APPENDIX 2

SUMMARY OF HUMAN HEALTH RISK-BASED EQUATIONS AND DEFAULT INPUT PARAMETER VALUES; USEPA REGION IX PRG DOCUMENT (OCTOBER 2002, TEXT ONLY)

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

1.0 Introduction

A summary of models and assumptions used to develop for human health, direct-exposure concerns is presented below. For addition information on the models refer to the document *Region IX Preliminary Remediation Goals* ("PRGs", USEPA 2002) and other documents as referenced. A copy of the text of this document is attached.

2.0 SOIL

2.1 Residential and Commercial/Industrial Action Levels

Human exposure assumptions are summarized in Table 1. With the exception of the construction/trench worker exposure scenario, parameter values in Table 1 were taken directly from the USEPA Region IX PRG document. Parameter values for the construction/trench worker exposure scenario are discussed in more detail in Appendix 1. Tables 2 and 3 summarize equations and parameter values used to develop the PRG Volatilization Factors and Particulate Emission Factor.

Age-Adjusted Exposure Factors

Carcinogenic risks under residential exposure scenarios were calculated using the following age-adjusted factors:

1) ingestion [(mg-yr)/kg-day)]:

$$IFS_{adj} = \frac{ED_c \text{ x } IRS_c}{BW_C} + \frac{(ED_r - ED_c) \text{ x } IRS_a}{BW_a}$$

2) dermal contact [(mg-yr)/kg-day)]:

$$SFS_{adj} = \frac{ED_c \text{ x } AF_c \text{ x } SA_c}{BW_C} + \frac{(ED_r - ED_c) \text{ x } AF_a \text{ x } IRS_a}{BW_a}$$

3) inhalation [(m3-yr)/kg-day)]:

$$InhF_{adj} = \frac{ED_c \text{ x } IRA_c}{BW_C} + \frac{(ED_r - ED_c) \text{ x } IRA_a}{BW_a}$$

Definition of terms and default parameter values used in the equations are presented in Tables a through c.

Direct exposure equations for soil are summarized as follows:

Equation 1: Combined Exposures to Carcinogenic Contaminants in Residential Soil

$$C(mg/kg) = \frac{TR \text{ x } AT_c}{EF_r \left[\left(\frac{IFS_{adj} \text{ x } CSF_o}{10^6 mg/kg} \right) + \left(\frac{SF_{adj} \text{ x } ABS \text{ x } CSF_o}{10^6 mg/kg} \right) + \left(\frac{InhF_{adj} \text{ x } CSF_i}{VF} \right) \right]}$$

Equation 2: Combined Exposures to Noncarcinogenic Contaminants in Residential Soil

$$C(mg/kg) = \frac{THQ \times BW_c \times AT_n}{EF_r \times ED_c \left[\left(\frac{I}{RfD_o} \times \frac{IRS_c}{10^6 mg/kg} \right) + \left(\frac{I}{RfD_o} \times \frac{SA_c \times AF_c \text{ x } ABS}{10^6 mg/kg} \right) + \left(\frac{I}{RfD_i} \times \frac{IRA_c}{VF} \right) \right]}$$

Equation 3: Combined Exposures to Carcinogenic Contaminants in Industrial Soil

$$C(mg/kg) = \frac{TR \times BW_a \times AT_c}{EF_o \times ED_o \left[\left(\frac{IRS_o \times CSF_o}{10^6 mg/kg} \right) + \left(\frac{SA_a \times AF_a \times ABS \times CSF_o}{10^6 mg/kg} \right) + \left(\frac{IRA_a \times CSF_i}{VF} \right) \right]}$$

Equation 4: Combined Exposures to Noncarcinogenic Contaminants in Industrial Soil

$$C(mg/kg) = \frac{THQ \times BW_a \times AT_n}{EF_o \times ED_o \left[\left(\frac{I}{RfD_o} \times \frac{IRS_o}{10^6 mg/kg} \right) + \left(\frac{I}{RfD_o} \times \frac{SA_a \times AF_a \times ABS}{10^6 mg/kg} \right) + \left(\frac{I}{RfD_i} \times \frac{IRA_a}{VF} \right) \right]}$$

Equation 5: Derivation of the Volatilization Factor

$$VF(m^3/kg) = (Q/C) \times \frac{(3.14 \text{ x } D_A \times T)^{1/2}}{(2 \times P_b \times D_A)} \times 10^{-4} (m^2/cm^2)$$

$$D_A = \frac{\left[\left(\Theta_a^{10/3} D_i H^i + \Theta_w^{10/3} D_w \right) / n^2 \right]}{P_b K_d + \Theta_w + \Theta_a H'}$$

Equation 6: Derivation of the Soil Saturation Limit

$$sat = \frac{S}{P_b} \left(K_d P_b + \Theta_w + H' \Theta_a \right)$$

Equation 7: Derivation of the Particulate Emission Factor (residential and occupation exposures)

$$PEF(m^3/kg) = Q/C \times \frac{3600s/h}{0.036 \times (1-V)(U_m/U_t)^3 \times F(x)}$$

Volatilization factors (VF) are used for volatile chemicals (defined as having a Henry's Law Constant (atm-m3/mol) greater than 10-5 and a molecular weight less than 200 grams/mol. The VF term in the soil equations is replaced in the equations with a Particulate Emission Factor (PEF) for non-volatile chemicals.

Use of the Volatilization Factor equation to predict vapor-phase concentrations of a chemical in air is not valid if free-product is present. In cases where a chemicals direct-contact screening level exceeds the chemicals theoretical saturation level, and the chemical is a liquid under ambient conditions, the direct-contact screening level is replaced with the chemicals saturation limit.

2.2 Construction/Trench Workers

Exposure assumptions for the construction/trench worker exposure scenario are summarized in Table 1. The assumed exposed skin area and soil ingestion rate are based on guidance presented in the USEPA *Exposure Factor handbook* (USEPA 1997). The inhalation rate, body weight, averaging time and target hazard quotient are set equal to assumptions used in the USEPA Region IX *Preliminary Remediation Goals* (USEPA 2002) 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 (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 that subchronic RfDs) and spreading the total exposure time over seven years is somewhat conservative but is consistent with the utility worker scenario. Due to the short exposure duration, a target risk of 1E-05 was used to calculate soil screening levels for carcinogens. A target hazard quotient of 1.0 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.

"Particulate Emission Factors (PEF)" are intended to relate the concentration of a chemical in soil to the concentration of the chemical in air-born dust. The PEF used for residential and occupational exposure scenarios (1.316E+09 mg-kg/mg/m^3) was taken directly from the USEPA *Region IX Preliminary Remediation Goals* guidance document (USEPA 2000). The PEF reflects a concentration of air-born particulate matter of approximately 0.76 ug/m^3. This PEF and associated concentration of air-born 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/m^3) corresponds to a concentration of air-born dust of approximately 700 ug/m^3.

3.0 INDOOR AIR

Target levels for indoor air were calculated based on equations incorporated into the Johnson and Ettinger Model spreadsheet published by the USEPA (USEPA 1997):

Equation 8: Residential Exposures to Carcinogenic Contaminants in Indoor Air

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

Equation 9: Occupational Exposures to Carcinogenic Contaminants in Indoor Air

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

Equation 10: Residential Exposures to Noncarcinogenic Contaminants in Indoor Air

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

Equation 11: Occupational Exposures to Noncarcinogenic Contaminants in Indoor Air

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

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 E-3 of Appendix 1.

4.0 DRINKING WATER

USEPA Region IX PRGs equations for calculation of risk-based goals for tapwater are noted below (USEPA 2002). Default parameter values are noted in Table 1. Unlike most promulgated Primary Maximum Contaminant Levels (MCLs) for drinking water, the PRG tapwater goals for volatile chemicals that take into account inhalation of vapors during showering and other activities:

Equation 12: Ingestion and Inhalation of Carcinogenic Contaminants in Tapwater

$$C(ug/L) = \frac{TR \times ATc}{EFr[(IFWadj \times CSFo) + (VFw \times InhFadj \times CSFi)]} \times 1000 ug/mg$$

Equation 13: Ingestion and Inhalation of Noncarcinogenic Contaminants in Tapwater

$$C(ug/L) = \frac{THQ \times BWa \times ATn}{EFr \times EDr\left[\left(\frac{IRWa}{RfDo}\right) + \left(\frac{VFw + IRAa}{RfDi}\right)\right]} \times 1000ug/mg$$

where VFw is the Volatilization Factor of water to air, assumed to be 0.5 L/m^3. A summary of screening levels developed through use of this model is provided in the Table F series 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, 2000, *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, 2001, Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites: U.S. Environmental Protection Agency, Solid Waste and Emergency Response, OSWER 9355.4-24, March 2001.

USEPA, 2002, Preliminary Remediation Goals: U.S. Environmental Protection Agency, Region IX, October 2002, www.epa.gov/region09/waste/sfund/prg/intro.htm.

