviewed. The measured α_m from field studies are compared to model-predicted vapor attenuation ratios (α_p) using the J&E model. Trends in the data are qualitatively evaluated and possible factors affecting vapor intrusion are considered. The paper also comments on the use of the J&E model to derive regulatory screening criteria.

J&E Model Input Parameters, Sensitivity, and Uncertainty

The basic form of the J&E model couples one-dimensional steady-state diffusion through soil, and diffusion and advection through a building envelope (i.e., foundation). A simple "box" model, which assumes uniform and instantaneous mixing of chemicals within the building enclosure, is used to estimate the indoor air concentration. Model sensitivity and uncertainty analysis and input needed for comparisons of

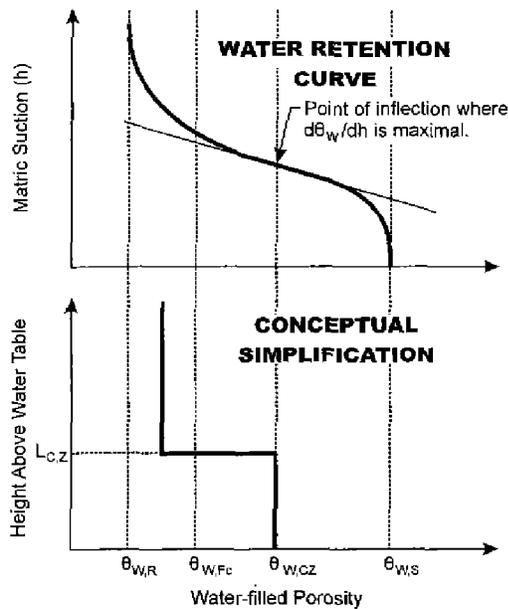


Figure 1. Conceptual simplification of water retention curve for purposes of estimating moisture contents and capillary rise ($\theta_{w,r}$, $\theta_{w,fc}$, $\theta_{w,cz}$, $\theta_{w,s}$ are the residual, field capacity, capillary zone, and saturated water contents).

model predictions to field data all require estimation of effective diffusion coefficient and soil gas advection rate. Because the available data varied, different methods were used to estimate these input parameters and interpret field data. The estimation methods subsequently used in this paper are discussed in the following sections.

Estimation of Effective Diffusion Coefficient (Air-Filled and Total Porosity)

The J&E model uses the Millington and Quirk (1961) relationship to estimate the effective diffusion coefficient (D_T^{eff}), as follows:

$$D_T^{eff} = (\theta_a^{10/3} / \theta^2) * D_{air} + 1/H^2 * (\theta_w^{10/3} / \theta^2) * D_{water}$$

where θ_a , θ_w , and θ are the air-filled, water-filled, and total porosity; D_{air} and D_{water} are free-air and free-water diffusion coefficients (L^2T^{-1}); and H^2 is the dimensionless Henry's law constant.

A common method for estimating air-filled and total porosity directly uses the measured soil moisture content and bulk density. A potential disadvantage is that soil disturbance during sampling can lead to inaccurate moisture, density, and hence, porosity estimates. Samples obtained adjacent to buildings may not be representative of conditions below buildings owing to the drying of soil that can occur.

A second method involves the use of the van Genuchten (VG) model (van Genuchten 1980) to predict the water retention parameters for U.S. Soil Conservation Service (SCS) soil types, based on VG model curve-fit parameters computed by Schaap and Leij (1998) (Simplified VG method). This method, developed by Environmental Quality Management Inc. (EQM 2000), is incorporated in U.S. EPA guidance for this

pathway. The VG model parameters are, in turn, used to develop a simplified step function for water-filled porosity (Figure 1). The capillary zone ($\theta_{w,cz}$) water-filled porosity is equal to the moisture content at the inflection point in the water retention curve where $d\theta_w/dh$ is maximal, as suggested by Waitz et al. (1996) (where θ_w and h equal the water-filled porosity and matric suction, respectively). Vapor-phase diffusion becomes negligible once the water-filled porosity exceeds the $\theta_{w,cz}$. The height of the capillary zone is estimated using an equation for capillary rise in a tube (Fetter 1994), and mean particle size for the SCS soil textural classifications (Nielson and Rogers 1990). The water-filled porosity above the capillary zone is user defined; we suggest a practical range below a building is between the residual water content and field capacity.

The simplified VG model likely predicts lower than actual water-filled porosity in soil, for the capillary transition zone (Figure 1). Because diffusion rates are much higher in air than water, this simplification likely results in conservative (high) diffusion estimates through the capillary transition zone. However, this conservatism may be counterbalanced by nonrepresentative assumptions for the ground water contamination source. The common paradigm for prediction of cross-media VOC transport is that dissolved chemicals are present below a static water table, and that transport through the capillary transition zone is limited to vapor- and aqueous-phase diffusion. In reality, there will be some lateral ground water flow and dispersive mixing of chemicals in the tension-saturated zone, and vertical movement of chemicals as a result of water-table fluctuations. There is limited information on VOC migration in the capillary transition zone. One study, involving a large chamber, showed that the pore-water concentrations in the tension-saturated zone were similar to those below the water table, and showed a sharp decline in concentrations near the top of the tension-saturated zone (McCarthy and Johnson 1993). The implication is that a more representative top boundary for dissolved ground water contaminants may be some distance above the water table.

Estimation of Soil Gas Advection Rate (Q_{soil})

The method often used with the J&E model for estimating the soil gas advection rate (Q_{soil}) through the building envelope is an analytical solution for two-dimensional soil gas flow to a small horizontal drain (Nazaroff 1992). This model is used to simulate gas flow to an edge crack located at the perimeter of a building (perimeter crack model). The Q_{soil} (L^3T^{-1}) is estimated as follows:

$$Q_{soil} = \frac{2 \pi k_a \Delta P X_{crack}}{\mu \ln \left(\frac{2 z_{crack}}{r_{crack}} \right)} \quad (2)$$

where k_a is the soil-air permeability (L^2), ΔP is the pressure difference between the building and ambient air, X_{crack} is the perimeter crack length (L), μ is the gas viscosity ($ML^{-1}T^{-1}$), z_{crack} is the depth to edge crack (L), and r_{crack} is the crack radius (L). The ratio of cracks to total subsurface foundation area (i.e., base and walls) (η) can be expressed as

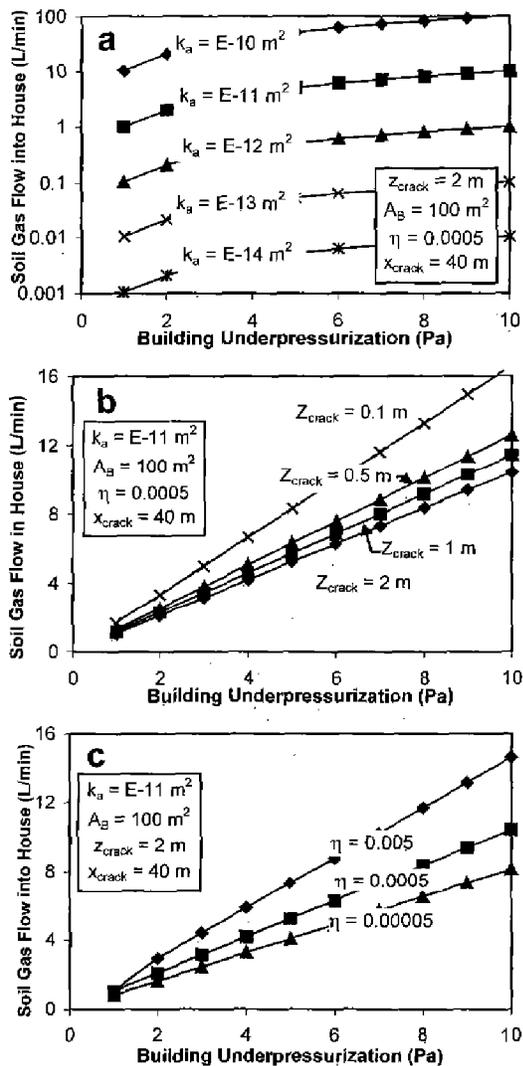


Figure 2. Sensitivity of soil gas flow to perimeter crack model (used in J&E model) to (a) soil-air permeability (k_a), (b) depth to perimeter crack (z_{crack}), and (c) crack ratio (η). X_{crack} = perimeter crack length, A_B = subsurface foundation area.

$$\eta = \frac{r_{crack} X_{crack}}{A_B} \quad (3)$$

where A_B is the subsurface foundation area (L^2). The perimeter crack model accounts for both soil gas flow through soil and the foundation, but is most sensitive to the soil-air permeability based on the analysis presented in Figure 2. For the range of values chosen for k_a , η , ΔP , and z_{crack} , by far the greatest variation is obtained for k_a with the predicted Q_{soil} ranging between ~ 0.001 and 100 L/min.

One method of estimating soil-air permeability is to use published values for saturated hydraulic conductivity and water retention parameters for a particular soil type (EQM 2000). This method involves the following steps: (1) obtain saturated hydraulic conductivity for soil texture type (Schaap and Leij 1998); (2) estimate intrinsic permeability from saturated hydraulic conductivity; (3) estimate effective total fluid saturation at field capacity;

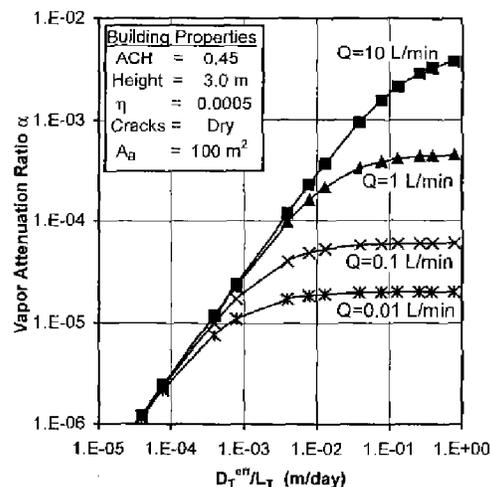


Figure 3. Sensitivity of vapor attenuation ratio (benzene) to soil-gas flow rate (Q) into building using perimeter crack model with dry dust-filled concrete cracks with total porosity = 0.3 Height = building height, $Q = Q_{soil}$, ACH = air exchanges per hour (other symbols previously defined).

(4) estimate relative air permeability using the relationship proposed by Parker et al. (1987); and (5) calculate effective soil-air permeability (relative air permeability multiplied by intrinsic permeability). The soil-air permeability can also be measured in the field (Garbesi and Sextro 1995; Hers and Zapf-Gilje 1998); however, this type of testing is rarely performed.

The Q_{soil} can also be estimated from a tracer test mass balance. When soil-gas advection is the primary mechanism for tracer intrusion into a building, the Q_{soil} can be estimated by measuring the concentrations of a chemical tracer in indoor air, outdoor air, and in soil vapor below a building, and measuring the building ventilation rate (Hers et al. 2002; Fischer et al. 1996; Garbesi et al. 1993; Rezvan et al. 1991; Garbesi and Sextro, 1989). The Q_{soil} values measured using this technique are compared to predicted rates using the perimeter crack model, for sites with coarse-grained soils (Table 1). The perimeter crack model predictions are both higher and lower than the measured values, but overall are within one order of magnitude of the measured values. Although the Q_{soil} predicted by models and measured using field tracer tests are uncertain, the results suggest that a "typical" range for houses on coarse-grained soils is on the order of 1 to 10 L/min.

J&E Model Sensitivity for Key Input Parameters

The sensitivity of the benzene α_p predicted by the J&E model is evaluated as a function of soil gas flow (Q_{soil}), the effective diffusion coefficient (D_T^{eff}), and contamination depth (L_T) (Figure 3). The D_T^{eff}/L_T ratio captures the influence of soil properties and depth to contamination source on α_p . For BTEX and most chlorinated solvent compounds, chemical-specific variation in the D_T^{eff}/L_T ratio is not significant because the free-air diffusion coefficients vary by only a factor of two, and the Henry's law constants vary by a factor of 10 (D_T^{eff}/L_T is less sensitive to H' than D_{air}). Because the effective diffusion coefficient is calculated using the Millington and Quirk (1961) relationship, the soil properties of relevance are the air-filled and total porosity. A high D_T^{eff}/L_T ratio is asso-

Table 1
Comparison of Measured and Model-Predicted Soil Gas Flow Rates Into Buildings

Site	Foundation Type	ΔP (Pa)	Subsurface Foundation Area (m ²)	Crack Ratio η	Depth to Perimeter Crack (m)	$k_{\text{soil-air}}$ (Darcy)	Soil Gas Flow Rates	
							Measured	Predicted
							Tracer (L/min)	PCM (L/min)
Chatterton Site (Hers et al. 2000)	Slab-on-grade	30	57	0.00033	0.3	10	2.7	29
	Slab-on-grade	10	57	0.00033	0.3	10	4.2	9.6
	Slab-on-grade	10	57	0.0001	0.3	10	2.9	8.2
Alameda Site Fischer et al. (1996)	Slab-on-grade	3	50	0.0001	0.2	10	1.4	2.4
Central California Site Garbese & Sextro (1989)	Filled hollow block basement w/coating	30	128	0.0001	2.5	3	67	8.3
Ben Lomond Garbesi et al. (1993)	Experimental basement	10	26	0.00075	1.8	6	9.7	2.3
Spokane Valley Houses Revzan et al. (1991)	Poured concrete basements	5	220	0.0001	2	200	102	110

Notes: Bold print values assumed, all other values measured, ΔP = building underpressurization, PCM = Perimeter Crack model.

Table 2
Qualitative Summary of Sensitive Parameters for the J&E Model

	Building Depressurized (Advection and Diffusion)	Building Not Depressurized (Diffusion Only)
High D_T^{eff}/L_T (shallow and/or dry soil)	Q_{soil} (advection controlled)	Building foundation cracks
Moderate D_T^{eff}/L_T	Q_{soil} and moisture content (MC)	Building foundation cracks and MC
Low D_T^{eff}/L_T (deep and/or wet soil)	Moisture content (diffusion controlled)	Moisture content (MC)

Note: Indoor air concentrations are directly proportional to source concentrations, building mixing height and ventilation rate.

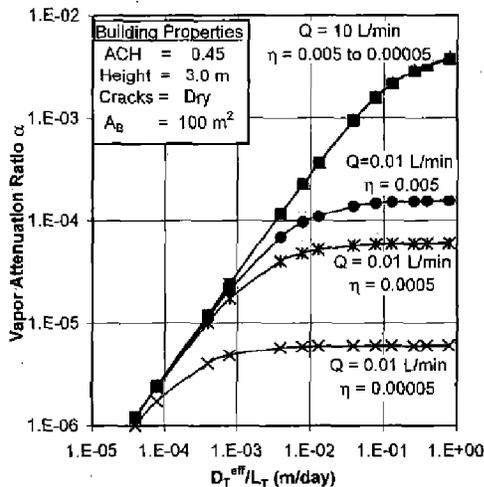


Figure 4. Sensitivity of vapor attenuation ratio (benzene) to soil-gas flow rate (Q) using perimeter crack model and foundation crack ratio (η) (other symbols previously defined).

ciated with dry soils and/or shallow contamination, whereas a low D_T^{eff}/L_T ratio is associated with wet soils and/or deep contamination. Based on the analysis in the sections that follow, sensitive parameters for the J&E model are also qualitatively summarized in Table 2.