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 $(mg/kg\text{-}d)^{-1}$	--	Chemical specific - Appendix 1, Table J
CSFi	Cancer slope factor inhaled $(mg/kg\text{-}d)^{-1}$	--	Chemical specific - Appendix 1, Table J
RfDo	Reference dose oral (mg/kg-d)	--	Chemical specific - Appendix 1, Table J
RfDi	Reference dose inhaled (mg/kg-d)	--	Chemical specific - Appendix 1, Table J
TRr/o	Target cancer risk - residential, occupational/ industrial exposure scenario	10^{-6}	USEPA 2002. See Appendix 1, Section 3.2 for exceptions
*TRctw	Target cancer risk - construction/trench worker exposure scenario	10^{-5}	HIDOH 2003
THQ	Target hazard quotient	1.0	USEPA 2002
BWa	Body weight, adult (kg)	70	RAGS (Part A), USEPA 1989 (EPA/540/1-89/002) Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
BWc	Body weight, child (kg)	15	
ATc	Average time – carcinogens (days)	25,550	RAGS (Page A), USEPA 1989 (EPA/540/1-89/002)
ATn	Average time – noncarcinogens (days)	ED*365	USEPA 2002
SAar	Exposed surface area, adult res. (cm^2/day)	5,700	Dermal Assessment, USEPA 2002 (EPA/540/R-99/005)
SAaw	Exposed surface area, adult occ. (cm^2/day)	3,300	Dermal Assessment, USEPA 2002 (EPA/540/R-99/005))
SAc	Exposed surface area, child (cm^2/day)	2,800	Dermal Assessment, USEPA 2002 (EPA/540/R-99/005))
*SAac/tw	Exposed surface area, construction/trench worker (cm^2/day)	5,800	Exposure Factors, USEPA 1997 (EPA/600/P-95/002Fa)
AFar	Adherence factor, adult res. (mg/cm^2)	0.07	Dermal Assessment, USEPA 2002 (EPA/540/R-99/005)
AFaw	Adherence factor, occupational (mg/cm^2)	0.20	Dermal Assessment, USEPA 2002 (EPA/540/R-99/005)
*AFctw	Adherence factor, construction/trench worker (mg/cm^2)	0.51	Massachusetts DEP (1994)
AFc	Adherence factor, child (mg/cm^2)	0.20	Dermal Assessment, USEPA 2002 (EPA/540/R-99/005)
ABS	Skin absorption (unitless): chemical specific	--	Dermal Assessment, USEPA 2002 (EPA/540/R-99/005)
IRAa	Inhalation rate – adult (m^3/day)	20	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
IRAc	Inhalation rate – child (m^3/day)	10	Exposure Factors, USEPA 1997 (EPA/600/P-95/002Fa)
*IRActw	Inhalation rate – construction/trench worker (m^3/day)	20	Exposure Factors, USEPA 1997 (EPA/600/P-95/002Fa)
IRWa	Drinking water ingestion – adult (L/day)	2	RAGS (Part A), USEPA 1989 (EPA/540/1-89/002)
IRWc	Drinking water ingestion – child (L/day)	1	PEA Cal-EPA (DTSC, 1994)
IRSa	Soil ingestion – adult (mg/day)	100	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
IRSc	Soil ingestion – child (mg/day)	200	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
IRSo	Soil ingestion – occupational (mg/day)	50	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
*IRSctw	Soil ingestion – construction/trench worker (mg/day)	330	USEPA 2001
EFr	Exposure frequency – residential (d/y)	350	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
EFo	Exposure frequency – occupational (d/y)	250	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
*EFctw	Exposure frequency – construction/trench worker (d/y)	20	Massachusetts DEP (1994)
EDr	Exposure duration – residential (years)	30	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
EDc	Exposure duration – child (years)	6[a]	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
EDo	Exposure duration – occupational (years)	25	Exposure Factors, USEPA 1991 (OSWER No. 9285.6-03)
*EDctw	Exposure duration – construction/trench worker (years)	7	modified from Massachusetts DEP (1994)
IFSadj	Ingestion factor, soils ([mg-yr]/[kg-d])	114	RAGS (Part B, v 1991 (OSWER No. 9285.7-01B)
SFSadj	Skin contact factor, soils ([mg-yr]/[kg-d])	361	By analogy to RAGS (Part B)
InhFadj	Inhalation factor ([m^3-yr]/[kg-d])	11	By analogy to RAGS (Part B)
IFWadj	Ingestion factor, water ([l-yr]/[kg-d])	1.1	By analogy to RAGS (Part B)
VFw	Volatilization factor for water (L/m^3)	0.5	RAGS (Part B), USEPA 1991 (OSWER No. 9285.7-01B)
PEFres/oc	Particulate emission factor (m^3/kg) - residential/occupational exposure scenarios	1.32E+09	Soil Screening Guidance (USEPA 1996a)
*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 (m3/kg)	-	Chemical specific; Soil Screening Guidance (USEPA 1996a,b)
sat	Soil saturation concentration (mg/kg)	-	Chemical specific; Soil Screening Guidance (USEPA 1996a,b)

Primary Reference: USEPA, 2002, *Preliminary Remediation Goals*: U.S. Environmental Protection Agency, Region IX, October 2002,
a Exposure duration for lifetime residents is assumed to be 30 years total. For carcinogens, exposures are combined for children (6 years) and adults (24 years).
* This document only. Not presented in USEPA Region IX PRGs.

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	Inverse of the mean conc. at the center of a 0.5-acre square source (g/m^2-s per kg/m^3)	68.81
T	Exposure interval (s)	9.5×10^8
rho_b	Dry soil bulk density (g/cm^3)	1.5
$theta_a$	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)
$theta_w$	Water-filled soil porosity (L_{water}/L_{soil})	0.15
rho_s	Soil particle density (g/cm^3)	2.65
Di	Diffusivity in air (cm^2/s)	Chemical-specific
H	Henry's Law constant (atm-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 (cm3/g) = Koc x foc	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)	1.316×10^9
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

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	tons/mo-acre	USEPA 1974, 1985
	2400	lbs/mo-acre	conversion
	1089	kgs/mo-acre	conversion
Volume Air Passing Over Site Per Month Per Acre (V_{air}):			
Length Perpendicular To Wind (L):	1	acre	Default EF area
	43560	ft^2	conversion
	4047	m^2	conversion
	64	m	L=Area^0.5
Air Mixing Zone Height (MZ):	2	m	model assumption
Ave Wind Speed (V):	4.69	m/s	USEPA 2000 (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=LxMZxVxS
Average Concentration Dust in Air ($C_{dust\text{-}air}$):			
Concentration Dust ($C_{dust\text{-}air}$)	6.95E-07	kg/m^3	(Cair = M_{dust}/Volume-air)
	0.695	mg/m^3	conversion
Particulate Emission Factor (PEF):			
Concentration soil in dust ($C_{dust\text{-}soil}$):	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=$C_{dust\text{-}soil}$/$C_{dust\text{-}air}$

Attachment

Text of USEPA Region IX Preliminary Remediation Goals Document (October 2002)

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION IX
75 Hawthorne Street
San Francisco, CA 94105

October 1, 2002

Subject: Region 9 PRGs Table 2002 Update

From: Stanford J. Smucker, Ph.D.
Regional Toxicologist (SFD-8-B)
Technical Support Team

To: PRGs Table Users

With this cover letter, we announce the update to the Region 9 PRGs table for 2002. The PRGs table contains over 600 preliminary remediation goals (PRGs) for contaminants in soil, air, and tap water. Region 9 PRGs are risk-based concentrations that are intended to assist risk assessors and others in initial screening-level evaluations of environmental measurements.

As their name implies, Region 9 PRGs may also be viewed as preliminary cleanup goals for an individual chemical, but in this context, they are best viewed as dynamic and subject to change because they are generic and based on direct contact exposures which may not address site-specific conditions and/or indirect exposure pathways at sites (See Exhibit 1-1 in "Region 9 PRGs Table Users Guide/Technical Background Document"). Also for planning purposes, these human health based PRGs should always be considered in conjunction with ARAR-based PRGs (e.g. MCLs), ecological benchmarks, and "background" conditions before establishing a final cleanup level for a particular site.

You can find the PRGs 2002 table, InterCalc tables, "Region 9 PRGs Table Users Guide/Technical Background Document", and additional helpful toxicological and risk assessment information at:

http://www.epa.gov/region09/waste/sfund/prg/ .

We view risk-based PRGs as "evergreen". Ongoing changes to the PRGs reflect continuing improvements in our scientific knowledge base and state-of-the-art approaches to risk assessment. In the new *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites* (Supplemental SSL Guidance, EPA 2001a), two different soil ingestion rates are assumed for non-construction workers: 100 mg/day is assumed for outdoor workers whereas 50 mg/day is assumed for indoor workers. The default value of 100 mg/day for outdoor workers is also recommended by EPA's Technical Review Workgroup for Lead (TRW), and it reflects increased exposures to soils for outdoor workers relative to their indoor counterparts. For more on this, please see Section 4.1 of the "Region 9 PRGs Table Users Guide/Technical Background Document" or refer to the Supplemental SSL Guidance available at the following website:

http://www.epa.gov/superfund/resources/soil/index.htm

Because the Region 9 PRGs are generic and intended for screening sites early in the investigation process (often before site-specific information is available), we have chosen to use the 100 mg/day soil ingestion (i.e. outdoor worker) assumption to calculate industrial soil PRGs. Please note that previous issues of the Region 9 PRGs table assumed 50 mg/day soil ingestion rate for workers. This change in soil ingestion rates is reflected in a somewhat lower (more stringent) industrial soils PRG for many contaminants. The appropriateness of this assumption for a particular site may be evaluated when additional information becomes available regarding site conditions or site development.