Sensitivity of α_p to Q_{soil}

For sensitivity analysis purposes, a Q_{soil} range of 0.01 to 10 L/min was chosen because it is considered representative of most houses or small buildings. The results indicate that Q_{soil} begins to have a significant influence on α_p when D_T^{eff}/L_T values are moderate to relatively large (>0.001 m/day) (Figure 3). The J&E model is described to be advection controlled for this scenario. When D_T^{eff}/L_T is relatively small (<0.001 m/day), α_p is not sensitive to Q_{soil} . The J&E model is described to be diffusion controlled for this scenario. The D_T^{eff}/L_T for case studies subsequently evaluated in this paper ranged from ~ 0.002 to 0.1 m/day. For these D_T^{eff}/L_T values, the maximum error in prediction caused by a four order of magnitude variation in Q_{soil} ranges from 3X to 100X.

Sensitivity of α_p to Crack Ratio

The influence of crack ratio (η) on α_p was evaluated for two different Q_{soil} values (Figure 4). For $Q_{\text{soil}} = 10$ L/min, α_p is not sensitive to η . When $Q_{\text{soil}} = 0.01$ L/min, a two order of magnitude change in η causes up to 25X change in α_p . The sensitivity of α_p to η increases as Q_{soil} decreases, with sensitivity highest for the diffusion-only case (i.e., $Q_{\text{soil}} = 0$). The crack ratio is of little importance for smaller D_T^{eff}/L_T or $Q_{\text{soil}} > 1$ L/min, which means that for the majority of sites crack ratio will not be important.

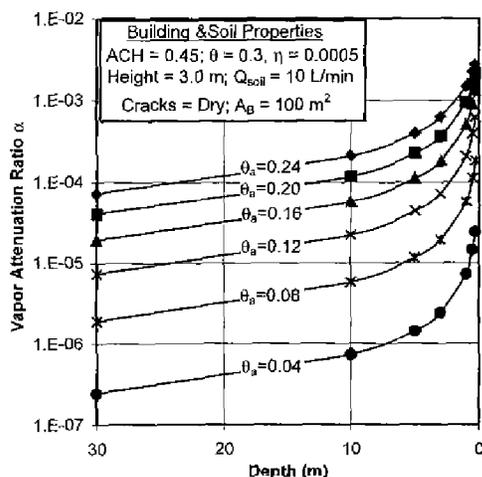


Figure 5. Sensitivity of vapor attenuation ratio (benzene) to water-filled porosity (θ_a). Other symbols previously defined.

Sensitivity of α_p to Air-Filled Porosity (Moisture Content)

The effect of air-filled porosity and depth to contamination was evaluated for a soil with moisture contents ranging from 3.6% to 15.6% (dry weight) and a constant total porosity of 0.3 (Figure 5). This variation in moisture content is potentially representative of the difference between a dry soil below a building compared to a wet soil within the capillary transition zone. The corresponding air-filled porosities are between 0.04 and 0.26. A Q_{soil} value of 10 L/min was assumed. For a constant depth to contamination, a 4X change in moisture content causes approximately or more than two orders of magnitude change in α_p . For a constant moisture content, α_p becomes sensitive to depth to contamination, at shallow depths. It is clear that soil layers with high moisture content will have a significant effect on the diffusive flux and vapor intrusion.

J&E Model Uncertainty for Range of Values

Vapor attenuation ratios predicted by the J&E model are provided for a range of soil gas advection rates and building properties, as a function of D_T^{eff}/L_T (Figure 6). For illustrative purposes, upper and lower soil-gas advection rates were estimated for four U.S. SCS soil textures (sand, loamy sand, sandy loam, and silt) using published values for saturated hydraulic conductivity and the perimeter crack model. The soil type only applies to soil immediately adjacent to the building, because the radius-of-influence for soil-gas advection is relatively limited. The estimated Q_{soil} values are highly uncertain; however, we note that the predicted values for sand (1 to 10 L/min) are consistent with the results of tracer tests for coarse-grained soils. The uncertainty in Q_{soil} increases for finer-grained soils because the influence of permeable soil layers and preferential pathways (e.g., utility back-fill) becomes more important. It is suggested that the Q_{soil} for sand be used when near the foundation soil is not well characterized.

The building properties input to the model are the crack ratio, dust-filled crack moisture content, building height, building air exchanges, and building foundation size. The upper and lower building properties given are subjectively considered to represent the range of values that would be encountered at most

sites, based on available information and the author's experience (Hers and Zapf-Gilje 1998; Hers et al. 2001). The sub-surface foundation area is for a house with a shallow basement or slab-on-grade foundation. Slightly lower α_p 's would be predicted for a deep basement with larger foundation area.

The graphs in Figure 6 illustrate the effect of variation in Q_{soil} and building properties on vapor attenuation ratio, but do not address uncertainty in D_T^{eff}/L_T , which is primarily caused by soil moisture content. To gain insight into uncertainty in model predictions owing to moisture content, a possible range in D_T^{eff}/L_T was evaluated for two hypothetical scenarios. The first scenario (Site 1) assumes a shallow soil vapor source (1.5 m depth) situated well above the water table. The second scenario (Site 2) assumes a relatively deep water table (6 m depth) and contamination that is limited to a dissolved ground water plume. Both sites were assumed to have uniform SCS loamy sand soil. The approach taken was to first obtain a plausible best estimate, and upper and lower range for D_T^{eff}/L_T . For Site 1, a constant air-filled porosity halfway between the residual water content and field capacity was assumed. For Site 2, the simplified VG method was used to estimate the air-filled and total porosity for the capillary zone. As shown in Table 3, the resulting porosities are expressed as relative water saturation values where $S = \theta_w/\theta$ and $\theta_a = \theta(1-S)$. The reason for using relative saturation values in the uncertainty analysis is that the air-filled and total porosity are expected to be strongly correlated. Therefore, uncertainty would be overestimated if these parameters are allowed to vary independently. This is prevented through the use of the relative saturation values. The uncertainty ranges given for total porosity and relative saturation are considered reasonable values for a well-characterized site.

Using the best estimate values and uncertainty ranges, the best estimate, lower and upper ranges are provided for the normalized effective diffusion coefficient (D_T^{eff}/L_T) (Table 3 and Figure 6). For Site 1, the upper and lower D_T^{eff}/L_T values vary by a factor of 2.4. For Site 2, the uncertainty is greater (factor of 23) because the sensitivity of D_T^{eff}/L_T to air-filled porosity within the capillary zone is high because moisture content is also high.

The overall uncertainty in the vapor attenuation ratio will be dependent on the available data. If there is information only on the contamination depth, the range in α_p can vary three to four orders of magnitude. When information on soil properties is also available, the uncertainty in D_T^{eff}/L_T and Q_{soil} is reduced resulting in α_p that vary over two orders of magnitude (Figure 6). When good quality site-specific data is available for both soil properties (e.g., moisture content) and building properties (e.g., ventilation rate, mixing height), it may be possible to reduce the uncertainty in α_p to approximately one order of magnitude.

Field-Based Methods for Evaluation of Vapor Intrusion

Three field-based approaches or methods are used to evaluate vapor intrusion: the indoor VOC method, the tracer method, and the flux chamber method. The indoor VOC method involves measurement of VOC concentrations in indoor air and at the contamination source. The α_m will vary depending on the contamination scenario. For sites with dissolved ground water plumes, the α_m is calculated using a

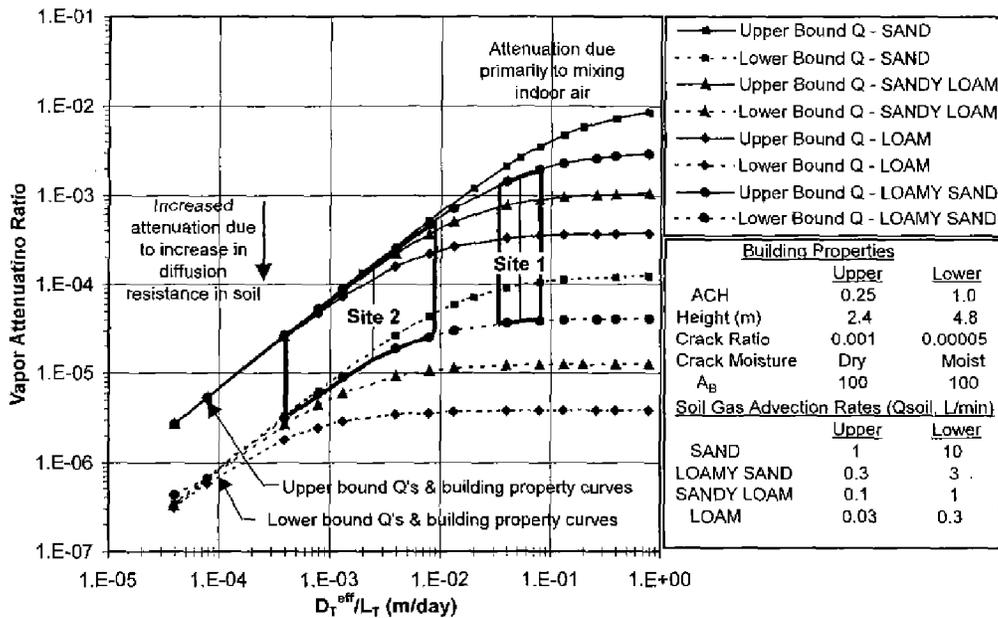


Figure 6. Predicted vapor attenuation ratio (benzene) for vapor concentrations at source and indoor air using Johnson and Ettinger (1991) model. Figure adapted from Johnson et al. (1998). Dry dust-filled cracks: Total porosity = 0.3; moist dust-filled cracks: water-filled porosity = 0.1, and total porosity = 0.3.

Parameters	Best Estimate Values		Uncertainty
	Site 1	Site 2	
Input Parameters			
Contamination	Above WT	Dissolved in Gdw	N/A
Contamination depth (m)	1.5	6.0	constant
U.S. SCS soil classification	Sandy Loam	Sandy Loam	N/A
Total porosity (θ)	0.390	0.390	+/- 10%
$S_R (\theta_w/\theta)$ above CZ (S)	0.265	0.265	+/- 25%
Height of CZ (L_{CZ}) (m)	N/A	0.250	+/- 25%
$S_R (\theta_w/\theta)$ in CZ (S_{CZ})	N/A	0.821	+12/-10%
Calculated Values			
D_T^{eff}/L_T lower est. (m/day)	0.0325	0.00038	
D_T^{eff}/L_T best est. (m/day)	0.0512	0.00248	
D_T^{eff}/L_T lowest est. (m/day)	0.0775	0.00861	
D_T^{eff}/L_T upper/lower range	2.4	23	

Notes: CZ = capillary zone, S_R = relative saturation, Gdw = Ground water, WT = water table.

predicted source vapor concentration (i.e., directly above the water table) estimated using the Henry's law constant assuming equilibrium partitioning between the dissolved and vapor phases. When measured source vapor concentrations are available, the α can be directly calculated. Because some deviation from equilibrium conditions would be expected, the α_m estimated using ground water and soil vapor data are not directly comparable. A key challenge for this approach is that there are numerous other "background" sources of VOCs in indoor and outdoor air for most chemicals of concern at contaminated

sites (Hers et al. 2001). The intrusion of soil vapor into buildings is also highly dependent on site-specific conditions and may vary over time. These factors complicate the interpretation of indoor air measurements when the goal is to deduce the subsurface-derived component.

The *tracer method* involves measurement of the indoor air concentration of a tracer injected below ground (SE_g), or a natural tracer such as radon (Fisher et al. 1996; Garbesi et al. 1993). The measured vapor intrusion for the tracer is, in turn, used to infer intrusion for the VOC of interest. Key factors affecting this approach are that boundary conditions for a tracer injected below a building may be different than those for the VOC of interest (e.g., if contamination is relatively deep) and that typically, an essentially inert tracer is used. When compared to the tracer, the mass loss or attenuation through sorption and/or biodegradation will be greater for most VOCs of interest. For these reasons, the tracer method will typically provide a conservative estimate of intrusion.

The *flux chamber* method involves measurement of soil-gas flow and/or VOC flux through cracks or openings in a building foundation. There are only a few published reports documenting the use of flux chambers to measure VOC flux into buildings (Figley and Snodgrass 1992; Hers and Zapf-Gilje 1998). Challenges for this approach are that these tests are difficult and costly to perform, and the uncertainty associated with "scaling up" the results for a small crack to an entire building.

Results and Discussion of Field Studies and Model Predictions

Indoor VOC Method

Vapor attenuation ratios are evaluated for 11 sites. The sites represent studies available to the authors with reasonable quality field data, and are for residential houses, ground-floor