In addition to changes in exposure factor assumptions, several chemicals have new or revised toxicity values that results in changes to the PRG calculations. To facilitate the users review, chemicals with new and revised toxicological criteria are presented in bold in the 2002 table and also listed here for convenience: **acetonitrile, benzyl chloride, boron, bromate, 1,3-butadiene, 1-butanol, butylbenzenes, cacodylic acid, cadmium (California State value), chloroform, chloronitrobenzenes, chrysene (California State value), cobalt, 1,2-dibromo-3-chloropropane (California State value), 1,1-dichloroethylene, diethylene glycol ethers, diethylformamide, dinitrobenzenes, di-n-octyl phthalate, diphenyl sulfone, ethylbenzene, HCH, hexachlorocyclopentadiene, kepone, lead (California State value), MTBE, 2-nitroaniline, carcinogenic PAHs, perchlorate, polychlorinated terphenyls, benzo(k)fluoranthene (California State value), propylbenzene, propylene glycol, quinoline, tetrachloroethylene, tetrahydrofuran, thiocyanate, 1,1,1-trichloroethane, trichloroethylene, 2,4,6-trichlorophenol, 1,2,3-trichloropropane, triphenylphosphine oxide, tris(2-chloroethyl) phosphate, vinyl chloride, and xylene.**

Also in this update to the "Region 9 PRGs Table User's Guide/Technical Background Document", we have added a brief discussion of special case chemicals for which an alternate approach was applied in the derivation of the Region 9 PRGs (Section 2.3). Increasingly, chemical-specific approaches are being used that do not lend themselves to a single PRG model. Special case chemicals that are discussed include: cadmium, chromium 6, lead, manganese, nitrate/nitrite, thallium, and vinyl chloride.

Finally it should be recognized by all that use the PRGs table that not all PRG values in the table are "created equal". For some chemicals, a robust data set exists upon which the toxicological criteria are based whereas for others, there may be relatively few studies that form the basis of the PRG calculation. Also, PRGs for some chemicals are based on withdrawn toxicity values or route-extrapolated values. Withdrawn and route-extrapolated numbers are shown in the table because we still need to deal with these contaminants during the long delays before replacement numbers are ready. Please consult with your toxicologist or agency risk assessor to best address potential uncertainties associated with chemical-specific PRGs, especially if the chemical is a risk driver at your site.

As with any risk-based tool, there exists the potential for misuse. We try to highlight potential problems in Section 3.8. However, it should be noted that the use of PRGs at a particular site becomes the responsibility of the user. It is recommended that the user verify the numbers with an agency toxicologist or risk assessor because the toxicity / exposure information in the table may contain errors or default assumptions that need to be refined based on further evaluation. If you find an error please send me a note via email at smucker.stan@epa.gov.

DISCLAIMER

Preliminary remediation goals (PRGs) focus on common exposure pathways and may not consider all exposure pathways encountered at CERCLA / RCRA sites (Exhibit 1-1). PRGs do not consider impact to groundwater or address ecological concerns. The PRG table is specifically not intended as a (1) stand-alone decision-making tool, (2) as a substitute for EPA guidance for preparing baseline risk assessments, (3) a rule to determine if a waste is hazardous under RCRA, or (4) set of final cleanup or action levels to be applied at contaminated sites.

The guidance set out in this document is not final Agency action. It is not intended, nor can it be relied upon to create any rights enforceable by any party in litigation with the United States. EPA officials may decide to follow the guidance provided herein, or act at variance with the guidance, based on an analysis of specific circumstances. The Agency also reserves the right to change this guidance at any time without public notice.

1.0 INTRODUCTION

Region 9 Preliminary Remediation Goals (PRGs) are risk-based tools for evaluating and cleaning up contaminated sites. They are being used to streamline and standardize all stages of the risk decision-making process.

The Region 9 PRG table combines current EPA toxicity values with "standard" exposure factors to estimate contaminant concentrations in environmental media (soil, air, and water) that the agency considers protective of humans (including sensitive groups), over a lifetime. Chemical concentrations above these levels would not automatically designate a site as "dirty" or trigger a response action. However, exceeding a PRG suggests that further evaluation of the potential risks that may be posed by site contaminants is appropriate. Further evaluation may include additional sampling, consideration of ambient levels in the environment, or a reassessment of the assumptions contained in these screening-level estimates (e.g. appropriateness of route-to-route extrapolations, appropriateness of using chronic toxicity values to evaluate childhood exposures, appropriateness of generic exposure factors for a specific site etc.).

The PRG concentrations presented in the table can be used to screen pollutants in environmental media, trigger further investigation, and provide an initial cleanup goal if applicable. When considering PRGs as cleanup goals, residential concentrations should be used for maximum beneficial uses of a property. Industrial concentrations are included in the table as an alternative cleanup goal for soils. **In general, it recommended that industrial PRGs not be used for screening sites unless they are used in conjunction with residential values.**

Before applying PRGs as screening tools or initial goals, the user of the table should consider whether the exposure pathways and exposure scenarios at the site are fully accounted for in the PRG calculations. Region 9 PRG concentrations are based on direct contact pathways for which generally accepted methods, models, and assumptions have been developed (i.e. ingestion, dermal contact, and inhalation) for specific land-use conditions and do not consider impact to groundwater or ecological receptors (see Developing a Conceptual Site Model below).

EXHIBIT 1-1
TYPICAL EXPOSURE PATHWAYS BY MEDIUM
FOR RESIDENTIAL AND INDUSTRIAL LAND USES[a]

EXPOSURE PATHWAYS, ASSUMING:		
MEDIUM	RESIDENTIAL LAND USE	INDUSTRIAL LAND USE
Ground Water	***Ingestion from drinking***	Ingestion from drinking
	Inhalation of volatiles	Inhalation of volatiles
	Dermal absorption from bathing	Dermal absorption
Surface Water	***Ingestion from drinking***	Ingestion from drinking
	Inhalation of volatiles	Inhalation of volatiles
	Dermal absorption from bathing	Dermal absorption
	Ingestion during swimming	
	Ingestion of contaminated fish	
Soil	***Ingestion***	***Ingestion***
	Inhalation of particulates	***Inhalation of particulates***
	Inhalation of volatiles	***Inhalation of volatiles***
	Exposure to indoor air from soil gas	Exposure to indoor air from soil gas
	Exposure to ground water contaminated by soil leachate	Exposure to ground water contaminated by soil leachate
	Ingestion via plant, meat, or dairy products	Inhalation of particulates from trucks and heavy equipment
	Dermal absorption	***Dermal absorption***

Footnote:
[a]Exposure pathways considered in the PRG calculations are indicated in boldface italics.

2.0 READING THE PRG TABLE

2.1 General Considerations

With the exceptions described below, PRGs 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. PRG concentrations that equate to a 10^{-6} cancer risk are indicated by "ca". PRG concentrations that equate to a hazard quotient of 1 for noncarcinogenic concerns are indicated by "nc".

If the risk-based concentrations are to be used for site screening, it is recommended that both cancer and noncancer-based PRGs be used. Both carcinogenic and noncarcinogenic values may be obtained at the Region 9 PRG homepage at:

http://www.epa.gov/region09/waste/sfund/prg/

It has come to my attention that some users have been multiplying the cancer PRG 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. For carcinogens, I have indicated by asterisk ("ca*") in the PRG table where the noncancer PRGs would be exceeded if the cancer value that is displayed is multiplied by 100. Two stars ("ca**") indicate that the noncancer values would be exceeded if the cancer PRG were multiplied by 10. There is no range of "acceptable" noncarcinogenic "risk" so that under no circumstances should noncancer PRGs be multiplied by 10 or 100, when setting final cleanup criteria. In the rare case where noncancer PRGs are more stringent than cancer PRGs set at one-in-one-million risk, a similar approach has been applied (e.g. "nc**").

In general, PRG concentrations in the printed table are risk-based but for soil there are two important exceptions: (1) for several volatile chemicals, PRGs are based on the soil saturation equation ("sat") and (2) for relatively less toxic inorganic and semivolatile contaminants, a non-risk based "ceiling limit" concentration is given as 10^{+5} mg/kg ("max"). At the Region 9 PRG website, the risk-based calculations for these same chemicals are also available in the "InterCalc Tables" if the user wants to view the risk-based concentrations prior to the application of "sat" or "max". For more information on why the "sat" value and not a risk-based value is presented for several volatile chemicals in the PRGs table, please see the discussion in Section 4.5.

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 PRG 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 PRG by 1/10th). If scaling is necessary, PRG users can do

this simply by referring to the "InterCalc Tables" at our website where risk-based soil concentrations are presented for all chemicals (see soil calculations, "combined" pathways column).
In spite of the fact that applying a ceiling limit is not a universally accepted approach, we have opted to continue applying a "max"soil concentration to the PRGs table for the following reasons:

- Risk-based PRGs 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 windborne dispersion assumptions) due to the presence of the foreign substance itself.
- PRGs currently do not address short-term exposures (e.g. pica children and construction workers). Although extremely high soil PRGs 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.

In addition to Region 9 PRG values, the PRGs table also includes California EPA PRGs ("CAL-Modified PRGs") for specific chemicals where CAL-EPA screening values may be "significantly" more restrictive than the federal values (see Section 2.4) and EPA OSWER soil screening levels (SSLs) for protection of groundwater (see Section 2.5).

2.2 Toxicity Values

Hierarchy of Toxicity Values

EPA toxicity values, known as noncarcinogenic reference doses (RfD) and carcinogenic slope factors (SF) were obtained from IRIS, NCEA through September 2002, and HEAST (1997). The priority among sources of toxicological constants in order of preference is as follows: (1) IRIS (indicated by "i"), (2) NCEA ("n"), (3) HEAST ("h"), (4) withdrawn from IRIS or HEAST and under review ("x") or obtained from other EPA documents ("o"). This hierarchy is subject to change once the HEAST tables are updated.

Inhalation Conversion Factors

As of January 1991, IRIS and NCEA databases no longer present RfDs or SFs for the inhalation route. These criteria have been replaced with reference concentrations (RfC) for noncarcinogenic effects and unit risk factors (URF) for carcinogenic effects. However, for purposes of estimating risk and calculating risk-based concentrations, inhalation reference doses (RfDi) and inhalation slope factors (SFi) are preferred. This is not a problem for most chemicals because the inhalation toxicity criteria are easily converted. To calculate an RfDi from an RfC, the following equation and assumptions may be used for most chemicals:

$$RfDi\ \frac{mg}{(kg\text{-}day)} = RfC\,(mg/m^3) \times \frac{20m^3}{day} \times \frac{1}{70kg}$$

Likewise, to calculate an SFi from an inhalation URF, the following equation and assumptions may be used:

$$SFi\ \frac{(kg\text{-}day)}{(mg)} = URF(m^3/ug) \times \frac{day}{20m^3} \times 70kg \times \frac{10^3\ ug}{mg}$$

Substances with New or Withdrawn Toxicity Values

To help users rapidly identify substances with new or revised toxicity values, these chemicals are listed in boldface type in the PRGs table. This issue of the table contains new or revised toxicity values for: **acetonitrile, benzyl chloride, boron, bromate, 1,3-butadiene, 1-butanol, butylbenzenes, cacodylic acid, cadmium (California State value), chloroform, chloronitrobenzenes, chrysene (California State value), cobalt, 1,2-dibromo-3-chloropropane (California State value), 1,1-dichloroethylene, diethylene glycol ethers, diethylformamide, dinitrobenzenes, di-n-octyl phthalate, diphenyl sulfone, ethylbenzene, HCH, hexachlorocyclopentadiene, kepone, lead (California State value), MTBE, 2-nitroaniline, carcinogenic PAHs, perchlorate, polychlorinated terphenyls, benzo(k)fluoranthene (California State value), propylbenzene, propylene glycol, quinoline, tetrachloroethylene, tetrahydrofuran, thiocyanate, 1,1,1-trichloroethane, trichloroethylene, 2,4,6-trichlorophenol, 1,2,3-trichloropropane, triphenylphosphine oxide, tris(2-chloroethyl) phosphate, vinyl chloride, and xylene.**

Chemicals that have been delisted because they are outdated, undocumented, or derived from a data base other than IRIS, HEAST or NCEA include: acifluorfen, 4-bromophenyl phenyl ether, chloroacetaldehyde, 2-chloroethyl vinyl ether, hexachlorodibenzo-p-dioxin mixture (HxCDD), maneb, methyl chlorocarbonate, nitrapyrin, nitric oxide, and 4-nitrophenol.

Route-to-Route Methods

Route-to-route extrapolations ("r") were frequently used when there were no toxicity values available for a given route of exposure. Oral cancer slope factors ("SFo") and reference doses ("RfDo") were used for both oral and inhaled exposures for organic compounds lacking inhalation values. Inhalation slope factors ("SFi") and inhalation reference doses ("RfDi") were used for both inhaled and oral exposures for organic compounds lacking oral values. Route extrapolations were not performed for inorganics due to portal of entry effects and known differences in absorption efficiency for the two routes of exposure.

An additional route extrapolation is the use of oral toxicity values for evaluating dermal exposures. For many chemicals, a scientifically defensible data base does not exist for making an adjustment to the oral slope factor/RfD to estimate a dermal toxicity value. Based on the current guidance (USEPA 2001b), the only chemical for which an adjustment is recommended is cadmium. An oral absorption efficiency of 5% is assumed for cadmium which leads to an estimated dermal reference dose (RfDd) of 2.5E-05 that was used in the soil PRG calculations for cadmium.

Although route-to-route methods may be a useful screening procedure, the appropriateness of these default assumptions for specific contaminants should be verified by a toxicologist or regional risk assessor. Please note that whenever route-extrapolated values are used to calculate risk-based PRGs, additional uncertainties are introduced in the calculation.

2.3 Region 9 PRGs Derived with Special Considerations

Most of the Region 9 PRGs are readily derived by referring to Equations 4-1 thru 4-8 contained in this "User's Guide/Technical Background Document" to the Region 9 PRGs. However, there are some chemicals for which the standard equations do no apply and/or adjustments to the toxicity values are recommended. These special case chemicals are discussed below.

Cadmium The PRGs 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 PRGs are considered screening values, we elected to use the more conservative RfD 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.

The water RfD for cadmium assumes a 5% oral absorption factor. The assumption of an oral absorption efficiency of 5% for Cadmium leads to an estimated dermal RfD of 2.5E-05. The PRG calculations incorporate these adjustments per recent guidance (USEPA 2001b).

Chromium 6 For Chromium 6 (Cr6), IRIS shows an air unit risk of 1.2E-2 per (ug/cu.m) or expressed as an inhalation cancer slope factor (adjusting for inhalation/body weight) of 42 $(mg/kg\text{-}day)^{-1}$. However, the supporting documentation in the IRIS file states that these toxicity values are based on an assumed 1:6 ratio of Cr6:Cr3. Because of this assumption, we in Region 9 prefer to present PRGs based on these cancer toxicity values as "total chromium" numbers.

In the PRG tables, we also include a Cr6 specific value (assuming 100% Cr6) that is derived by multiplying the "total chromium" value by 7, yielding a cancer potency factor of 290 $(mg/kg\text{-}day)^{-1}$. This is considered to be an overly conservative assumption by some within the Agency. However, this calculation is also consistent with the State of California's interpretation of the Mancuso study that forms the basis of Cr6's toxicity values.

If you are working on a project outside of California (and outside of Region 9), you may want to contact the appropriate regulatory officials to determine what their position is on this issue. As mentioned, Region 9 also includes PRGs for "total chromium" which is based on the same ratio (1:6 ratio Cr6:Cr3) that forms the basis of the cancer slope factor of 42 $(mg/kg\text{-}day)^{-1}$ presented in IRIS.

Lead Residential PRGs for Lead (Region 9 EPA and California EPA) are derived based on pharmacokinetic models. Both EPA's Integrated Exposure Uptake Biokinetic (IEUBK) Model and California's LeadSpread model are designed to predict the probable blood lead concentrations for children between six months and seven years of age who have been exposed to lead through various sources (air, water, soil, dust, diet and *in utero* contributions from the mother). Run in the reverse, these models also allow the user to calculate lead PRGs that are considered "acceptable" by EPA or the State of California.

The California LeadSpread model can also estimate PRGs for non-residential exposures (e.g. worker) whereas EPA uses a second Adult Lead Model to estimate PRGs for an industrial setting.

For more information on EPA' Lead models used to estimate residential and industrial PRGs, please refer to the following website:

http://www.epa.gov/oerrpage/superfund/programs/lead/

For more information on California's LeadSpread Model and Cal-Modified PRGs for lead, please go to:
http://www.dtsc.ca.gov/ScienceTechnology/ledspred.html

Manganese The IRIS RfD (0.14 mg/kg-day) includes manganese from all sources, including diet. The author of the IRIS assessment for manganese recommends 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 is applied in the derivation of the Region 9 PRGs for soil and water. For more information regarding the Manganese RfD, you may want to contact Dr. Bob Benson at (303) 312-7070.

Nitrates/Nitrates Tap water PRGs for Nitrates/Nitrites are based on the MCL as there is no available RfD for these compounds. For more information, please see IRIS at:
http://www.epa.gov/iriswebp/iris/index.html

Thallium IRIS has many values for the different salts of thallium. However, our analytical data packages typically report "thallium". Therefore, as a practical matter it makes more sense to report a PRG for plain thallium. We have done this by making the adjustment contained in the IRIS file for thallium sulfate based on the molecular weight of the thallium in the thallium salt. The adjusted oral RfD for plain thallium is 6.6 E-05 mg/kg-day which we use to calculate a thallium PRG.