Table 4
Measured and Model-Predicted Vapour Attenuation Ratios

Site & Reference	Contaminant or Tracer	Building and Foundation Type	Soil Conditions	Depth (m) ¹	Chemical	Source Concentration (ug/L)	N Indoor Air ²	α_m Stat	Measured α_m	J&E model α_p^3	Comments
Indoor VOC Method											
"Virginia (Motiva) Site", Fan and Quinn (2000)	petroleum HC, NAPL above water	SFR, basements, attached garages, cement block foundations	claystone saprolite k ~ 0.01 darcy	0.5	benzene	V: 410	13	50th	<8.3E-6	3.70E-06	
"Chatterton Site" Delta, B.C. Canada	BTX	research greenhouse	surface silt to f. sand, underlain by	1.4	benzene	V: 15,000	3-4	Avg	<5.3E-7	1.3E-05	C1: $\Delta P = 0$ Pa, $\eta = 3.3E-4$
Hers et al. (1998)	petro-chemical plant	slab-on-grade poured concrete	m. sand with		toluene	V: 20,000	3-4	Avg	<1.9E-6	1.3E-05	C1: $\Delta P = 0$ Pa, $\eta = 3.3E-4$
Hers et al. (2000a)	NAPL above water table	2 mm edge crack	k ~ 10 darcies		benzene	V: 15,000	3-4	Avg	4.0E-07	5.9E-05	C2: $\Delta P = 2.5$ Pa, $\eta = 1E-4$
					toluene	V: 20,000	3-4	Avg	5.9E-07	5.9E-05	C2: $\Delta P = 2.5$ Pa, $\eta = 1E-4$
					benzene	V: 15,000	3-4	Avg	9.9E-05	7.8E-05	C3: $\Delta P = 10$ Pa, $\eta = 1E-4$
					toluene	V: 20,000	3-4	Avg	1.3E-04	7.8E-05	C3: $\Delta P = 10$ Pa, $\eta = 1E-4$
					benzene	V: 15,000	3-4	Avg	7.2E-06	8.0E-05	C4: $\Delta P = 10$ Pa, $\eta = 3.3E-4$
					toluene	V: 20,000	3-4	Avg	3.4E-05	8.0E-05	C4: $\Delta P = 10$ Pa, $\eta = 3.3E-4$
					benzene	V: 15,000	3-4	Avg	5.8E-06	2.9E-05	C5: $\Delta P = 30$ Pa, $\eta = 3.3E-4$
					toluene	V: 20,000	3-4	Avg	2.2E-05	2.9E-05	C5: $\Delta P = 30$ Pa, $\eta = 3.3E-4$
"Paulsboro Site", NJ USA, Laubacher et al. (1997)	gasoline NAPL above water table	SFR basement	sand, some silt	2.74	benzene	V: 576	15	Avg	<1.6E-6	4.3E-04	
"Alameda (Air Station) Site", CA, USA Fischer et al. (1996)	gasoline NAPL above water table	small commercial building, slab-on-grade poured concrete	sand k ~ 1 to 3 darcy	0.7 0.7	benzene iso-pentane	V: 200 V: 28,000	1 1	N/A	<9E-6 <9E-7	2.45E-04 2.46E-04	
"Mass. DEP Sites" USA, Fitzpatrick & Fitzgerald (1996)	petroleum hydrocarbon	N/A (3 sites)	N/A	N/A	benzene	N/A	-	N/A	1E-5 to 4E-5	INS	INS
"Midwest School Site" USA, Moseley and Meyer (1992)	petroleum HC NAPL above water table	Built 50's, at-grade construction, crawl-space, large paved area	sand & gravel, discontinuous clay lenses	- 3	benzene total HC	N/A	N/A	N/A	HC-like odours -- 1E-4	INS	crawlspace conc.: benzene - 8.3 mg/m ³ , Total HC ~ 500 mg/m ³
"CDOT HDQ Site" Colorado, USA Johnson et al. (2000)	chlorinated solvents, dissolved plume	mostly apartments, few SFRs, mostly slab-on-grade, few crawl-spaces & basements, AC mostly window units, heating natural gas, baseboard, and/or fireplaces	weathered & fractured claystone above water table	4.6	1,1 DCE 1,1 DCE TCE TCE 1,1,1 TCA 1,1,1 TCA above 3 CS	G: 10-10,000 G: 10-10,000 G: 3-3,000 G: 3-3,000 G: 10-1,000 G: 10-1,000 above 3 CS	115- 150 115- 150 115- 150 150	Geom Geom Geom Geom Geom Geom Geom	4.8E-06 2.0E-05 1.4E-05 7.0E-05 1.7E-05 6.6E-05 1.2E-05	8.6E-05 2.4E-04 ⁴	average for 3 chlorinated solvents (CS)
"Redfields Site" Colorado, USA Envirogroup (1999)	chlorinated solvents, dissolved plume	SFRs, built 50's and 60's, mostly basements or crawlspaces, no combustion air intakes	clay & silt, some sand layers, mostly sand or silt near WT	6.1 to 7.3	1,1 DCE 1,1 DCE 1,1 DCE	G: 10-1,000 G: 10-1,000 G: 10-1,000	65 65 65	50th Avg 90th	1.50E-05 7.60E-05 1.20E-04	INS	α_m values for houses above plume with DCE groundwater concentration > 10 ug/L
Hamilton Site Colorado, USA (2001), unpublished	chlorinated solvents, dissolved plume	SFRs, built 50's mostly basements	primarily sand & gravel, some clay & silt layers	9.7 to 11	1,1 DCE	G: 15-30 G: 15-30	32 32	30th 90th	6.80E-05 1.40E-04	INS	Gravel at water table
"Lowry (Air Force Base) Site" Colorado, USA Versar (2000)	chlorinated solvents, dissolved	SFR: mostly basements, some crawlspaces	silty sand to silt, generally silty sand near water table	6.1 to 7	1,1 DCE TCE 1,1 DCE TCE	G: 1.4-1.9 G: 120-170 V: > 29 V: > 1,000	>50 >50 >50 >50	50th 50th 50th 50th	2.20E-05 2.20E-05 6.50E-04 7.70E-04	INS	max G $\alpha_m = 6.2E-04$ max G $\alpha_m = 1.2E-03$ max V _{SS} $\alpha_m = 8.3E-03$ max V _{SS} $\alpha_m = 1.4E-02$
"Mountain View Site" California, USA Wu (2000)	chlorinated solvents, leach-field & dissolved ⁵	SFRs, built 1998, at-grade construction with moisture vapor barrier	mostly silty/clayey sand & gravel, some sand or silt lenses	1.5 10.7	TCE TCE	V: 84 G: 735	14 14	Max Max	2.80E-04 <1.3E-5 7.80E-05	INS	α_m shallow vapour α_m groundwater, depth to groundwater = 10.7 m
"Mass. DEP Sites" USA, Fitzpatrick & Fitzgerald (1996)	chlorinated solvents	N/A (19 sites)	N/A	N/A	CS	N/A	N/A	N/A	2E-6 to 1E-1	INS	high α_m associated with highly permeable building envelopes (earthen floor, block walls & sumps)
Tracer and Flux Chamber Tests											
"Central California Site", Garbesi & Sextro (1989)	SF ₆	SFR, basement poured slab, block walls coated with asphalt	sandy loam to loamy sand, k = 0.1 to 10 darcies	sub-slab	SF ₆	N/A	N/A	N/A	- 1E-3	N/A	$\Delta P = 30$ Pa
"Alameda Site" Fischer et al. (1996)	SF ₆	small commercial, slab on-grade, concrete	sand, k = 1 to 3 darcy	sub-slab	SF ₆	N/A	N/A	N/A	2E-4 to 4E-4	N/A	$\Delta P = 3$ (estimate based on wind loading)
U.S. Sites Little et al. (1992)	radon	SFRs	N/A	sub-slab	radon	N/A	N/A	N/A	1.6E-3 ⁶	N/A	
"Spokane River Valley Sites", WA, USA Rezvan et al. (1992)	radon	SFRs (14), 8 houses slab-on-grade, 6 basement	highly permeable sand & gravel, k ~ 200 darcies	sub-slab	radon	N/A	N/A	N/A	~ 7.9E-3 to 4.5E-2	N/A	water conditions, mean house volume = 500 m ³ , ACH = 0.5/hr

Notes: ¹Depth to contamination from underside of foundation slab; ²N = Number of indoor air samples tested; ³Best estimate unless otherwise noted; ⁴Upper range; ⁵Contamination likely in unsaturated zone; ⁶2nd highest α_m value; ⁷Alpha (α) estimated using mean radon content of soil combined with appropriate constant divided by radon concentration in U.S. homes (55 Bq m⁻³); ⁸N/A = not available or applicable, SFR = single family residence, SF₆ = sulphur hexafluoride; V = vapor, V_{SS} = sub-slab, G = ground water, bgs = below ground surface, HC = hydrocarbon, AC = air-conditioning, INS = insufficient data, ACH = air exchanges per hour, WT = water table, CS = chlorinated solvents.

Table 5
Input Parameter Values Used for Johnson and Ettinger (1991) Model¹

Parameter	Virginia	Chatterton	Paulsboro	Alameda	Midwest	CDOT			Lowry	Mountain
	Site	Site	Site	Site	Site	HDQ	Redfields	Hamilton	Site	West
US SCS soil type used for D_T^{eff}/L_T	N/A	N/A	N/A	N/A	N/A	N/A	Loamy	Sand	Loamy	N/A
Depth to contamination (L_T) (m)	0.5	1.4	2.74	0.7	3.0	4.8	6.1	10.3	0.25 ¹	1.5 ²
Total porosity unsaturated zone (θ)	0.43	0.36	0.39	0.36	0.4	0.4	0.39	0.375	0.39	10.7 ³
Air-filled θ unsaturated zone (θ_a)	0.28	0.21	0.23	0.22	0.25	0.26	0.287	0.319	0.287	0.41
Height of capillary zone (L_c) (m)	N/A	N/A	N/A	N/A	N/A	0.2	0.25	—	0.17	0.2
Total θ capillary zone (θ_c)	N/A	N/A	N/A	N/A	N/A	0.4	0.39	0.375	0.39	0.41
Air-filled θ capillary zone ($\theta_{a,c}$)	N/A	N/A	N/A	N/A	N/A	0.08	0.07	0.12	0.07	0.1
D_T^{eff}/L_T (m/day)	0.12 ⁴	0.023 ⁴	0.014 ⁴	0.054 ⁴	0.016 ⁴	3.4E-3 ⁶	2.4E-3 ⁷	8.4E-3 ⁷	0.49 ⁸	0.013 ¹⁰
Soil-air permeability k_a (10^{-12} m ²)	0.01	10	10	3	—	N/A ¹²	—	—	2.4E-3 ⁹	1.5E-3 ¹¹
Building underpressurization (Pa)	1	0, 2.5, 10, 30	5	3	—	N/A ¹²	—	—	—	—
Foundation crack ratio (η)	1.5E-03	3.3E-4 to 1E-4	1.E-04	1.E-04	—	1.E-04	—	—	—	—
x_{crack} (m)	55.9	26.8	27.6	26.8	—	N/A ¹²	—	—	—	—
z_{crack} (m)	2.0	0.3	2.13	0.2	—	N/A ¹²	—	—	—	—
Q_{soil} (L/min)	0.0016	8.2 to 29	2.8	2.2	—	10	—	—	—	—
Total θ dust-filled cracks (θ_{crack})	0.43	0.25	0.25	0.25	—	0.4	—	—	—	—
Air-filled θ dust-filled cracks ($\theta_{a,crack}$)	0.28	0.25	0.25	0.25	—	0.26	—	—	—	—
Air exchange per hour (ACH)	0.76	0.42 to 14.3	0.42	2.1	—	0.45	—	—	—	—
Building mixing height (m)	2.0	2.19	2.74	2.4	—	3.0	—	—	—	—
Subsurface building area (A_B) (m ²)	186	57	39	50	—	89	—	—	—	—

Notes: ¹Depth to sub-slab soil gas probes; ²Depth to shallow gas probes; ³Depth to ground water; ⁴Benzene; ⁵Iso-pentene; ⁶Average 1, 1 DCE, TCE and 1,1,1 TCA; ⁷1,1 DCE; ⁸DCE for sub-slab vapor source (TCE value is 0.43); ⁹DCE for ground water source (value for TCE is 2.2E-03); ¹⁰TCE for shallow vapor source; ¹¹TCE for ground water source; ¹² Q_{soil} is estimated directly; therefore x_{crack} , z_{crack} , ΔP and k_a not needed; ¹³Building foundation thickness not included since has negligible effect.

apartments, or small commercial buildings. Site characteristics and estimated input parameters are summarized, and measured and J&E model-predicted vapor attenuation ratios (α_m and α_p) are compared (Tables 4 and 5, Figure 7). In most cases, the vapor attenuation ratios are estimated by the authors using site data; in a few cases, the ratios given in references cited in Table 4 are reported. This has led to differences in the statistical estimators used to characterize the variability in α_m and α_p . For completeness, the vapor attenuation ratios reported for several Massachusetts sites are also included in Table 4; these sites are not included in the 11 case study sites discussed later.

The quality and quantity of site characterization data, and ability to distinguish measured indoor air concentrations from background VOC sources varies from site to site. For three sites, the VOC concentrations in a relatively large number of houses above the contaminant plume were significantly greater than house concentrations in background areas, resulting in fairly reliable α_m estimates. For the remaining sites, either the vapor-derived VOC concentrations in indoor air were significant in only a small subset of houses above the contaminant plume, or there was no significant difference between above plume and background indoor air concentrations. The vapor attenuation ratio is not measurable when there is no significant vapor-derived component; however, the indoor air concentrations can be used to calculate upper bound α_m values, represented as "less than" values in Table 4, and dashed lines in Figure 7.

For each site (except Chatterton), a predictive "envelope" for

α_p was generated. A best estimate D_T^{eff}/L_T was directly calculated when reasonably good quality moisture content data was available. When good quality data was not available, the U.S. SCS soil texture class was inferred based on soil descriptions and the simplified VG method was used to calculate D_T^{eff}/L_T . We recognize that inference of soil texture is approximate and subjective. The upper and lower bound D_T^{eff}/L_T values were approximated using the same variability calculated for the two hypothetical sites discussed earlier (Table 3). The upper and lower bounds for Q_{soil} and building properties are the curves presented in Figure 6. A Q_{soil} range of 1 to 10 L/min (i.e., representative of sand) was assumed for all sites (except Virginia) because either coarse soils were present below building foundations, or there was no information on soil type (in these cases, sand was assumed to be present below foundations). Based on the fine-grained near-foundation soils at the Virginia site, a Q_{soil} range of 0.03 to 0.3 L/min (i.e., representative of loam) was assumed. When there was sufficient information on building properties and soil gas advection potential, the J&E model-predicted α_p was also estimated (represented as symbols in Figure 7). For the Chatterton site, only the best estimate α_p were plotted because testing at this site involved an experimental building and test cases not representative of generalized predictive envelopes in Figure 6.

Measured Vapor Attenuation Ratios at Petroleum Hydrocarbon Sites

Case study sites with petroleum hydrocarbon contamination have coarse-grained soils (except for the Virginia site) and

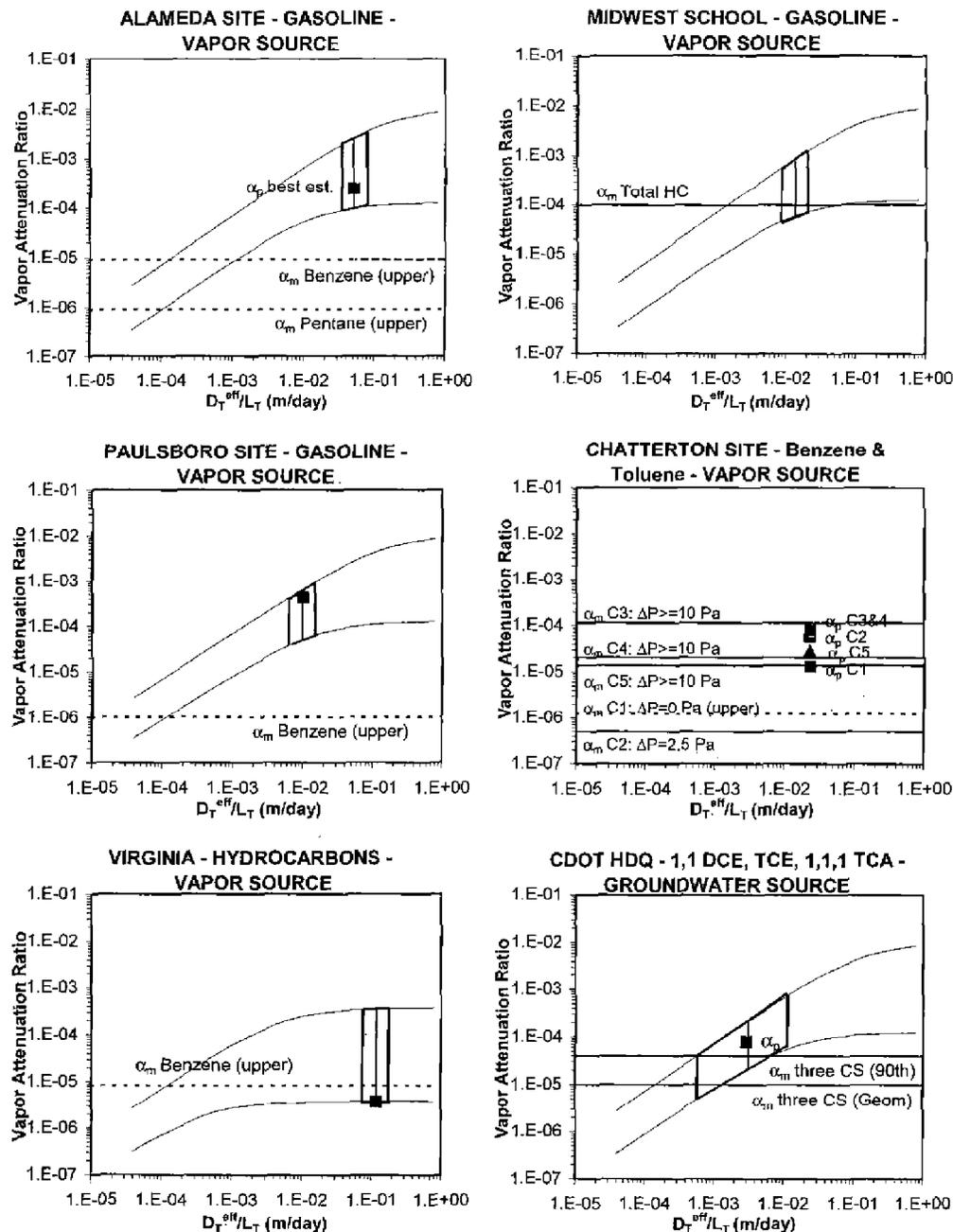


Figure 7a. Comparison between measured and J&E model-predicted vapor attenuation ratio (benzene). Upper and lower bound curves from Figure 6 are included. Dashed lines indicate that α_m is upper bound value. Symbols are best estimate α_p values.

shallow to moderate depths to contamination (0.5 to 3 m). Extensive residual nonaqueous phase liquid (NAPL) is present above the water table at the Chatterton site. There is evidence for some residual NAPL above the water table at the Alameda, Paulsboro, Virginia, and Midwest School sites. Indoor air testing was limited to a single or small number of buildings at each case study site. For petroleum sites, near-source vapor concentrations are available and therefore the α_m is directly calculated (vapor α_m).