Vinyl Chloride In EPA's recent reassessment of vinyl chloride toxicity, IRIS presents two cancer slope factors for vinyl chloride (VC): one that is intended to be applied towards evaluating adult risks and a second more protective slope factor that takes into account the unique susceptibility of developing infants and young children. For residential PRGs, the Region 9 PRGs table applies the more conservative cancer potency factor that addresses exposures to both children and adults whereas for the industrial soils PRG, the adult only cancer slope factor is applied.

Because of the age-dependent vulnerability associated with vinyl chloride exposures, and due to the method that is applied in deriving the cancer slope factor for VC, an assumption of a 70 year exposure over the lifetime is assumed, consistent with the way that the toxicity value for VC was derived. Therefore, instead of the usual exposure assumption of 6 years as a child and 24 years as an adult that is assumed for carcinogenic substances, we have revised the exposure assumption for VC to 6 years as a child and 64 years as adult. Since most of the cancer risk is associated with the first 30 years of exposure to VC, there is actually little difference between a 30 year exposure assumption (typically assumed for Superfund risk assessments) and the 70 year exposure assumption that is assumed in calculating the PRG for VC.

2.4 "Cal-Modified PRGs"

When EPA Region 9 first came out with a Draft of the PRGs table in 1992, there was concern expressed by California EPA's Department of Toxic Substances and Control (DTSC) that for some chemicals the risk-based concentrations calculated using Cal-EPA toxicity values were "significantly" more protective than the risk-based PRGs calculated by Region 9. At an interagency meeting

comprised of mostly toxicologists, it was agreed that PRG values are at best order-of-magnitude estimates, so that if we assume a logarithmic scale, then a difference greater than 3.3 (½ log above or below) would be considered a significant difference. Therefore, for individual chemicals where California PRG values are significantly more protective than Region 9 EPA PRGs, Cal-Modified PRGs are included in the Region 9 PRGs table. For more information on Cal-Modified PRGs, the reader may want to contact Dr. Michael Wade in Cal-EPA's Department of Toxic Substances (DTSC) at (916) 255-6653.

Please note that in the State of California, Cal-Modified PRGs should be used as screening levels for contaminated sites because they are more stringent than the Federal numbers.

2.5 Soil Screening Levels

Generic, soil screening levels (SSLs) for the protection of groundwater have been included in the PRG table for 100 of the most common contaminants at Superfund sites. Generic SSLs are derived using default values in standardized equations presented in EPA OSWER's *Soil Screening Guidance* series, available on the web at http://www.epa.gov/superfund/resources/soil/index.htm .

The SSLs were developed using a default dilution-attenuation factor (DAF) of 20 to account for natural processes that reduce contaminant concentrations in the subsurface. Also included are generic SSLs that assume no dilution or attenuation between the source and the receptor well (i.e., a DAF of 1). These values can be used at sites where little or no dilution or attenuation of soil leachate concentrations is expected at a site (e.g., sites with shallow water tables, fractured media, karst topography, or source size greater than 30 acres).

In general, if an SSL is not exceeded for the migration to groundwater pathway, the user may eliminate this pathway from further investigation.

It should be noted that in the State of California, the California Regional Water Quality Control Board has derived "California SSLs" for a number of pathways including migration to groundwater. These are not included in the Region 9 PRGs table, but may be accessed at the following website:

http://www.swrcb.ca.gov/rwqcb2/rbsl.htm

Or, for more information on the "California SSLs", please contact Dr Roger Brewer at: (510) 622-2374.

2.6 Miscellaneous

Volatile organic compounds (VOCs) are indicated by "1" in the VOC column of the table and in general, are defined as those chemicals having a Henry's Law constant greater than 10^{-5} (atm-m^3/mol) and a molecular weight less than 200 g/mole). Three borderline chemicals (dibromochloromethane, 1,2-dibromochloropropane, and pyrene) which do not strictly meet these criteria of volatility have also been included based upon discussions with other state and federal agencies and after a consideration of vapor pressure characteristics etc. Volatile organic chemicals are evaluated for potential volatilization from soil/water to air using volatilization factors (see Section 4.1).

Chemical-specific dermal absorption values for contaminants in soil and dust are presented for arsenic, cadmium, chlordane, 2,4-D, DDT, lindane, TCDD, PAHs, PCBs, and pentachlorophenols as recommended in the "Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Interim Guidance" (USEPA 2001b). Otherwise, default skin absorption fractions are assumed to be 0.10 for nonvolatile organics. Please note that previous defaults of 0.01 and 0.10 for inorganics and VOCs respectively, have been withdrawn per new guidance.

3.0 USING THE PRG TABLE

The decision to use PRGs at a site will be driven by the potential benefits of having generic risk-based concentrations in the absence of site-specific risk assessments. The original intended use of PRGs was to provide initial cleanup goals for individual chemicals given specific medium and land-use combinations (see RAGS Part B, 1991), however risk-based concentrations have several applications. They can also be used for:

- Setting health-based detection limits for chemicals of potential concern
- Screening sites to determine whether further evaluation is appropriate
- Calculating cumulative risks associated with multiple contaminants

A few basic procedures are recommended for using PRGs properly. These are briefly described below. Potential problems with the use of PRGs are also identified.

3.1 Developing a Conceptual Site Model

The primary condition for use of PRGs is that exposure pathways of concern and conditions at the site match those taken into account by the PRG framework. Thus, it is always 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 PRGs at the site and the need for additional information. For those pathways not covered by PRGs, a risk assessment specific to these additional pathways may be necessary. Nonetheless, the PRG lookup values will still be useful in such situations for focusing further investigative efforts on the exposure pathways not addressed.

To develop a site-specific CSM, perform an extensive records search and compile existing data (e.g. available site sampling data, historical records, aerial photographs, and hydrogeologic information). Once this information is obtained, CSM worksheets such as those provided in ASTM's *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites* (1995) can be used to tailor the generic worksheet model to a site-specific CSM. The final CSM diagram represents linkages among contaminant sources, release mechanisms, exposure pathways and routes and receptors. It summarizes our understanding of the contamination problem.

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

- Are there potential ecological concerns?
- Is there potential for land use other than those covered by the PRGs (that is, residential and industrial)?

- Are there other likely human exposure pathways that were not considered in development of the PRGs (e.g. impact to groundwater, local fish consumption, raising beef, dairy, or other livestock)?

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

If any of these four conditions exist, the PRG may need to be adjusted to reflect this new information. Suggested websites for the evaluation of pathways not currently addressed by Region 9 PRG's are presented in Exhibit 3-1.

EXHIBIT 3-1
SUGGESTED WEBSITES FOR EVALUATING EXPOSURE PATHWAYS NOT CURRENTLY ADDRESSED BY REGION 9 PRGs

EXPOSURE PATHWAY	WEBSITE
Migration of contaminants to an underlying potable aquifer	EPA Soil Screening Guidance: http://www.epa.gov/superfund/resources/soil/index.htm California Water Board Guidance: http://www.swrcb.ca.gov/rwqcb2/rbsl.htm
Ingestion via plant uptake	EPA Soil Screening Guidance: http://www.epa.gov/superfund/resources/soil/index.htm EPA Fertilizer Risk Assessment: http://www.epa.gov/epaoswer/hazwaste/recycle/fertiliz/risk/
Ingestion via meat, dairy products, human milk	EPA Protocol for Combustion Facilities: http://www.epa.gov/epaoswer/hazwaste/combust/riskvol.htm#volume1 California "Hot Spots" Risk Guidelines: http://www.oehha.ca.gov/air/hot_spots/HRSguide.html
Inhalation of volatiles that have migrated into basements or other enclosed spaces.	EPA's Version of Johnson & Ettinger Model: http://www.epa.gov/oerrpage/superfund/programs/risk/airmodel/johnson_ettinger.htm
Ecological pathways	EPA Ecological Soil Screening Guidance: http://www.epa.gov/superfund/programs/risk/ecorisk/ecossl.htm NOAA Sediment Screening Table: http://response.restoration.noaa.gov/cpr/sediment/squirt/squirt.html

3.2 Background Levels Evaluation

A necessary step in determining the applicability of Region 9 risk-based PRGs is the consideration of background contaminant concentrations. There is new EPA guidance on determining background at sites. *Guidance for Characterizing Background Chemicals in Soil at Superfund Sites* (USEPA 2001c) is available on the web at: http://www.epa.gov/superfund/programs/risk/background.pdf .

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. Before embarking on an extensive sampling and analysis program to determine local background concentrations in the area, one should first compile existing data on the subject. Far too often there is pertinent information in the literature that gets ignored, resulting in needless expenditures of time and money.