At the Virginia, Chatterton (depressurization (ΔP) = 0 Pa case), Paulsboro, and Alameda sites, there was no difference between indoor air concentrations measured in building(s)

above the plume and in background areas, indicating that the α_m are unknown. For these sites, the α_m calculated using the measured indoor air concentrations are upper-bound values and range from $< 4.0 \times 10^{-7}$ to $< 9.0 \times 10^{-6}$. For the Chatterton $\Delta P = 2.5$ Pa case, there was a statistically significant difference in indoor and background indoor air concentrations; however, the α_m remained low (4.0×10^{-7} to 5.9×10^{-7}). For the Chatterton $\Delta P = 10$ and 30 Pa cases, there was a significant increase in indoor air concentrations and α_m .

At the Midwest School site, hydrocarbon-like odors were noted indoors during a period of relatively heavy rains and high water table in September 1992. Subsequent analysis of indoor

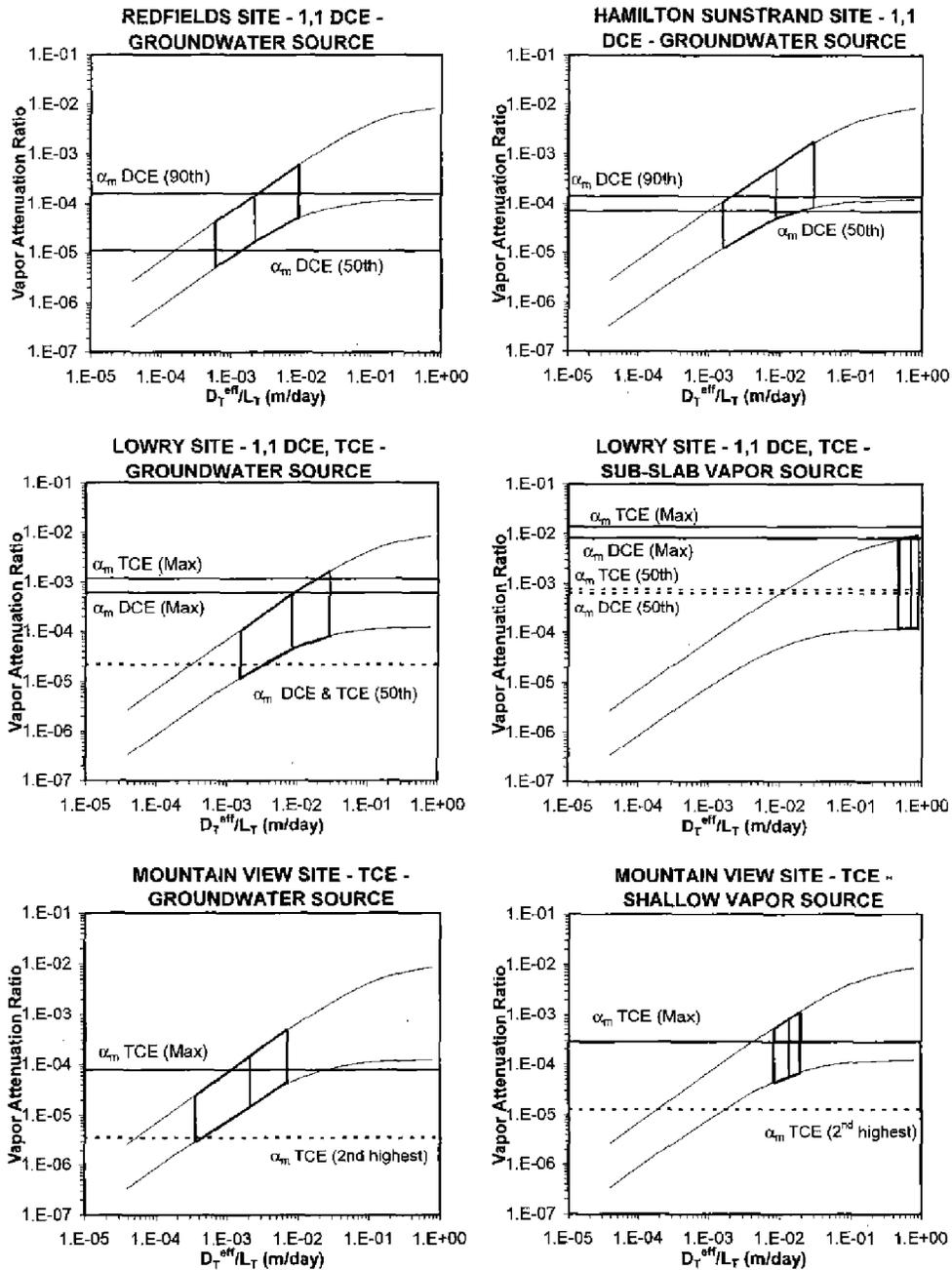


Figure 7b. Comparison between measured and J&E model-predicted vapor attenuation ratio (benzene). Upper and lower bound curves from Figure 6 are included. Dashed lines indicate that α_m is upper bound.

air during October 1992 indicated that hydrocarbon concentrations in indoor air were elevated but could not be conclusively distinguished from background sources at this time. However, the benzene (8 mg/m^3) and total hydrocarbon concentrations (500 mg/m^3) in an unventilated crawlspace below the ground floor were well above background levels. Based on a rough estimate of the source vapor concentrations and odor thresholds for hydrocarbons, the α_m may have been on the order of 1×10^{-4} .

Field data, including soil vapor profiles, indicate there was significant bioattenuation of hydrocarbon vapors for the Alameda and Chatterton ($\Delta P = 0$ and 2.5 Pa cases) sites. This

is consistent with other studies indicating that biodegradation can result in significant vadose zone attenuation of hydrocarbon vapors, provided sufficient O_2 is present (Ostendorf and Kampbell 1991; Ririe and Sweeney 1995). For higher underpressurizations (10 and 30 Pa), at the Chatterton site hydrocarbon vapor concentrations were elevated because of increased vapor flux from deeper soil, and reduced travel times (Hers et al. 2002). The relatively high α_m at the Chatterton site are from the combined effect of shallow contamination, relatively permeable soils, and high building underpressurizations.

The Paulsboro and Midwest School sites had elevated

hydrocarbon vapor levels directly below the building slab. For the Midwest School site, we speculate that elevated indoor hydrocarbon concentrations may have been a result of limited biodegradation owing to a large building and paved area, which reduced oxygen recharge, combined with factors that contributed to vapor intrusion into the building. These factors include building construction (i.e., crawlspace) and/or a sanitary sewer that was located near the water table within the hydrocarbon plume, which may have acted as a preferential pathway. At the Virginia site, contamination was shallow but no significant vapor intrusion was measured possibly because of the presence of fine-grained soils and/or building construction (i.e., tight foundations).

Comparison to Model Predictions for Petroleum Hydrocarbon Sites

Comparisons for the Chatterton ($\Delta P = 0$ and 2.5 Pa cases), Paulsboro, and Alameda sites indicate that the best estimate α_p are one to two orders of magnitude higher than the measured or upper bound α_m indicating the J&E model results in conservative predictions for these sites. Comparisons for the Chatterton ($\Delta P = 10$ and 30 Pa cases) and Virginia sites indicate the best estimate α_p are similar to the α_m . The high soil-gas advection rates for the Chatterton site resulted in significant vapor intrusion rates and hence similar α_p and α_m . For the Virginia site, the α_p is lower than at other sites owing to the influence of the fine-grained soils. For the Midwest site, the predictive envelope for α_p also intersects the α_m ; however, the α_m is highly uncertain.

Measured Vapor Attenuation Ratios at Chlorinated Solvent Sites

At four case study sites with chlorinated solvent contamination (CDOT, Redfields, Hamilton, and Lowry), dissolved plumes have migrated below houses (Table 4). The depth to the water table at these sites ranged from ~4.8 to 10.7 m below ground surface. The ground water plumes at these sites are relatively long and narrow, resulting in significant spatial variability in dissolved ground water concentrations. At the fifth site (Mountain View), houses were constructed on top of a former leach field where chlorinated solvents had been disposed of. Therefore, in addition to ground water, shallow soil is likely contaminated at this site. Soil grain size at the sites is variable (Table 4). For all sites, the α_m are estimated using vapor concentrations predicted from ground water data (ground water α_m). For the Lowry and Mountain View sites, soil vapor data were also available; therefore, the α_m is also directly calculated using vapor data (unless otherwise noted, the α_m given below are for the ground water source scenario).

For the CDOT site, the differences in three chlorinated solvent concentrations (1,1 DCE, TCE, and 1,1,1 TCA) in houses above the plume and at background locations are statistically significant. However, the ground water and indoor air data were found to be unreliable at the periphery of the plume and therefore low ground water and indoor air concentrations were removed from the database prior to calculating the α_m . The resulting database comprises several hundred tests from apartments and houses. The methodology used to estimate α_m is further described in Johnson et al. (2000). The geometric mean and 90th percentile α_m for the CDOT site are 1.0×10^{-5} and 5.2×10^{-5} . Analysis of the intrusion database for the site indi-

cated no strong correlation between seasons and α_m , or difference between basement and slab-on-grade construction (personal communication, Dr. Jeff Kurtz, EMSI Inc.).

For the Redfields site, the difference in 1,1 DCE concentrations in houses above the plume and at background locations are statistically significant. A data screening procedure similar to that used for the CDOT site resulted in α_m only being estimated in areas where the 1,1 DCE concentrations in ground water exceeded 10 $\mu\text{g/L}$. A visual interpolation method was used to estimate ground water concentrations below houses. The resulting database comprises 65 houses nearest to the Redfields site. The 50th and 90th percentile α_m for the Redfields site are 1.1×10^{-5} and 1.2×10^{-4} . Synoptic data for the Redfields site indicated a slight correlation between indoor 1,1 DCE concentrations and season, for some houses, with winter-time values that were two to three times higher than summer-time values (personal communication, Dr. David Folkes 2000).

For the Hamilton site, the difference in 1,1 DCE concentrations in houses above the plume and at background locations are statistically significant. Because ground water data was limited, the attenuation ratio analysis is for a strip of 32 houses parallel and closest to the long axis of the plume (and wells) in the area with 1,1 DCE concentrations above ~10 $\mu\text{g/L}$. The 50th and 90th percentile α_m for the Hamilton site are 6.8×10^{-5} and 1.4×10^{-4} .

At the Lowry site, the database evaluated consists of more than a year of quarterly testing at 13 houses above and near the periphery of the plume. Concurrent testing of indoor air, and subslab vapor concentrations for houses with slab-on-grade or basement construction, and crawlspace air for houses with crawlspaces was conducted. At one house, the maximum TCE and 1,1 DCE concentrations in indoor air were 51 $\mu\text{g/m}^3$ and 0.91 $\mu\text{g/m}^3$, suggesting significant vapor intrusion. At three other houses, the TCE concentrations in indoor air were mostly between 5 and 15 $\mu\text{g/m}^3$. Compared to published background data for TCE (Hers et al. 2001) and data for houses along the periphery of the plume, it is possible that concentrations at these three houses included a soil vapor-derived component. The indoor air concentrations were at background levels in remaining houses.

Measured vapor attenuation ratios are estimated for a subset of four Lowry houses with nearby ground water data. For this data subset, the maximum indoor air TCE concentration was 51 $\mu\text{g/m}^3$, but exceeded 5 $\mu\text{g/m}^3$ in only one house. Therefore, most α_m are upper bound values. When all data are used, the 50th percentile and maximum ground water α_m are 2.2×10^{-5} and 1.2×10^{-3} for TCE, and 2.2×10^{-5} and 6.2×10^{-4} for 1,1 DCE. The maximum, as opposed to 90th percentile α_m , was calculated owing to the relatively limited number of tests for this site. The Lowry subslab vapor concentrations were highly variable and elevated below certain houses (e.g., TCE up to 10,000 $\mu\text{g/m}^3$), but near background levels below other houses above the plume. An analysis of the house data subset where indoor air TCE concentrations exceeded 5 $\mu\text{g/m}^3$ and/or subslab TCE concentrations exceeded 1000 $\mu\text{g/m}^3$ indicated that the 50th percentile and maximum subslab vapor α_m are 7.7×10^{-4} and 1.4×10^{-2} . Available synoptic data for the Lowry site indicated no significant seasonal variation in subslab or indoor air concentrations.

At the Mountain View site, indoor air in seven houses

above the contaminated area and two "background" houses in a noncontaminated area was tested on two occasions. The indoor TCE concentration in one house was 12 and 25 $\mu\text{g}/\text{m}^3$, whereas the TCE concentrations in remaining houses were at background levels (0.26 to 1.1 $\mu\text{g}/\text{m}^3$) (Wu 2000). The maximum ground water α_m is 7.8×10^{-5} while the shallow vapor maximum α_m is 2.8×10^{-4} .

When all five sites are evaluated, the results can be summarized as follows. The 50th percentile (or geometric mean) and 90th percentile (or maximum) α_m values for the ground water to indoor air pathway were remarkably similar for all sites (approximately 1×10^{-5} and 1×10^{-4} , respectively). For individual sites, there is significant house-to-house variability in α_m (e.g., two order of magnitude difference for Redfields site); however, based on the available data there appear to be only slight, if any, seasonally induced variations in vapor intrusion, and similar intrusion rates for houses with basement and slab-on-grade construction. Potential sources of variability in α_m include inaccurate estimation of water table ground water concentrations below houses, geological heterogeneity, differences in house construction and depressurization, and differences in ventilation rates and house activities during indoor air testing. At the Lowry and Mountain View sites, no significant vapor intrusion could be measured for most houses. One likely reason for the generally nonsignificant intrusion is that ground water concentrations are lower at these sites, compared to the CDOT, Redfields, and Hamilton sites. Another possible factor for the Mountain View site is the building construction, which consists of at-grade foundation slab with (moisture) vapor barrier. Overall, the results suggest that geologic conditions and diffusion rates have the greatest influence on vapor intrusion rates at the chlorinated solvent sites, and that building factors are less important.