Generally EPA does not clean up below natural background. In some cases, the predictive risk-based models generate PRG levels that lie within or even below typical background. If natural background concentrations are higher than the risk-based PRGs, an adjustment of the PRG is probably needed. Exhibit 3-2 presents summary statistics for selected elements in soils that have background levels that may exceed risk-based PRGs. An illustrative example of this is naturally occurring arsenic in soils which frequently is higher than the risk-based concentration set at a one-in-one-million cancer risk (the PRG for residential soils is 0.39 mg/kg). After considering background concentrations in a local area, EPA Region 9 has at times used the non-cancer PRG (22 mg/kg) to evaluate sites recognizing that this value tends to be above background levels yet still falls within the range of soil concentrations (0.39-39 mg/kg) that equates to EPA's "acceptable" cancer risk range of 10E-6 to 10E-4.

Where anthropogenic "background" levels exceed PRGs 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.

EXHIBIT 3-2
BACKGROUND CONCENTRATIONS OF SELECTED ELEMENTS IN SOILS

TRACE	U.S. STUDY DATA[1]			CALIFORNIA DATA[2]		
ELEMENT	Range	GeoMean	ArMean	Range	GeoMean	ArMean
Arsenic	<.1-97	5.2 mg/kg	7.2 mg/kg	0.59-11	2.75 mg/kg	3.54 mg/kg
Beryllium	<1-15	0.63 "	0.92 "	0.10-2.7	1.14 "	1.28 "
Cadmium	<1-10	--	<1	0.05-1.7	0.26	0.36
Chromium	1-2000	37	54	23-1579	76.25	122.08
Nickel	<5-700	13	19	9.0-509	35.75	56.60

[1]Shacklette and Hansford, "Element Concentrations in Soils and Other Surficial Materials of the Conterminous United States",USGS Professional Paper 1270, 1984.

[2]Bradford et. al, "Background Concentrations of Trace and Major Elements in California Soils", Kearney Foundation Special Report, UC-Riverside and CAL-EPA DTSC, March 1996.

3.3 Screening Sites with Multiple Pollutants

A suggested stepwise approach for PRG-screening of sites with multiple pollutants is as follows:

- Perform an extensive records search and compile existing data.

- Identify site contaminants in the PRG table. Record the PRG concentrations for various media and note whether PRG is based on cancer risk (indicated by "ca") or noncancer hazard (indicated by "nc"). Segregate cancer PRGs from non-cancer PRGs and exclude (but don't eliminate) non-risk based PRGs ("sat" or "max").

- For cancer risk estimates, take the site-specific concentration (maximum or 95 UCL) and divide by the PRG concentrations that are designated for cancer evaluation ("ca"). 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:

$$Risk = \left[\left(\frac{conc_x}{PRG_x}\right) + \left(\frac{conc_y}{PRG_y}\right) + \left(\frac{conc_z}{PRG_z}\right) \right] \times 10^{-6}$$

- For non-cancer hazard estimates. Divide the concentration term by its respective non-cancer PRG designated as "nc" 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 PRG that is not listed in the printed copy of the table sent to folks on the mailing list. To obtain these values, the user should view or download the PRG table at our website and display the appropriate sections.]**

$$Hazard\ Index = \left[\left(\frac{conc_x}{PRG_x}\right) + \left(\frac{conc_y}{PRG_y}\right) + \left(\frac{conc_z}{PRG_z}\right) \right]$$

For more information on screening site risks, the reader should contact EPA Region 9's Technical Support Team.

3. 4 Potential Problems

As with any risk-based tool, the potential exists for misapplication. In most cases the root cause will be a lack of understanding of the intended use of Region 9 PRGs. In order to prevent misuse of PRGs, the following should be avoided:

- Applying PRGs to a site without adequately developing a conceptual site model that identifies relevant exposure pathways and exposure scenarios,

- Not considering background concentrations when choosing PRGs as cleanup goals,

- Use of PRGs as cleanup levels without the nine-criteria analysis specified in the

National Contingency Plan (or, comparable analysis for programs outside of Superfund),

- Use of PRGs as cleanup levels without verifying numbers with a toxicologist or regional risk assessor,

Use of antiquated PRG tables that have been superseded by more recent publications,

- Not considering the effects of additivity when screening multiple chemicals, and

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

4.0 TECHNICAL SUPPORT DOCUMENTATION

Region 9 PRGs consider human exposure hazards to chemicals from contact with contaminated soils, air, and water. The emphasis of the PRG equations and technical discussion are aimed at developing screening criteria for soils, since this is an area where few standards exist. For air and water, additional reference concentrations or standards are available for many chemicals (e.g. MCLs, non-zero MCLGs, AWQC, and NAAQS) and consequently the discussion of these media are brief.

4.1 Soils - Direct Ingestion

Calculation of risk-based PRGs for direct ingestion of soil is based on methods presented in RAGS HHEM, Part B (USEPA 1991a) and *Soil Screening Guidance* (USEPA 1996a,b, USEPA 2001a). Briefly, these methods backcalculate a soil concentration level from a target risk (for carcinogens) or hazard quotient (for noncarcinogens).

<u>Residential Soil PRGs</u>

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). To take into account the higher soil intake rate for children, two different approaches are used to estimate PRGs, depending on whether the adverse health effect is cancer or some effect other than cancer.

For carcinogens, the method for calculating PRGs 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 31 years old. 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 USEPA RAGs Part B (1991a).

For noncarcinogenic concerns, the more protective method of calculating a soil PRG is to evaluate childhood exposures separately from adult exposures. In other words, an age-adjustment factor is not applied as was done for carcinogens. This approach is considered conservative because it combines the higher 6-year exposure for children with chronic toxicity criteria. In their analysis of the method, the Science Advisory Board (SAB) indicated that, for most chemicals, the approach may be overly

protective. However, they noted that there are specific instances when the chronic RfD may be based on endpoints of toxicity that are specific to children (e.g. fluoride and nitrates) or when the dose-response is steep (i.e., the dosage difference between the no-observed-adverse-effects level [NOAEL] and an adverse effects level is small). Thus, for the purposes of screening, EPA Region 9 has adopted this approach for calculating soil PRGs for noncarcinogenic health concerns.

Industrial Soil PRGs

In the new *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites* (Supplemental SSL Guidance, EPA 2001a), two different soil ingestion rates are assumed for non-construction workers: 100 mg/day is assumed for outdoor workers whereas 50 mg/day is assumed for indoor workers. The default value of 100 mg/day for outdoor workers is also recommended by EPA's Technical Review Workgroup for Lead (TRW), and it reflects increased exposures to soils for outdoor workers relative to their indoor counterparts. For more on this, please see the Supplemental SSL Guidance available at the following website:

http://www.epa.gov/superfund/resources/soil/index.htm

Because the Region 9 PRGs are generic and intended for screening sites early in the investigation process (often before site-specific information is available), we have chosen to use the 100 mg/day soil ingestion (i.e. outdoor worker) assumption to calculate industrial soil PRGs. Please note that previous issues of the Region 9 PRGs table assumed 50 mg/day soil ingestion rate for workers. This change in soil ingestion rates is reflected in a somewhat lower (more stringent) industrial soils PRG for many contaminants. The appropriateness of this assumption for a particular site may be evaluated when additional information becomes available regarding site conditions or site development.

4.2 Soils - Vapor and Particulate Inhalation

Agency toxicity criteria indicate that risks from exposure to some chemicals via inhalation far outweigh the risk via ingestion; therefore soil PRGs have been designed to address this pathway as well. The models used to calculate PRGs for inhalation of volatiles/particulates are updates of risk assessment methods presented in RAGS Part B (USEPA 1991a) and are identical to the *Soil Screening Guidance: User's Guide and Technical Background Document* (USEPA 1996a,b).

It should be noted that the soil-to-air pathway that is evaluated in the PRGs calculations is based on direct inhalation exposures that result from the volatilization or particulate emissions of chemicals from soil to outdoor air. The soil PRG calculations currently do not evaluate potential for volatile contaminants in soil to migrate indoors. For this evaluation, a site-specific assessment is required because the applicable model, the Johnson and Ettinger model, is extremely sensitive to a number of model parameters that do not lend themselves to standardization on a national basis. For more information on the indoor air model and/or to download a copy, please go to:

http://www.epa.gov/oerrpage/superfund/programs/risk/airmodel/johnson_ettinger.htm

To address the soil-to-outdoor air pathways, the PRG calculations incorporate volatilization factors (VF_s) for volatile contaminants and particulate emission factors (PEF) for nonvolatile contaminants. These factors relate soil contaminant concentrations to air contaminant concentrations that may be inhaled on-site. The VF_s and PEF equations can be broken into two separate models: an emission model to estimate emissions of the contaminant from the soil and a dispersion model to simulate the dispersion of the contaminant in the atmosphere.

The box model in RAGS Part B has been replaced with a dispersion term (Q/C) derived from a modeling exercise using meteorological data from 29 locations across the United States because the box model may not be applicable to a broad range of site types and meteorology and does not utilize state-of-the-art techniques developed for regulatory dispersion modeling. The dispersion model for both volatiles and particulates is the AREA-ST, an updated version of the Office of Air Quality Planning and Standards, Industrial Source Complex Model, ISC2. However, different Q/C terms are used in the VF and PEF equations. Los Angeles was selected as the 90th percentile data set for volatiles and Minneapolis was selected as the 90th percentile data set for fugitive dusts (USEPA1996 a,b). A default source size of 0.5 acres was chosen for the PRG calculations. This is consistent with the default exposure area over which Region 9 typically averages contaminant concentrations in soils. If unusual site conditions exist such that the area source is substantially larger than the default source size assumed here, an alternative Q/C could be applied (see USEPA 1996a,b).