Comparison to Model Predictions for Chlorinated Solvent Sites

Comparisons for sites with the most reliable data (CDOT, Redfields, and Hamilton) indicates that the predictive envelope for the α_p intersects the α_m . The centroid of the predictive envelope is in all cases higher than the 50th percentile α_m suggesting, on average, the J&E model would result in conservative predictions. For the CDOT site, the best estimate α_p is approximately eight times higher than the 50th percentile α_m . For the Lowry site, the predictive envelope is below the α_m for one house with significant vapor intrusion, indicating a non-conservative prediction in this case. For the Mountain View site, the predictive envelope for α_p intersects the maximum α_m . Overall, the J&E model in most cases results in conservative predictions (i.e., α_p is higher than α_m). However, the comparisons highlight the potential for nonconservative predictions if a combination of low Q_{soil} and low D_T^{eff}/L_T are used.

Tracer Method

There are several sites where tracer tests can be used to estimate α , which range from $\sim 2 \times 10^{-4}$ at the Alameda site to 4.5×10^{-2} at the Spokane River (Valley) sites (Table 4). The Spokane River sites were calculated using an assumed average house volume (500 m^3) and building ventilation rate (air changes per hour (ACH) = 0.5 hour^{-1}) and therefore are approximate. Soils at the Spokane River site are very permeable, and α is based on winter conditions (i.e., highest expected

seasonal building depressurization); therefore, the α for this site is considered an upper range value. It should be remembered that tracer studies represent α values for near-field boundary conditions and, therefore, are not representative of intrusion at many sites contaminated with VOCs. The tracer test α values are, however, consistent with the upper range of the J&E model predictions (Figure 6).

Flux Chamber Method

A method that has been used for radon assessments is the equivalent leakage area (ELA) method (Grimsrud et al. 1982; CSGB 1986). The ELA is obtained by developing an empirical relationship between the soil-gas flow into a building and building depressurization. Soil-gas flows are measured using flux chambers and mass flow meters. In one study involving multiple measurements of soil-gas flow through various building foundation cracks at 10 houses in Saskatchewan, Canada, the total house foundation ELA for the foundation edge cracks and utility penetrations ranged from 0.15 to 16.4 cm^2 (Figley and Snodgrass 1992). The contribution to total ELA from untrapped floor drains, present at a few houses, was excluded from this analysis since untrapped drains are uncommon in newer construction. For example, the National Building Code of Canada (1995) requires sealing of floor drainage systems that have the potential to allow soil-gas entry (Section 9.13.8.3).

The measured total ELA can be used to estimate soil-gas intrusion rates using the method in Figley (1997). A building depressurization representative of severe winter conditions (10 Pa), as proposed by Figley (1997), and possible values for the house volume (500 m^3) and building ventilation rate (0.3 ACH) produces α values between 3.6×10^{-4} and 3.8×10^{-2} . The α obtained in this manner is conservative because it assumes an unlimited and uniform soil-vapor source directly below the foundation slab (i.e., contaminants in vapor are replenished as fast as they are swept into the building).

Flux chamber tests have also been used to measure VOC flux rates through concrete cracks (Schmidt and Zdeb 1997; Hers and Zapf-Gilje 1998). Both studies indicated detectable VOCs were measured in soil gas transmitted through cracks, and the study by Hers and Zapf-Gilje (1998) indicated that the scaled-up flux for the entire building was of the same order as flux measured by the indoor VOC method.

Regulatory Implications

The J&E model is widely used for regulatory and guidance purposes in North America. Several agencies have developed generic screening criteria for the vapor intrusion pathway (Massachusetts 1993; Michigan 1998; Connecticut 1998). Semigenic soil standards have been developed in Canada, based on two soil types (fine- and coarse-grained) and two building types (CCME 2000). Guidance recently developed by the U.S. EPA consists of a multitiered framework to evaluate the soil vapor intrusion pathway (U.S. EPA 2002). A primary (initial) screening step is used to identify sites with significant potential for vapor intrusion (e.g., odors, product in sumps or directly below foundation), and where indoor air monitoring and/or engineering controls is warranted. A secondary screening step involves the use of semigenic curves for α , based

on soil type and depth, and target breathing concentrations in indoor air to back-calculate acceptable source ground water and soil vapor concentrations. Depending on the results of the secondary screening, there is the option to conduct a site-specific pathway assessment.

Derivation of regulatory criteria requires the prediction of cross-media transfer of contaminants, and vapor transport and intrusion into buildings. For the regulatory agencies cited previously (excluding Massachusetts), cross-media transfer between VOCs in ground water and soil vapor is predicted using the Henry's law constant assuming equilibrium partitioning. Under the Massachusetts guidance, the Henry's law constant is divided by 10 to account for source vapor concentrations that are typically lower than those predicted assuming equilibrium partitioning. The vapor attenuation ratios incorporated into regulatory criteria depend on whether the assumed contamination scenario is a dissolved ground water plume or an unsaturated zone contamination source. For a ground water source, the α incorporates vapor transport through both the capillary transition zone and unsaturated zone. For an unsaturated zone source, the α incorporates transport through just the unsaturated zone. For the agencies cited previously, the ground water source α ranges from 4.6×10^{-6} to 1.5×10^{-3} whereas the vapor source α ranges from 3.9×10^{-7} to 6.2×10^{-3} . An analysis of the previous regulatory criteria indicates that the key factor affecting the α is the Q_{soil} value chosen or estimated for predictive purposes. Of lesser importance is the assumed generic or semigeneric soil type.

When vapor attenuation ratios incorporated in regulatory criteria are compared to measured ratios for field studies presented in this paper, it is apparent that the low end of the regulatory range may not be conservative for some sites. Of greatest concern would be sites with nonbiodegradable chemicals, shallow to moderate depth contamination, and high advection potential (i.e., coarse soil, high building under-pressurization).

Conclusions and Recommendations

A comprehensive evaluation of the J&E model characteristics and sensitivity, and comparisons of measured to model-predicted vapor attenuation ratios (α_m and α_p), have been provided for residential houses, ground-floor apartments, and small commercial buildings. Based on this analysis, the following conclusions can be drawn:

1. The J&E model is moderately too highly sensitive to soil-gas advection rate into the building (Q_{soil}), at D_T^{eff}/L_T values above $\sim 1 \times 10^{-3}$. Except when Q_{soil} is low, the J&E model is relatively insensitive to building foundation properties. At best, the range or uncertainty in J&E model predictions is about one order of magnitude when relatively good quality site-specific data is available.
2. Estimation of effective diffusion coefficient is subject to considerable uncertainty. Some of this uncertainty can be reduced through better site characterization, including careful lithological descriptions, testing of moisture content, grain size distribution and water retention, and appropriate consideration of the effect of surface barriers on soil moisture content.
3. Several radon and VOC tracer studies indicate that measured Q_{soil} values at coarse-grained soil sites, for single fam-

ily residences, ranged from ~ 1 to 10 L/min. Depending on the input values chosen, much lower Q_{soil} values can be predicted using the soil-gas advection model typically used in conjunction with the J&E model.

4. There are only a limited number of high quality and comprehensive field studies that can be used to help validate models for the vapor intrusion pathway.
5. For petroleum hydrocarbon sites, the vapor α_m for the Chatterton site (high ΔP cases) and Midwest site were on the order of 1×10^{-5} to 1×10^{-4} (the Midwest value is uncertain). For the remaining cases and sites, the possible upper bound vapor α_m ranged from $\sim 5 \times 10^{-7}$ to 1×10^{-5} .
6. For chlorinated solvent sites, the ground water α_m were on the order of 1×10^{-6} to 1×10^{-4} for the three sites with the most reliable data sets (CDOT, Redfields, and Hamilton). For one site with a smaller and somewhat less reliable data set (Lowry), the maximum ground water α_m was $\sim 1 \times 10^{-3}$ while the maximum subslab vapor α_m was $\sim 1 \times 10^{-2}$.
7. For the tracer and flux chamber studies, the α_m was on the order of 1×10^{-4} to 1×10^{-2} . In the context of VOC intrusion, these α_m represent conservative upper bounds owing to boundary conditions and tracer properties that are generally different than those at VOC-contaminated sites.
8. For almost all case studies, the best estimate J&E model-predicted α_p were one to two orders of magnitude less than the 50th percentile or median α_m , indicating that when best estimate and average conditions are evaluated, the J&E model predictions are conservative. There were a few cases studies where the best estimate α_p was less than the 90th percentile or maximum α_m , indicating the J&E model predictions are nonconservative for a small subset of houses or apartments. The comparisons also highlight the potential for non-conservative model predictions if a combination of low Q_{soil} and low D_T^{eff}/L_T are used.

The observed variability in α_m between different field sites, and individual houses at some sites, highlights the complexity of processes affecting vapor intrusion. Numerous factors potentially affect the vapor intrusion pathway including biodegradation, chemical transformation, sorption, contaminant source depletion, geologic heterogeneity, soil properties (moisture content, permeability, organic carbon content), building properties, meteorological conditions, and building ventilation rates. In light of this complexity, it is important to recognize the vapor intrusion modeling paradigm typically followed is a compartmental model for steady-state one-dimensional diffusion through soil, and diffusion and advection through a building foundation having an idealized edge or perimeter crack (J&E model). Often, a homogeneous soil is assumed, although it is relatively easy to model diffusion for multiple soil layers assuming site information is available (Johnson et al. 1998). Simulation of vapor transport through the building foundation and mixing of VOCs within the building airspace is highly simplified. Although not used for this study, it is noted that the J&E model has been modified to include first-order biodegradation for a dominant soil layer (Johnson et al. 1998) and oxygen-limited first-order biodegradation (Johnson et al. 2001).

Notwithstanding the above, the question remains: Can the

J&E model (or other similar screening models) be reliably used for the vapor intrusion pathway? Our answer is a qualified yes, provided that appropriate input values are used and the model sensitivity, uncertainty, and limitations are recognized. The answer may also depend on what the model is used for. For example, the use of the J&E model to set generic criteria is problematic owing to model sensitivity and uncertainty, and the wide range in possible site conditions. In our opinion, a semigenetic approach that incorporates site-specific information on critical factors affecting vapor intrusion (e.g., Q_{soil} and soil properties) improves on a single criteria approach. The technically preferred approach is to use the J&E model on a fully site-specific basis, and to calibrate model predictions using soil vapor profiles, and when possible, indoor air data. In all cases, an appropriate framework for model use and understanding of model characteristics is essential when using models for regulatory purposes.

Several data gaps and sources of uncertainty remain. Additional field-based studies should be conducted to evaluate the vapor intrusion pathway for different site conditions, and to more fully assess specific factors affecting vapor intrusion. Data that would contribute to a more in-depth pathway analysis include soil properties such as moisture content and porosity, soil vapor concentration profiles below buildings, building properties such as depressurization, and meteorological data. Further evaluation of biodegradation kinetics for hydrocarbon vapors, effect of surface barriers (e.g., buildings) on biodegradation, and chlorinated solvent transformation processes are also needed.

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References

American Society for Testing and Materials (ASTM). 1995. Standard guide for risk-based corrective action applied at petroleum release sites. E-1739-95.

Canadian General Standards Board. 1986. Determination of the airtightness of building envelopes by the fan depressurization method. CAN/CSGB-149.10-M86.

Canadian Council for Ministers of the Environment. 2000. Canada wide standards for petroleum hydrocarbon compounds in soil. June.

Connecticut Department of Environmental Protection. 1998. Residential volatilization criterion. RCSA 22a-133k, Appendix E.

EnviroGroup Limited. 1999. Indoor air assessment report—Redfield Rifle Scope Site. April.

Environmental Quality Management Inc. 2000. User's guide for the Johnson and Ettinger (1991) model for subsurface vapor intrusion into buildings (revised). Prepared for E.H. Pechan and Associates Inc. Submitted to U.S. EPA.

Fan, A., and E.A. Quinn. 2000. Case study: Residential indoor air assessment above a hydrocarbon plume. Presentation to U.S. EPA EI Forum, RCRA National Conference, Washington, D.C., August 15.

Fetter, C.W. 1994. *Applied Hydrogeology*, 3rd ed. Englewood Cliffs, New Jersey: Prentice-Hall.

Figley, D.A., and L.J. Snodgrass. 1992. Comparative foundation air leakage performance of ten residential concrete basements. In *Proceedings of the 85th Annual Meeting of Air and Waste Management Association*, June 21-26.

Figley, D.A. 1997. A guide for estimating indoor concentrations of soil gas pollutants in houses. Report prepared for CMHC.

Fischer, M.L., A.J. Bentley, K.A. Dunkin, A.T. Hodgson, W.W. Nazaroff, R.G. Sextro, and J.M. Daisey. 1996. Factors affecting indoor air concentrations of volatile organic compounds at a site of subsurface gasoline contamination. *Environmental Science and Technology* 30, no. 10: 2948-2957.

Folkes, D. 2000. Envirogroup Inc., personal communication.

Garbesi, K., and R.G. Sextro. 1989. Modeling and field evidence of pressure-driven entry of soil gas into a house through permeable below-grade walls. *Environmental Science and Technology* 23, no. 12: 1481-1487.

Garbesi, K., R.G. Sextro, W.J. Fisk, M.P. Modera, and K.L. Revzan. 1993. Soil-gas entry into an experimental basement: Model measurement comparisons and seasonal effects. *Environmental Science and Technology* 27, no. 3: 466-473.

Grimsrud, D.T., M.H. Sherman, and R.C. Sonderegger. 1982. Calculating infiltration: Implications for a construction quality standard. In *Proceedings of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers and the U.S. Department of Energy Conference: Thermal Performance of the Exterior Envelopes of Buildings II*. Las Vegas, Nevada, December.

Hers, I., and R. Zapf-Gilje. 1998. Canadian consortium research project: Field validation of soil gas transport to indoor air pathway. In *Proceedings of the 1998 Petroleum Hydrocarbon and Organic Chemicals in Ground Water Conference*. American Petroleum Institute/National Ground Water Association, Houston, Texas; 251-266. Westerville, Ohio: NGWA.

Hers, I., R. Zapf-Gilje, D. Evans, and L. Li. 2002. Comparison, validation and use of models for predicting indoor air quality from soil and groundwater contamination. *Soil and Sediment Contamination* 11, no. 4: 491-527.

Hers, I., J. Atwater, L. Li, and R. Zapf-Gilje. 2000. Evaluation of vadose zone biodegradation of BTX vapors. *Journal of Contaminant Hydrology* 46, 233-264.

Hers, I., R. Zapf-Gilje, L. Li, and J. Atwater. 2001. The use of indoor air measurements to evaluate exposure and risk from subsurface VOCs. *Journal of the Air and Waste Management Association* 51, 174-185.

Johnson, P.C., and R. Bittinger. 1991. Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. *Environmental Science and Technology* 25, no. 8: 1445-1452.

Johnson, P.C., W. Kembrowski, and R.L. Johnson. 1998. Assessing the significance of subsurface contaminant vapor migration to enclosed spaces: Site specific alternatives to generic estimates. API Publication 4674. Washington, D.C.: American Petroleum Institute.