Volatilization Factor for Soils

Volatile chemicals, defined as those chemicals having a Henry's Law constant greater than 10^{-5} (atm-m^3/mol) and a molecular weight less than 200 g/mole, were screened for inhalation exposures using a volatilization factor for soils (VF_s). Please note that VF_s's are available at our website.

The emission terms used in the VF_s are chemical-specific and were calculated from physical-chemical information obtained from several sources. The priority of these sources were as follows: *Soil Screening Guidance* (USEPA 1996a,b), *Superfund Chemical Data Matrix* (USEPA 1996c), *Fate and Exposure Data* (Howard 1991), *Subsurface Contamination Reference Guide* (EPA 1990a), and *Superfund Exposure Assessment Manual* (SEAM, EPA 1988). When there was a choice between a measured or a modeled value (e.g. Koc), we went with modeled values. In those cases where Diffusivity Coefficients (Di) were not provided in existing literature, Di's were calculated using Fuller's Method described in SEAM. A surrogate term was required for some chemicals that lacked physico-chemical information. In these cases, a proxy chemical of similar structure was used that may over- or under-estimate the PRG for soils.

Equation 4-9 forms the basis for deriving generic soil PRGs for the inhalation pathway. The following parameters in the standardized equation can be replaced with specific site data to develop a simple site-specific PRG

- Source area
- Average soil moisture content
- Average fraction organic carbon content
- Dry soil bulk density

The basic principle of the VF_s model (Henry's law) is applicable only if the soil contaminant concentration is at or below soil saturation "sat". Above the soil saturation limit, the model cannot predict an accurate VF-based PRG. How these particular cases are handled, depends on whether the contaminant is liquid or solid at ambient soil temperatures (see Section 4.5).

Particulate Emission Factor for Soils

Inhalation of chemicals adsorbed to respirable particles (PM_{10}) were assessed using a default PEF equal to 1. 316 x 10^9 m^3/kg that 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 in Equation 4-11, which corresponds to a receptor point concentration of approximately 0.76 ug/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.

The impact of the PEF on the resultant PRG concentration (that combines soil exposure pathways for ingestion, skin contact, and inhalation) can be assessed by accessing the Region 9 PRG website and viewing the pathway-specific soil concentrations. Equation 4-11 forms the basis for deriving a generic PEF for the inhalation pathway. For more details regarding specific parameters used in the PEF model, the reader is referred to *Soil Screening Guidance: Technical Background Document* (USEPA 1996a).

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

4.3 Soils - Dermal Exposure

Dermal Contact Assumptions

Exposure factors for dermal contact with soil are based on recommendations in "Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Interim Guidance" (USEPA 2001b). Recommended RME (reasonable maximum exposure) defaults for adult workers' skin surface areas (3300 cm^2/day) and soil adherence factors (0.2 mg/cm^2) now differ from the defaults recommended for adult residents (5700 cm^2/day, 0.07 mg/cm^2) as noted in Exhibit 4-1. This is due to differences in the range of activities experienced by workers versus residents.

Dermal Absorption

Chemical-specific skin absorption values recommended by the Superfund Dermal Workgroup were applied when available. Chemical-specific values are included for the following chemicals: arsenic, cadmium, chlordane, 2,4-D, DDT, lindane, TCDD, PAHs, PCBs, and pentachlorophenols.

The "Supplemental Guidance for Dermal Risk Assessment" (USEPA 2001b) recommends a default dermal absorption factor for semivolatile organic compounds of 10% as a screening method for the majority of SVOCs without dermal absorption factors. Default dermal absorption values for other chemicals (VOCs and inorganics) are not recommended in this new guidance. Therefore, the assumption of 1% for inorganics and 10% for volatiles is no longer included in the Region 9 PRG table. This change has minimal impact on the final risk-based calculations because human exposure to VOCs and inorganics in soils is generally driven by other pathways of exposure.

4.4 Soils - Migration to Groundwater

The methodology for calculating SSLs for the migration to groundwater was developed to identify chemical concentrations in soil that have the potential to contaminate groundwater. 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 backcalculated from acceptable ground water concentrations (i.e. nonzero MCLGs, MCLs, or risk-based PRGs). First, the acceptable groundwater concentration is multiplied by a dilution factor to obtain a target leachate concentration. For example, if the dilution factor is 10 and the acceptable ground water concentration is 0.05 mg/L, the target soil leachate concentration would be 0.5 mg/L. The partition equation (presented in the *Soil Screening Guidance* document) is then used to calculate the total soil concentration (i.e. SSL) corresponding to this soil leachate concentration.

The SSL methodology was designed for use during the early stages of a site evaluation when information about subsurface conditions may be limited. Because of this constraint, the methodology is based on conservative, simplifying assumptions about the release and transport of contaminants in the subsurface. For more on SSLs, and how to calculate site-specific SSLs versus generic SSLs presented in the PRG table, the reader is referred to the *Soil Screening Guidance* document (USEPA 1996a,b).

4.5 Soil Saturation Limit

The soil saturation concentration "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 "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 "sat" concentrations must be compared with each VF-based PRG because a basic principle of the PRG 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 PRG that exceeds the "sat" concentration are set equal to "sat" whereas for solids (e.g., PAHs), soil screening decisions are based on the appropriate PRGs for other pathways of concern at the site (e.g., ingestion).

4.6 Tap Water - Ingestion and Inhalation

Calculation of PRGs for ingestion and inhalation of contaminants in domestic water is based on the methodology presented in RAGS HHEM, Part B (USEPA 1991a). Ingestion of drinking water is an appropriate pathway for all chemicals. For the purposes of this guidance, however, inhalation of volatile chemicals from water is considered routinely only for chemicals with a Henry's Law constant of 1×10^{-5} atm-m^3/mole or greater <u>and</u> with a molecular weight of less than 200 g/mole.

For volatile chemicals, an upperbound volatilization constant (VF_w) is used that is based on all uses of household water (e.g showering, laundering, and dish washing). Certain assumptions were made. For example, it is assumed that the volume of water used in a residence for a family of four is 720 L/day, the volume of the dwelling is 150,000 L and the air exchange rate is 0.25 air changes/hour (Andelman in RAGS Part B). Furthermore, it is assumed that the average transfer efficiency weighted by water use is 50 percent (i.e. half of the concentration of each chemical in water will be transferred into air by all water uses). Note: the range of transfer efficiencies extends from 30% for toilets to 90% for dishwashers.

4.7 Default Exposure Factors

Default exposure factors were obtained primarily from RAGS Supplemental Guidance Standard Default *Exposure Factors* (OSWER Directive, 9285.6-03) dated March 25, 1991 and more recent information from U.S. EPA's Office of Solid Waste and Emergency Response, U.S. EPA's Office of Research and Development, and California EPA's Department of Toxic Substances Control (see Exhibit 4-1).

Because contact rates may be different for children and adults, carcinogenic risks during the first 30 years of life were calculated using age-adjusted factors ("adj"). Use of age-adjusted factors are especially important for soil ingestion exposures, which are higher during childhood and decrease with age. However, for purposes of combining exposures across pathways, additional age-adjusted factors are used for inhalation and dermal exposures. These factors approximate the integrated exposure from birth until age 30 combining contact rates, body weights, and exposure durations for two age groups - small children and adults. Age-adjusted factors were obtained from RAGS PART B or developed by analogy (see derivations next page).

For soils only, noncarcinogenic contaminants are evaluated in children separately from adults. No age-adjustment factor is used in this case. The focus on children is considered protective of the higher daily intake rates of soil by children and their lower body weight. For maintaining consistency when evaluating soils, dermal and inhalation exposures are also based on childhood contact rates.