Johnson, P.C., J. Kurtz, R. Bryan, and R. Ettinger. 2000. In-depth review of Colorado (CDOT facility) data. Presentation at U.S. EPA RCRA EI Forum, August 15-16. Washington, D.C.: U.S. EPA.

Johnson, P.C., V.A. Hermes, and S. Roggemans. 2001. An oxygen-limited hydrocarbon vapor migration attenuation screening model. Submitted to *Environmental Science and Technology*.

Kurtz, J. 2001. EMSI Inc., personal communication, Denver, Colorado.

Laubacher, R.C., P. Bartholomae, P. Velasco, and H.J. Reisinger. 1997. An evaluation of the vapor profile in the vadose zone above a gasoline plume. In *Proceedings of the 1997 Petroleum Hydrocarbon and Organic Chemicals in Ground Water Conference*. American Petroleum Institute/National Ground Water Association; 396-409. Westerville, Ohio: NGWA.

Massachusetts Department of Environmental Protection. 1993. Massachusetts contingency plan (GW-2 Standards), 310 CMR 40.0000, 1993 and as amended.

McCarthy, K.L., and R.L. Johnson. 1993. Transport of volatile organic compounds across the capillary fringe. *Water Resources Research* 29, no. 6: 1675-1683.

- Michigan Department of Environment Quality (DEQ) 1998. Part 201 generic groundwater and soil volatilization to indoor air inhalation criteria: Technical support document.
- Millington, R.J., and J.M. Quirk. 1961. Permeability of porous solids. *Trans. Faraday Society*, 1200-1207.
- Moseley, C.L., and M.R. Meyer. Petroleum contamination of an elementary school: A case history involving air, soil-gas and groundwater monitoring. *Environmental Science and Technology* 26, no. 2: 185-192.
- Nazaroff, W.W. 1992. Radon transport from soil to air. *Review of Geophysics* 30, no. 2: 137-160.
- Neilson, K.K., and V.C. Rogers. 1990. Radon transport properties of soil classes for estimating indoor radon entry. In *Proceedings of 29th Hanford Symposium of Health and the Environment. Indoor Radon and Lung Cancer: Reality or Myth? Part 1*; F.T. Cross, ed. Columbus, Ohio: Battelle Press.
- Ostendorf, D.W., and D.H. Kampbell. 1991. Biodegradation of hydrocarbon vapors in the unsaturated zone. *Water Resources Research* 27, no. 4: 453-462.
- Parker, J.C., R.J. Lenhard, and T. Kuppusamy. 1987. A parametric model for constitutive properties governing multiphase flow in porous media. *Water Resources Research* 23, no. 4: 618-624.
- Revzan, K.L., W.J. Fisk, and A.J. Gadgil. 1991. Modeling radon entry into houses with basements: Model description and verification. *Indoor Air* 2, 173-189.
- Ririe, T., and R. Sweeney. 1995. Fate and transport of volatile hydrocarbons in the vadose zone. In *Proceedings of the Petroleum Hydrocarbon and Organic Chemicals in Ground Water Conference*. American Petroleum Institute/National Ground Water Association; Houston, Nov. 29-Dec. 1, 529-542. Westerville, Ohio: NGWA.
- Schaap, M.G., and F.J. Leij. 1988. Database related accuracy and uncertainty of pedotransfer functions. *Soil Science* 163, 765-779.
- Schmidt, C.E., and T.F. Zdeb. 1998. Direct measurement of indoor infiltration through a concrete slab using the U.S. EPA flux cham-

- ber. In *Proceedings of the 1998 Air and Waste Management Association*. Paper #98, TA9C.01.
- U.S. Environmental Protection Agency. 2001. Draft supplemental guidance for evaluating the vapor intrusion to indoor air pathway. OSWER. Washington, D.C.: U.S. EPA.
- Van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44, 892.
- Versar Inc. 2000. Draft final operable unit 5-Groundwater. Ground-to-indoor air VOC migration pathway investigation report.
- Waitz, M.F.W., J.I. Freijer, P. Keule, and F.A. Swartjes. 1996. The VOLASOIL risk assessment model based on CSOIL for soils contaminated with volatile compounds. Bilthoven, The Netherlands: National Institute of Public Health and the Environment.
- Wu, J. 2000. Feasibility of indoor air testing (former GTE property) Mountain View, California: Case example. Presentation at U.S. EPA RCRA EI Forum, August 15-16, Washington, D.C.

Biographical Sketches

Ian Hers is completing Ph.D. studies at the University of British Columbia and is a senior consultant with Golder Associates Ltd. (ihers@golder.com) in Vancouver, British Columbia.

Loretta Y. Li is an associate professor in the Department of Civil Engineering at The University of British Columbia, with degrees from McGill University and Queen's University.

Paul C. Johnson is an associate professor and the assistant chair in the Department of Civil and Environmental Engineering at Arizona State University. His degrees are in chemical engineering, a B.S. from the University of California, Davis, and a Ph.D. from Princeton University.

Reidar Zapf-Gilje is an adjunct professor at the University of British Columbia (rzapf-gilje@shaw.ca) where he teaches graduate courses in the Department of Civil Engineering.

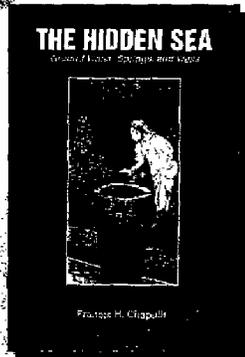


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APPENDIX 4

EXAMPLE PRINTOUTS OF VAPOR INTRUSION MODELS

1. Groundwater to indoor air, residential exposure scenario.
2. Groundwater to indoor air, commercial/industrial exposure scenario.
3. Soil to indoor air, residential exposure scenario.
4. Soil to indoor air, commercial/industrial exposure scenario.
5. Soil Gas to indoor air, residential exposure scenario.
6. Soil Gas to indoor air, commercial/industrial exposure scenario.

GW-ADV
Version 3.0; 02/03

CALCULATE RISK-BASED GROUNDWATER CONCENTRATION (enter "X" in "YES" box)

YES **OR**

Reset to Defaults

CALCULATE INCREMENTAL RISKS FROM ACTUAL GROUNDWATER CONCENTRATION (enter "X" in "YES" box and initial groundwater conc. below)

YES

ENTER
Initial
Chemical groundwater
CAS No. conc.,
(numbers only, C_w
no dashes) ($\mu\text{g/L}$)

127184

**Groundwater Vapor Emissions To Indoor Air
Residential Exposure Scenario
High Permeability Soil Scenario**

FOR EXAMPLE ONLY

Chemical
Tetrachloroethylene

MORE
↓

ENTER Average soil/ groundwater temperature, T_s (°C)	ENTER Depth below grade to bottom of enclosed space floor, L_f (cm)	ENTER Depth below grade to water table, L_{WT} (cm)	ENTER Totals must add up to value of L_{WT} (cell G28)			ENTER Soil stratum directly above water table, (Enter A, B, or C)	ENTER SCS soil type directly above water table	ENTER Soil stratum A SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined stratum A soil vapor permeability, k_v (cm^2)
Thickness of soil stratum A, h_A (cm)	Thickness of soil stratum B, h_B (cm)	Thickness of soil stratum C, h_C (cm)								
15	15	300	100	200		B	CL	S		

MORE
↓

ENTER Stratum A SCS soil type Lookup Soil Parameters	ENTER Stratum A soil dry bulk density, ρ_b^A (g/cm^3)	ENTER Stratum A soil total porosity, n^A (unitless)	ENTER Stratum A soil water-filled porosity, θ_w^A (cm^3/cm^3)	ENTER Stratum B SCS soil type Lookup Soil Parameters	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	ENTER Stratum C SCS soil type Lookup Soil Parameters	ENTER Stratum C soil dry bulk density, ρ_b^C (g/cm^3)	ENTER Stratum C soil total porosity, n^C (unitless)	ENTER Stratum C soil water-filled porosity, θ_w^C (cm^3/cm^3)
S	1.50	0.430	0.15	CL	1.5	0.43	0.3				

MORE
↓

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP (g/cm-s^2)	ENTER Enclosed space floor length, L_B (cm)	ENTER Enclosed space floor width, W_B (cm)	ENTER Enclosed space height, H_B (cm)	ENTER Floor-wall seam crack width, w (cm)	ENTER Indoor air exchange rate, ER (1/h)	ENTER Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
15	40	961	961	244	0.1	1	5

MORE
↓

ENTER Averaging time for carcinogens, AT_C (yrs)	ENTER Averaging time for noncarcinogens, AT_{NC} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)	ENTER Target risk for carcinogens, TR (unitless)	ENTER Target hazard quotient for noncarcinogens, THQ (unitless)
70	30	30	350	1.0E-06	0.2

END

Used to calculate risk-based groundwater concentration.

DATA ENTRY SHEET

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H ($\text{atm}\cdot\text{m}^3/\text{mol}$)	Henry's law constant reference temperature, T_R ($^\circ\text{C}$)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B ($^\circ\text{K}$)	Critical temperature, T_C ($^\circ\text{K}$)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF ($\mu\text{g}/\text{m}^3$) ⁻¹	Reference conc., RfC (mg/m^3)
5.00E-02	9.50E-06	1.76E-02	25	8,288	394.40	620.20	9.49E+01	2.06E+02	5.9E-06	2.7E-01

END

DATA ENTRY SHEET

Exposure duration, τ (sec)	Source-building separation, L_T (cm)	Stratum A soil air-filled porosity, θ_a^A (cm^3/cm^3)	Stratum B soil air-filled porosity, θ_a^B (cm^3/cm^3)	Stratum C soil air-filled porosity, θ_a^C (cm^3/cm^3)	Stratum A effective total fluid saturation, S_{fe} (cm^3/cm^3)	Stratum A soil intrinsic permeability, k_i (cm^2)	Stratum A soil relative air permeability, k_{rg} (cm^2)	Stratum A soil effective vapor permeability, k_v (cm^2)	Thickness of capillary zone, L_{cz} (cm)	Total porosity in capillary zone, n_{cz} (cm^3/cm^3)	Air-filled porosity in capillary zone, $\theta_{a,cz}$ (cm^3/cm^3)	Water-filled porosity in capillary zone, $\theta_{w,cz}$ (cm^3/cm^3)	Floor-wall seam perimeter, X_{crack} (cm)
9.46E+08	285	0.280	0.130	ERROR	0.257	1.00E-07	0.703	7.04E-08	46.88	0.43	0.055	0.375	3,844

Bldg. ventilation rate, $Q_{building}$ (cm^3/s)	Area of enclosed space below grade, A_B (cm^2)	Crack-to-total area ratio, η (unitless)	Crack depth below grade, Z_{crack} (cm)	Enthalpy of vaporization at ave. groundwater temperature, $\Delta H_{v,TS}$ (cal/mol)	Henry's law constant at ave. groundwater temperature, H_{TS} ($\text{atm}\cdot\text{m}^3/\text{mol}$)	Henry's law constant at ave. groundwater temperature, H'_{TS} (unitless)	Vapor viscosity at ave. soil temperature, μ_{TS} (g/cm-s)	Stratum A effective diffusion coefficient, D_A^{eff} (cm^2/s)	Stratum B effective diffusion coefficient, D_B^{eff} (cm^2/s)	Stratum C effective diffusion coefficient, D_C^{eff} (cm^2/s)	Capillary zone effective diffusion coefficient, D_{cz}^{eff} (cm^2/s)	Total overall effective diffusion coefficient, D_T^{eff} (cm^2/s)	Diffusion path length, L_d (cm)
6.26E+04	9.24E+05	4.16E-04	15	9,502	1.01E-02	4.26E-01	1.77E-04	3.90E-03	3.05E-04	0.00E+00	2.18E-05	1.06E-04	285

Convection path length, L_p (cm)	Source vapor conc., C_{source} ($\mu\text{g}/\text{m}^3$)	Crack radius, r_{crack} (cm)	Average vapor flow rate into bldg., Q_{soil} (cm^3/s)	Crack effective diffusion coefficient, D^{crack} (cm^2/s)	Area of crack, A_{crack} (cm^2)	Exponent of equivalent foundation Peclet number, $\exp(\text{Pe}^f)$ (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ ($\mu\text{g}/\text{m}^3$)	Unit risk factor, URF ($\mu\text{g}/\text{m}^3$) ⁻¹	Reference conc., RfC (mg/m^3)
15	4.26E+02	0.10	8.33E+01	3.90E-03	3.84E+02	#NUM!	5.49E-06	2.34E-03	5.9E-06	2.7E-01

END

DATA ENTRY SHEET

RISK-BASED GROUNDWATER CONCENTRATION CALCULATIONS:

Indoor exposure groundwater conc., carcinogen (µg/L)	Indoor exposure groundwater conc., noncarcinogen (µg/L)	Risk-based indoor exposure groundwater conc., (µg/L)	Pure component water solubility, S (µg/L)	Final indoor exposure groundwater conc., (µg/L)
1.77E+02	2.41E+04	1.77E+02	2.06E+05	1.77E+02

INCREMENTAL RISK CALCULATIONS:

Incremental risk from vapor intrusion to indoor air, carcinogen (unitless)	Hazard quotient from vapor intrusion to indoor air, noncarcinogen (unitless)
NA	NA

MESSAGE AND ERROR SUMMARY BELOW: (DO NOT USE RESULTS IF ERRORS ARE PRESENT)

MESSAGE: The values of Csource and Cbuilding on the INTERCALCS worksheet are based on unity and do not represent actual values.

SCROLL
DOWN
TO "END"

END

DATA ENTRY SHEET

SCS Soil Type	Soil Properties Lookup Table						Bulk Density			SCS Soil Name
	K_s (cm/h)	α_1 (1/cm)	N (unitless)	M (unitless)	n (cm^3/cm^3)	θ_1 (cm^3/cm^3)	Mean Grain Diameter (cm)	(g/cm^3)	θ_w (cm^3/cm^3)	
C	0.61	0.01496	1.253	0.2019	0.459	0.098	0.0092	1.43	0.215	Clay
CL	0.34	0.01581	1.416	0.2938	0.442	0.079	0.016	1.48	0.168	Clay Loam
L	0.50	0.01112	1.472	0.3207	0.399	0.061	0.020	1.59	0.148	Loam
LS	4.38	0.03475	1.746	0.4273	0.390	0.049	0.040	1.62	0.076	Loamy Sand
S	26.78	0.03524	3.177	0.6852	0.375	0.053	0.044	1.66	0.054	Sand
SC	0.47	0.03342	1.208	0.1722	0.385	0.117	0.025	1.63	0.197	Sandy Clay
SCL	0.55	0.02109	1.330	0.2481	0.384	0.063	0.029	1.63	0.146	Sandy Clay Loam
SI	1.82	0.00658	1.679	0.4044	0.489	0.050	0.0046	1.35	0.167	Silt
SIC	0.40	0.01622	1.321	0.2430	0.481	0.111	0.0039	1.38	0.216	Silty Clay
SICL	0.46	0.00839	1.521	0.3425	0.482	0.090	0.0056	1.37	0.198	Silty Clay Loam
SIL	0.76	0.00506	1.663	0.3987	0.439	0.065	0.011	1.49	0.180	Silt Loam
SL	1.60	0.02667	1.449	0.3099	0.387	0.039	0.030	1.62	0.103	Sandy Loam

For example only. Constants reflect values presented in Appendix 1, Table H of the HEER Office EHE guidance and may have been modified in later editions of the guidance

		Chemical Properties Lookup Table													
CAS No.	Chemical	Organic carbon partition coefficient, K_{oc}	Diffusivity in air, D_a	Diffusivity in water, D_w	Pure component water solubility, S	Henry's law constant H'	Henry's law constant at reference temperature, H	Henry's law constant reference temperature, T_R	Normal boiling point, T_B	Critical temperature, T_C	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$	Unit risk factor, URF	Reference conc., RIC	URF extrapolated (X)	RIC extrapolated (X)
		(cm^3/g)	(cm^2/s)	(cm^2/s)	(mg/L)	(unitless)	($\text{atm}\cdot\text{m}^3/\text{mol}$)	($^\circ\text{C}$)	($^\circ\text{K}$)	($^\circ\text{K}$)	(cal/mol)	($\mu\text{g}/\text{m}^3$) ⁻¹	(mg/m^3)		
127184	Tetrachloroethylene	9.49E+01	5.00E-02	9.50E-06	2.06E+02	7.20E-01	1.76E-02	25	394.40	620.20	8,288	5.9E-06	2.7E-01	L	

GW-ADV
Version 3.0; 02/03

Reset to
Defaults

CALCULATE RISK-BASED GROUNDWATER CONCENTRATION (enter "X" in "YES" box)

YES **X**

CALCULATE INCREMENTAL RISKS FROM ACTUAL GROUNDWATER CONCENTRATION (enter "X" in "YES" box and initial groundwater conc. below)

YES

**Groundwater Vapor Emissions To Indoor Air
Commercial/Industrial Exposure Scenario
High Permeability Soil Scenario**

FOR EXAMPLE ONLY

ENTER	ENTER								
Chemical CAS No. (numbers only, no dashes)	Initial groundwater conc., C_w ($\mu\text{g/L}$)	Chemical				Soil stratum directly above water table, (Enter A, B, or C)	SCS soil type directly above water table	Soil stratum A SCS soil type (used to estimate soil vapor permeability)	User-defined stratum A soil vapor permeability, k_v (cm^2)
127184		Tetrachloroethylene				B	CL	S	
ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER
Average soil/groundwater temperature, T_s ($^{\circ}\text{C}$)	Depth below grade to bottom of enclosed space floor, L_f (cm)	Depth below grade to water table, L_{WT} (cm)	Totals must add up to value of L_{WT} (cell G28) Thickness of soil stratum A, h_A (cm)			Thickness of soil stratum B, (Enter value or 0) h_B (cm)	Thickness of soil stratum C, (Enter value or 0) h_C (cm)	OR	
15	15	300	100	200					

MORE
↓

ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER
Stratum A SCS soil type	Stratum A soil dry bulk density, ρ_b^A (g/cm^3)	Stratum A soil total porosity, n^A (unitless)	Stratum A soil water-filled porosity, θ_w^A (cm^3/cm^3)	Stratum B SCS soil type	Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	Stratum B soil total porosity, n^B (unitless)	Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	Stratum C SCS soil type	Stratum C soil dry bulk density, ρ_b^C (g/cm^3)	Stratum C soil total porosity, n^C (unitless)	Stratum C soil water-filled porosity, θ_w^C (cm^3/cm^3)
S	1.50	0.430	0.15	CL	1.5	0.43	0.3				

MORE
↓

ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER	ENTER
Enclosed space floor thickness, L_{crack} (cm)	Soil-bldg. pressure differential, ΔP (g/cm-s^2)	Enclosed space floor length, L_B (cm)	Enclosed space floor width, W_B (cm)	Enclosed space height, H_B (cm)	Floor-wall seam crack width, w (cm)	Indoor air exchange rate, ER (1/h)	Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
15	40	961	961	244	0.1	2	5

MORE
↓

ENTER	ENTER	ENTER	ENTER	ENTER	ENTER
Averaging time for carcinogens, AT_C (yrs)	Averaging time for noncarcinogens, AT_{NC} (yrs)	Exposure duration, ED (yrs)	Exposure frequency, EF (days/yr)	Target risk for carcinogens, TR (unitless)	Target hazard quotient for noncarcinogens, THQ (unitless)
70	25	25	250	1.0E-06	0.2

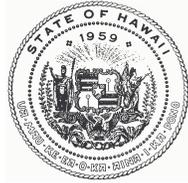
END

Used to calculate risk-based groundwater concentration.

DATA ENTRY SHEET

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H ($\text{atm}\cdot\text{m}^3/\text{mol}$)	Henry's law constant reference temperature, T_R ($^\circ\text{C}$)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B ($^\circ\text{K}$)	Critical temperature, T_C ($^\circ\text{K}$)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF ($\mu\text{g}/\text{m}^3$) ⁻¹	Reference conc., RfC (mg/m^3)
5.00E-02	9.50E-06	1.76E-02	25	8,288	394.40	620.20	9.49E+01	2.06E+02	5.9E-06	2.7E-01

END



STATE OF HAWAII
DEPARTMENT OF HEALTH
P. O. BOX 3378
HONOLULU, HI 96801-3378

In reply, please refer to:
File: EHA/HEER Office

2011-716-RB

December 2011

To: Interested Parties

From: Roger Brewer, Ph.D., Environmental Risk Assessor, HEER

Subject: *Screening for Environmental Hazards at Site with Contaminated Soil and Groundwater*, Fall 2011 Updates

This technical memorandum summarizes updates to Environmental Action Levels (EALs) published by the Hazard Evaluation and Emergency Response (HEER) office of the Hawai'i Department of Health (HDOH). The background and development of the EALs is described in the HEER office guidance *Screening for Environmental Hazards at Site with Contaminated Soil and Groundwater* ("EHE" guidance; HDOH 2011). The Fall 2011 updates replace and take precedence over earlier editions of the EALs.

A detailed review of revisions to the 2009 EALs is provided in the attachment to this memorandum and in the appendices of the updated EHE guidance. Significant revisions to the EALs include:

- Soil action levels presented in EAL Surfer for **dioxins** revised to reflect June 2010 updates (HDOH 2010a);
- Reference to October June 2010 update of categories for **arsenic** contaminated soil added to Surfer notes box (HDOH 2010b);
- Soil action levels for **aldrin and dieldrin** revised to reflect higher confidence in noncancer studies and common co-occurrence in termiticide-treated soil in the absence of other chemicals (final Tier 1 soil action levels increased);
- Target noncancer Hazard Quotient for **thallium** adjusted to 1.0 to help take into account natural background presence of thallium in soil;
- Inhalation toxicity factor (Reference Concentration) and target risk for "**TPH**" in **indoor air and soil gas** revised based on soil gas study carried out by HEER office (increased TPH soil gas action level for vapor intrusion hazards);
- **Physiochemical constants** for chemicals updated to reflect change in USEPA Regional Screening Level guidance (HDOH EALs not significantly affected);
- **Sorption coefficient** used to define "low-mobility chemicals" revised downward from 30,000 cm³/g to 5,000 cm³/g (final Tier 1 action levels for several **PAHs** and **organochlorine pesticides** increased to more appropriately reflect direct-exposure action level, rather than leaching based action level);
- Alternate Volatilization Factor (estimates vapor emissions from soil) that takes into account poor air flow in trenches used to calculate **VOC soil action levels for trench**

and construction workers (USEPA 2002, see Appendix 2). Reduced previous action levels by a factor of approximately four.

- Updates to **background metals in soils** added (see Appendix 1, Section 7);
- Soil ecotoxicity action levels eliminated (increase in action levels for some **metals** to reflect direct exposure action levels, rather than generic, ecotoxicity based action levels);
- Aquatic (and associated groundwater) **acute toxicity action levels for PAHs** updated to reflect generic action level for PAHs (increased some groundwater action levels).
- Additional discussion on development of **Tier 1 vs Site-Specific Soil Action Levels** provided (Volume 1, Section 4.1);
- Additional discussion of site-specific evaluation of **leaching of contaminants from soil** (Volume 1, Section 4.3.3 and Appendix 1, Section 4.4);
- Additional discussion on distinguishing **background levels of VOCs in indoor air** from vapor intrusion added (Volume 1, Section 4.5);
- Expanded discussion of **vapor intrusion models and action levels** included in Appendix 1, Chapter 2;
- HDOH technical memorandum discussing the natural occurrence of **hexavalent chromium in groundwater** added to Appendix 8;
- Note regarding the presence of apparently natural, **background lead in caprock sediment groundwater** above action levels added to Volume 1, Section 4.3);
- **EAL Surfer** updated.

A summary of the more significant changes to the 2009 Tier 1 EALs is provided in Table 1 (organochlorine pesticides), Table 2 (metals) and Table 3 (Total Petroleum Hydrocarbons in soil gas). Groundwater action levels were not affected in this update of the EALs. These updates reflect site-specific studies carried out in Hawai'i by HEER staff and environmental consultants since publication of the 2009 EHE guidance. This includes reviews of toxicity factors, soil batch tests for evaluation of leaching hazards, carbon range soil gas data from petroleum-contaminated sites and background metal concentrations in soils. Separate reports on background metals in soils and the measurement, chemistry and toxicity of petroleum vapors in soil gas are to be published separately by the HEER office.

The EHE document and associated EALs will be revised and updated on a regular basis. Comments and suggestions from the general public are welcome at any time. Updates will be posted to the HDOH EHE website and notification sent to persons on the EHE mailing list. Workshops to present and discuss the EALs will also be held periodically. To provide comments or be included on the mailing list for updates and workshop announcements, please contact:

Roger Brewer
Hawai'i Department of Health
Hazard Evaluation and Emergency Response
Telephone: 1-808-586-4328
E-mail: roger.brewer@doh.hawaii.gov

Table 1. Updates to Tier 1 EALs for Organochlorine Pesticides (2009 EAL noted in parentheses).

Chemical	Groundwater IS a Potential Source of Drinking Water (mg/kg)		Groundwater is Not a Potential Source of Drinking Water (mg/kg)	
	Surface Water <150m	Surface Water >150m	Surface Water <150m	Surface Water >150m
ACENAPHTHENE	120 (20)	120 (20)	120 (23)	140 (140)
ALDRIN	0.92 (0.029)	0.92 (0.029)	0.92 (0.029)	0.92 (0.029)
ANTHRACENE	4.3 (2.5)	4.3 (2.5)	4.3 (2.5)	4.3 (2.5)
BIPHENYL, 1,1-	10 (0.52)	10 (0.52)	10 (5.2)	10 (5.2)
DIELDRIN	1.5 (0.003)	1.5 (0.007)	1.5 (0.003)	1.5 (0.03)
ENDOSULFAN	18 (0.032)	18 (0.12)	18 (0.032)	18 (0.12)
ENDRIN	3.7 (0.004)	3.7 (0.06)	3.7 (0.004)	3.7 (0.06)
FLUORENE	100 (7.3)	130 (130)	100 (7.3)	130 (130)
HEPTACHLOR EPOXIDE	0.053 (0.003)	0.053 (0.046)	0.053 (0.003)	0.053 (0.046)
PHENANTHRENE	69 (11)	69 (18)	69 (11)	69 (18)
TRIFLURALIN	24 (14)	24 (14)	54 (32)	54 (32)

Table 2. Updates to Tier 1 EALs for Metals.

Chemical	Residential			Commercial/Industrial		
	2009 (mg/kg)	2011 (mg/kg)	2011 Basis	2009 (mg/kg)	2011 (mg/kg)	2011 Basis
ANTIMONY	6.3	6.3	DE	40	82	DE
ARSENIC (total)	20	*24	BG	20	*24	BG
BARIUM	750	1,000	GC	1,500	2,500	GC
BERYLLIUM	4.0	31	DE	8.0	150	DE
CADMIUM	12	14	DE	12	120	BG
CHROMIUM (Total)	500	*1,100	BG	500	*1,100	BG
CHROMIUM III	750	*1,100	BG	750	*1,100	BG
CHROMIUM VI	8.0	29	DE	8.0	480	DE
COBALT	40	180	DE	80	180	DE
COPPER	230	626	DE	230	2,500	DE
LEAD	200	200	DE	800	800	DE
MERCURY	4.7	4.7	DE	10	61	DE
MOLYBDENUM	40	78	DE	40	1,000	DE
NICKEL	150	760	DE	150	870	DE
SELENIUM	10	78	DE	10	1,000	DE
SILVER	20	78	DE	40	1,000	DE
THALLIUM	1.0	0.78	DE	13	10	DE
VANADIUM	110	*770	BG	200	1,000	DE
ZINC	600	1,000	GC	600	2,500	GC

DE: Direct Exposure; BG: Background; GC: Gross Contamination. *Estimated Upper Bound of naturally occurring metal in volcanic soils. Natural background concentration may be higher in some areas. Thallium action level may be below natural background in some areas (likely to be natural background if detected and no known, past releases of thallium salts at site). Background metals likely to be lower in carbonate-rich, coast sediments and soils. Compare soil data for vanadium directly to direct-exposure action levels if a release of one or more of these metals is known to have occurred in carbonate-rich, coastal soils.

Table 3. Updates to TPH soil gas action levels.

Chemical	Reference Concentration (ug/m ³)		Soil Gas Action Level (ug/m ³)			
			2009		2011	
	2009	2011	Residential	Commercial/Industrial	Residential	Commercial/Industrial
TPH(gasolines)	50	225	26,000	73,000	230,000	660,000
TPH(middle distillates)	110	225	57,000	160,000	230,000	660,000

TPH = Total Petroleum Hydrocarbons; middle distillates includes diesel fuels.

ATTACHMENT

Technical Overview of Fall 2011 Updates to 2009 HDOH/HEER Tier 1 EALs

HDOH 2011, *Screening for Environmental Hazards at Sites with Contaminated Soil and Groundwater* (December 2011), Hawai'i Department of Health, Hazard Evaluation and Emergency Response, <http://hawaii.gov/health/environmental/hazard/index.html>

1. Adjustment of target risk and soil action levels for aldrin and dieldrin. Soil action levels for aldrin and dieldrin revised to reflect higher confidence in noncancer studies. Updated action levels are noted in Table one of the cover memo. Aldrin was sometimes used as an alternative to Technical Chlordane as a termiticide for treatment of soil around and under wooden structures. Dieldrin is a breakdown product of aldrin. The target noncancer Hazard Quotient for each chemical was adjusted to 0.5, based on the common co-occurrence in termiticide-treated soil in the absence of other chemicals and a target, cumulative Hazard Index of 1.0. The target cancer risk was adjusted upwards to 10^{-4} .

Cumulative risk should be evaluated if other contaminants are identified in the soil at concentrations that approach or exceed their respective, direct-exposure action levels (e.g., Technical Chlordane). Lead in the soil around structures (e.g., from lead-based paint) should be evaluated separately.

2. Residential Soil Action Level for Lead. The 2009 Tier 1 soil action levels for lead in residential soils ("Unrestricted" land use) was 200 mg/kg. This was based on a published, plant toxicity screening level in soil (see Appendix 1, Table A and B series in 2009 document). An action level of 400 mg/kg was presented in the document for residential, direct-exposure hazards. This action level was based on a "Preliminary Remediation Goal (PRG)" (more recently referred to as the "Regional Screening Level (RSL)") published by the USEPA in the 1990s and still presented in their 2011 RSL guidance (USEPA 2011a).

The USEPA PRG/RSL is intended to reflect a maximum, target lead blood level in children of 10 ug/dl. Recent USEPA guidance recommends reduce this target level be reduced to 5 ug/dl (USEPA 2011b). In order to reflect this change, the residential direct-exposure soil action level for lead in this update of the HEER EHE guidance has been reduced from 400 mg/kg to 200 mg/kg. This is intended to serves as an interim action level until such time that the USEPA PRG for lead in soil is formally updated. Note that the final Tier 1 soil action level for lead remains unchanged at 200 mg/kg, even though the 2009 soil ecotoxicity action level for lead of 200 mg/kg has been dropped (see note Number 5). The commercial/industrial soil action level for lead of 800 mg/kg was not changed (based on USEPA commercial/industrial PRG/RSL).

3. Update of chemical sorption coefficients. Sorption coefficients (koc) presented in Appendix 1, Table H of the EHE guidance were updated to reflect revisions to generic koc values used in the June 2011 edition of the USEPA Regional Screening Levels guidance (USEPA 2011a). Coefficients used in the 2009 EALs were based on an earlier edition of the same guidance. Sorption coefficients are included in models used to generate soil action levels for direct exposure, vapor intrusion and leaching hazards. The updates to the sorption coefficients resulted in only minor changes to the soil action levels.

4. Default sorption coefficient (koc) used to define "low mobility" chemicals in soil leaching models reduced from 30,000 cm³/g to 5,000 cm³/g. Sorption coefficients (koc) are used to estimate how strongly a chemical will bind to organic carbon in soil and are a key component of soil leaching models. Chemicals with low sorption coefficients, like MTBE (11 cm³/g) and PCE (95 cm³/g) are highly mobile and a significant proportion of the chemical will preferentially dissolve into pore water and leachate, posing a potential threat to underlying groundwater. Published koc values are multiplied by the assumed organic carbon content of the soil to calculate an adjusted, "Kd" coefficient for modeling (e.g., Kd = koc x 0.2% organic carbon). Chemicals with high sorption coefficients, like PCBs (131,000 cm³/g) and chlordane (87,000 cm³/g) will become tightly bound to soil particles and relatively immobile in soil. These chemicals do not pose significant risk to groundwater unless pure product manages to reach the water table.

The approach used to develop soil action levels for potential leaching hazards is discussed in Appendix 1 of the EHE guidance. A generic algorithm is used to develop action levels for chemicals with an assumed moderate to high mobility. Chemicals with a sorption coefficient greater than 30,000 gm/cm³ were considered to be very low mobility and not a significant threat to groundwater. Leaching based soil action levels were set at that chemicals theoretical saturation limit in soil (i.e, the maximum amount of the chemical that could be sorbed onto soil particles or dissolved in pore water before free product began to appear).

In 2007 the HEER office published guidance on the use of laboratory "batch tests" to more accurately evaluate the leachability of chemicals in soil on a site-specific basis (HDOH 2007). The specific batch test used is referred to as the Synthetic Precipitation Leaching Parameter or "SPLP" test. The test can be used to directly measure the Kd sorption coefficient (or more accurately a *desorption* coefficient) for a chemical in the soil rather than relying on generic factors and assumed soil properties, as done for the soil action levels.

Since 2007 time batch test data have consistently indicated that aged-chemicals in soil are much less mobile and pose a much lower threat to groundwater than the generic sorption coefficient and associated action levels would otherwise suggest. A significant number of batch tests have in particular been carried out on soil contaminated with organochlorine pesticides, such as chlordane, dieldrin and aldrin. These tests suggest that the published sorption coefficients and generic leaching model used *over predict* contaminant mobility and potential impacts to groundwater by at least an order of magnitude.

Examples of default versus measured sorption coefficients from studies in Hawai'i are provided below (measured as "Kd," see HDOH 2007). A Kd value greater than 20 indicates that the chemical is essentially "immobile."

Chemical	¹ Published Koc Value (cm³/g)	² Modeled Kd Value (cm³/g)	³ Measured Kd Value (cm³/g)
Assumed Moderate- to High-Mobility Chemicals			
⁴ Ametryn	450	0.45	30
⁴ Atrazine	230	0.23	6.9
⁶ Benzene	170	0.17	8.4 to 203
⁷ Dieldrin	11,000	11	650-690
⁴ Diuron	136	0.14	86

⁴ Trifluralin	9,680	9.7	5,000
Assumed Low-Mobility Chemicals			
⁷ Aldrin	106,000	106	5,800-6,600
⁵ Arsenic	(not applicable)	29?	2,100 to 19,000
⁸ Chlordane	87,000	87	4,200-7,800
⁴ Dioxins	257,000	257	10,000-51,000

1. Default koc value used in leaching models (from USEPA 2011a); refer to EHE guidance Appendix 1, Table H (HDOH 2011).
2. Calculated Kd used in EAL soil leaching model = koc x assumed Total Organic Carbon fraction of 0.001.
3. Based on results of SPLP batch test for soil samples collected at the noted site (HDOH 2007).
4. *Site Investigation Report and Environmental Hazard Evaluation, East Kapolei II Pesticide Mixing and Loading Site*, Enviroservices & Training Center, LLC, March 2010.
5. *Remedial Alternatives Analysis & Response Action Report*, Former Ka'u Agribusiness, ASCI-ERM, November 2008. Leaching based soil action levels for arsenic not included in EHE guidance; site-specific batch test data require. Noted Kd from USEPA SSL and RSL guidance (USEPA 1996, 2011a).
6. *Remedial Investigation Report, Former GASCO Facility*, Weston Solutions, April 1, 2009.
7. *Results of Leachability Testing for Organochlorine Pesticides in Soil using the Synthetic Precipitation Leaching Procedure, Earhart I-4 Neighborhood, Hickam Air Force Base, Hawai'i*, Tetra Tech, December 18, 2009.
8. *Removal Action Plan and Environmental Hazard Evaluation, Ironwoods at Kailua*, Tetra Tech EM, Inc., July 18, 2011 (draft).

As can be seen from the table, soil action levels calculated using generic sorption coefficients and assumed Kd values tend to significantly over predict the mobility of the chemical in soil. Although not routinely measured, organic carbon in the soils is typically 1% or less and does not by itself explain the increased Kd value. The higher Kd value is instead most likely associate with secondary sorption onto or diffusion into clays, as well as an increased difficulty in *desorption* of an aged chemical in soil from organic carbon.

Based on soil SPLP batch test data collected in Hawai'i the default sorption coefficient (koc) used to define "low mobility" chemicals in soil leaching models was reduced from 30,000 cm³/g to 5,000 cm³/g. The theoretical soil saturation concentration is then used as the default leaching based soil action level for potential leaching hazards for all chemicals with a published koc that exceeds this value. This has proven to be a useful approach to verifying the leachability of presumed low-mobility chemicals in soil. This significantly increased the leaching based action levels for several chemicals, especially PAHs and organochlorine pesticides. Chemicals affected include: Acenaphthene, Anthracene, 1,1 Biphenyl, Endosulfan, Endrin, Fluorene, Heptachlor, Heptachlor Epoxide, Phenanthrene, Trifluralin. The following table summarizes the changes in the 2009 versus 2011 action levels (2009 action level noted in parentheses):

*Chemical	Groundwater IS a Potential Source of Drinking Water		Groundwater is Not a Potential Source of Drinking Water	
	Surface Water <150m	Surface Water >150m	Surface Water <150m	Surface Water >150m
ACENAPHTHENE	120 (20)	120 (20)	120 (23)	170 (200)
ANTHRACENE	4.3 (2.5)	4.3 (2.5)	4.3 (2.5)	4.3 (2.5)
BIPHENYL, 1,1-	210 (0.52)	210 (0.52)	210 (5.2)	210 (5.2)
DIELDRIN	30 (0.003)	30 (0.007)	30 (0.003)	30 (1.2)
ENDOSULFAN	18 (0.032)	18 (0.12)	18 (0.032)	18 (0.12)
ENDRIN	30 (0.004)	30 (0.07)	30 (0.004)	30 (0.07)
FLUORENE	100 (7.3)	370 (460)	100 (7.3)	460 (560)

HEPTACHLOR EPOXIDE	12 (0.003)	12 (0.046)	12 (0.003)	12 (0.046)
PHENANTHRENE	69 (11)	69 (18)	69 (11)	69 (18)
TRIFLURALIN	24 (14)	24 (14)	54 (32)	54 (32)

*Chemicals listed in the EHE guidance with a koc value between 5,000 and 30,000 cm³/g. *Reduction* of some action levels (e.g., fluorine) reflects a significant *reduction* of the published koc value used in the model, based on updates to the USEPA RSLs. This offset use of the alternative saturation model.

These changes are reflected in Table 1 in main technical memorandum. Note that a lower action level in Table 1 than presented above reflects use of the direct-exposure action level over leaching based action level for final, Tier 1 EAL. The above table only summarized changes to leaching based soil action levels, while Table 1 comprehensively summarizes changes to all categories of action levels and presents the lowest. Site-specific SPLP batch tests are recommended in cases where the saturation level is exceeded (see HDOH 2007).

5. Naturally occurring, background levels of metals in soil updated. The HEER office undertook a review of background concentrations of metals in soil in 2011 (to be published in late 2011 or early 2012). The estimated Upper Bound concentration of metals in volcanic soils was incorporated into Appendix 1 of the EHE guidance for consideration in selection of final, Tier 1 EALs. Updated action levels are noted in Table 2 of the cover memo. Target noncancer Hazard Quotient for **thallium** adjusted to 1.0 to help take into account natural background and lack of available soil data.

The Background Threshold Value noted in Table 2 reflects the maximum-reported concentration of the metal in the samples compiled for the study. *Higher* concentrations are possible in volcanic soils due to localized, metal-rich volcanic deposits or due to testing of small aliquots of discrete soil samples with non-representative nuggets of metal-rich, iron hydroxides.. Background metals likely to be *lower* in carbonate-rich, coast sediments and soils. Compare soil data for nickel, thallium and vanadium directly to direct-exposure action levels if a release of one or more of these metals is known to have occurred in carbonate-rich, coastal soils.

Naturally occurring trace metals in the volcanic and caprock soils of Hawai'i are not significantly bioavailable and do not pose a risk to human health. Similar trace metals are used in the production of steel and other alloys. With perhaps the exception of lead, these trace metals *will not be released to soil in a bioavailable form* upon use or even degradation (e.g., rusting) of metallic objects (e.g., tanks, heavy equipment, etc.). Toxicity factors and associated, risk-based soil action levels are likewise based on soluble, highly bioavailable forms of these metals (e.g., thallium salts). *The soil action levels do not apply to metals in soil likely to be associated with natural background or degraded, metallic objects.*

6. Soil ecotoxicity action levels discontinued. The use of generic, published soil action levels for terrestrial ecotoxicity has always been contentious issue, due to site-specific differences in soil type and more importantly pertinent, ecological receptors. An internal HEER review also indicated that naturally occurring concentrations of metals in the iron-rich, volcanic soils of Hawai'i often exceed generic, ecotoxicity soil screening levels developed for use in soils more typical of granitic, continental geologic settings (to be published in 2011 or 2012). In Hawai'i these metals are tightly bound to soil particles (e.g., iron hydroxides) and not significantly toxic. This negates the use of generic screening levels developed outside of the state. Site-specific assessment will instead be required in rare cases where a sensitive ecohabit is present.

7. Childhood Adjustment Factor deleted from vapor intrusion models. Earlier editions of the USEPA Residential Preliminary Remediation Goals (PRGs, 2004 and earlier) included a “Childhood Adjustment Factor” of 0.791 for indoor air PRGs (carcinogens only; reduced initially calculated goal by approximately 20%). This adjustment factor was incorporated into HEER EAL models used to generate indoor air, soil gas, soil and groundwater action levels for vapor intrusion (not shown in Appendix 2 Indoor Air action level equations). Use of the adjustment factor was discontinued in post-2004 updates of the USEPA PRGs due to the already conservative nature of the model assumptions (now referred to as Regional Screening Levels; see USEPA 2011). Eliminating the adjustment factor increased indoor air, soil gas, soil and groundwater residential action levels by approximately 20% in the Fall 2011 update of the EHE guidance.

8. Tapwater risk-based action levels corrected to only consider inhalation of vapors during showering for volatile chemicals (action levels not significantly affected).

9. Noncancer RfC for TPH revised based on carbon range data for soil gas samples collected at petroleum release sites (same RfC used for both gasolines and middle distillates. Target noncancer Hazard Quotient revised to 1.0, based on overwhelming predominance of non-BTEX/PAH, "TPH" compounds in petroleum vapors. TPH soil gas action levels significantly increased. Refer to accompanying EAL update memo for details (HDOH 2011).

TPH: Expand on RfCs & NCEA toxicity factors, soil gas carbon range data. Note current TO-17 study and pending updates to soil gas sample collection data. Note that field methods for the collection of soil gas samples presented in the HEER office Technical Guidance Manual are currently being revised.

Use To method to determine TPH in soil gas. Current carbon range approaches do not adequately quantify TPH in soil gas. Use site-specific carbon range makeup

References:

HDOH, 2007, *Pesticides in former agricultural lands and related areas - Updates on investigation and assessment* (May 11, 2007): Hawai'i Department of Health, Solid & Hazardous Waste Branch, www.hawaii.gov/health/environmental/hazard/eal2005.html.

HDOH, 2010a, Update to Soil Action Levels for TEQ Dioxins and Recommended Soil Management Practices (June 2010): Hawai'i Department of Health, Office of Hazard Evaluation and Emergency Response, <http://www.hawaiidoh.org/>

HDOH, 2010b, Update to Soil Action Levels for Inorganic Arsenic and Recommended Soil Management Practices (October 2010): Hawai'i Department of Health, Office of Hazard Evaluation and Emergency Response, <http://www.hawaiidoh.org/>

HDOH 2011, *Screening For Environmental Hazards at Sites With Contaminated Soil and Groundwater* (Fall 2011), Hawai'i Department of Health, Hazard Evaluation and Emergency Response, <http://hawaii.gov/health/environmental/hazard/index.html>

TetraTech, 2011, *Report for the Hawaii Department of Health on Aldrin/Dieldrin Concentrations in Soil at the Hickam Air Force Base* (April 5, 2011): Tetra Tech Corporation, 130pp (available from HDOH, HEER office).

USEPA, 1996a, *Soil Screening Guidance: Technical Background Document*: U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Publication 9355.4-17A, May, 1996.

USEPA, 2002, *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites*: U.S. Environmental Protection Agency, Solid Waste and Emergency Response, OSWER 9355.4-24, December 2002, http://www.epa.gov/superfund/resources/soil/ssg_main.pdf

USEPA, 2011a, *Screening Levels for Chemical Contaminants*: U.S. Environmental Protection Agency, May 2008 (updated June 2011), prepared by Oak Ridge National Laboratories, <http://www.epa.gov/region09/waste/sfund/prg/>

USEPA, 2011b, *OPPT Program-Specific Regional Offices Priorities, Lead Risk Reduction Program (update)*: U.S. Environmental Protection Agency, Office of Chemical Safety and Pollution Prevention, *in* National Program Manager Guidance Final, FY 2012, EPA-740-B-11-001, http://www.epa.gov/planandbudget/annualplan/FY12_OCSPP_NPM_Gdnce.pdf