(1) ingestion([mg-yr]/[kg-d]:

$$IFS_{adj} = \frac{ED_c \times IRS_c}{BW_c} + \frac{(ED_r - ED_c) \times IRS_a}{BW_a}$$

(2) skin contact([mg-yr]/[kg-d]:

$$SFS_{adj} = \frac{ED_c \times AF \times SA_c}{BW_c} + \frac{(ED_r - ED_c) \times AF \times SA_a}{BW_a}$$

(3) inhalation ([m^3-yr]/[kg-d]):

$$InhF_{adj} = \frac{ED_c \times IRA_c}{BW_c} + \frac{(ED_r - ED_c) \times IRA_a}{BW_a}$$

EXHIBIT 4-1
STANDARD DEFAULT FACTORS

Symbol	Definition (units)	Default	Reference
CSFo	Cancer slope factor oral (mg/kg-d)-1	--	IRIS, HEAST, or NCEA
CSFi	Cancer slope factor inhaled (mg/kg-d)-1	--	IRIS, HEAST, or NCEA
RfDo	Reference dose oral (mg/kg-d)	--	IRIS, HEAST, or NCEA
RfDi	Reference dose inhaled (mg/kg-d)	--	IRIS, HEAST, or NCEA
TR	Target cancer risk	10^{-6}	--
THQ	Target hazard quotient	1	--
BWa	Body weight, adult (kg)	70	RAGS (Part A), EPA 1989 (EPA/540/1-89/002)
BWc	Body weight, child (kg)	15	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
ATc	Averaging time - carcinogens (days)	25550	RAGS(Part A), EPA 1989 (EPA/540/1-89/002)
ATn	Averaging time - noncarcinogens (days)	ED*365	
SAa	Exposed surface area for soil/dust (cm^2/day)		Dermal Assessment, EPA 2000 (EPA/540/R-99/005)
	– adult resident	5700	
	– adult worker	3300	
SAc	Exposed surface area, child in soil (cm^2/day)	2800	Dermal Assessment, EPA 2000 (EPA/540/R-99/005)
AFa	Adherence factor, soils (mg/cm^2)		Dermal Assessment, EPA 2000 (EPA/540/R-99/005)
	– adult resident	0.07	
	– adult worker	0.2	
AFc	Adherence factor, child (mg/cm^2)	0.2	Dermal Assessment, EPA 2000 (EPA/540/R-99/005)
ABS	Skin absorption defaults (unitless):		
	– semi-volatile organics	0.1	Dermal Assessment, EPA 2000 (EPA/540/R-99/005)
	– volatile organics	–	Dermal Assessment, EPA 2000 (EPA/540/R-99/005)
	– inorganics	–	Dermal Assessment, EPA 2000 (EPA/540/R-99/005)
IRAa	Inhalation rate - adult (m^3/day)	20	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
IRAc	Inhalation rate - child (m^3/day)	10	Exposure Factors, EPA 1997 (EPA/600/P-95/002Fa)
IRWa	Drinking water ingestion - adult (L/day	2	RAGS(Part A), EPA 1989 (EPA/540/1-89/002)
IRWc	Drinking water ingestion - child (L/day)	1	PEA, Cal-EPA (DTSC, 1994)
IRSa	Soil ingestion - adult (mg/day)	100	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
IRSc	Soil ingestion - child (mg/day),	200	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
IRSo	Soil ingestion - occupational (mg/day)	100	Soil Screening Guidance (EPA 2001a)
EFr	Exposure frequency - residential (d/y)	350	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
EFo	Exposure frequency - occupational (d/y)	250	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
EDr	Exposure duration - residential (years)	30[a]	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
EDc	Exposure duration - child (years)	6	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
EDo	Exposure duration - occupational (years)	25	Exposure Factors, EPA 1991 (OSWER No. 9285.6-03)
	Age-adjusted factors for carcinogens:		
IFSadj	Ingestion factor, soils ([mg-yr]/[kg-d])	114	RAGS(Part B), EPA 1991 (OSWER No. 9285.7-01B)
SFSadj	Dermal factor, soils ([mg-yr]/[kg-d])	361	By analogy to RAGS (Part B)
InhFadj	Inhalation factor, air ([m^3-yr]/[kg-d])	11	By analogy to RAGS (Part B)
IFWadj	Ingestion factor, water ([L-yr]/[kg-d])	1.1	By analogy to RAGS (Part B)
VFw	Volatilization factor for water (L/m^3)	0.5	RAGS(Part B), EPA 1991 (OSWER No. 9285.7-01B)
PEF	Particulate emission factor (m^3/kg)	See below	Soil Screening Guidance (EPA 1996a,b)
VFs	Volatilization factor for soil (m^3/kg)	See below	Soil Screening Guidance (EPA 1996a,b)
sat	Soil saturation concentration (mg/kg)	See below	Soil Screening Guidance (EPA 1996a,b)

Footnote:
[a]Exposure duration for lifetime residents is assumed to be 30 years total. For carcinogens, exposures are combined for children (6 years) and adults (24 years) .

4.8 Standardized Equations

The equations used to calculate the PRGs for carcinogenic and noncarcinogenic contaminants are presented in Equations 4-1 through 4-8. The PRG equations update RAGS Part B equations. The methodology backcalculates a soil, air, or water concentration level from a target risk (for carcinogens) or hazard quotient (for noncarcinogens). For completeness, the soil equations combine risks from ingestion, skin contact, and inhalation simultaneously. **Note: the electronic version of the table also includes pathway-specific PRGs, should the user decide against combining specific exposure pathways; or, the user wants to identify the relative contribution of each pathway to exposure.**

To calculate PRGs for volatile chemicals in soil, a chemical-specific volatilization factor is calculated per Equation 4-9. Because of its reliance on Henry's law, the VF_s model is applicable only when the contaminant concentration in soil is at or below saturation (i.e. there is no free-phase contaminant present). Soil saturation ("sat") corresponds to the contaminant concentration in soil at which the adsorptive limits of the soil particles and the solubility limits of the available soil moisture have been reached. Above this point, pure liquid-phase contaminant is expected in the soil. If the PRG calculated using VF_s was greater than the calculated sat, the PRG was set equal to sat, in accordance with *Soil Screening Guidance* (USEPA 1996 a,b). The equation for deriving sat is presented in Equation 4-10.

PRG EQUATIONS

Soil Equations: For soils, equations were based on three exposure routes (ingestion, skin contact, and inhalation).

Equation 4-1: Combined Exposures to Carcinogenic Contaminants in Residential Soil

$$C(mg/kg) = \frac{TR \times AT_c}{EF_r \left[\left(\frac{IFS_{adj} \times CSF_o}{10^6 mg/kg} \right) + \left(\frac{SFS_{adj} \times ABS \times CSF_o}{10^6 mg/kg} \right) + \left(\frac{InhF_{adj} \times CSF_i}{VF_s^a} \right) \right]}$$

Equation 4-2: Combined Exposures to Noncarcinogenic Contaminants in Residential Soil

$$C(mg/kg) = \frac{THQ \times BW_c \times AT_n}{EF_r \times ED_c \left[\left(\frac{1}{RfD_o} \times \frac{IRS_c}{10^6 mg/kg} \right) + \left(\frac{1}{RfD_o} \times \frac{SA_c \times AF \times ABS}{10^6 mg/kg} \right) + \left(\frac{1}{RfD_i} \times \frac{IRA_c}{VF_s^a} \right) \right]}$$

Equation 4-3: Combined Exposures to Carcinogenic Contaminants in Industrial Soil

$$C(mg/kg) = \frac{TR \times BW_a \times AT_c}{EF_o \times ED_o \left[\left(\frac{IRS_o \times CSF_o}{10^6 mg/kg} \right) + \left(\frac{SA_a \times AF \times ABS \times CSF_o}{10^6 mg/kg} \right) + \left(\frac{IRA_a \times CSF_i}{VF_s^a} \right) \right]}$$

Footnote:
[a]Use VF_s for volatile chemicals (defined as having a Henry's Law Constant [atm-m^3/mol] greater than 10^{-5} and a molecular weight less than 200 grams/mol) or PEF for non-volatile chemicals.

Equation 4-4: Combined Exposures to Noncarcinogenic Contaminants in Industrial Soil

$$C(mg/kg) = \frac{THQ \times BW_a \times AT_n}{EF_o \times ED_o[(\frac{1}{RfD_o} \times \frac{IRS_o}{10^6 mg/kg}) + (\frac{1}{RfD_o} \times \frac{SA_a \times AF \times ABS}{10^6 mg/kg}) + (\frac{1}{RfD_i} \times \frac{IRA_a}{VF_s^a})]}$$

Tap Water Equations:

Equation 4-5: Ingestion and Inhalation Exposures to Carcinogenic Contaminants in Water

$$C(ug/L) = \frac{TR \times AT_c \times 1000ug/mg}{EF_r\ [(IFW_{adj} \times CSF_o) + (VF_w \times InhF_{adj} \times CSF_i)]}$$

Equation 4-6: Ingestion and Inhalation Exposures to Noncarcinogenic Contaminants in Water

$$C(ug/L) = \frac{THQ \times BW_a \times AT_n \times 1000ug/mg}{EF_r \times ED_r\ [(\frac{IRW_a}{RfD_o}) + (\frac{VF_w \times IRA_a}{RfD_i})]}$$

Air Equations:

Equation 4-7: Inhalation Exposures to Carcinogenic Contaminants in Air

$$C(ug/m^3) = \frac{TR \times AT_c \times 1000ug/mg}{EF_r \times InhF_{adj} \times CSF_i}$$

Equation 4-8: Inhalation Exposures to Noncarcinogenic Contaminants in Air

$$C(ug/m^3) = \frac{THQ \times RfD_i \times BW_a \times AT_n \times 1000ug/mg}{EF_r \times ED_r \times IRA_a}$$

Footnote:

[a]Use VF_s for volatile chemicals (defined as having a Henry's Law Constant [atm-m^3/mol] greater than 10^{-5} and a molecular weight less than 200 grams/mol) or PEF for non-volatile chemicals.

SOIL-TO-AIR VOLATILIZATION FACTOR (VF_s)

Equation 4-9: Derivation of the Volatilization Factor

$$VF_s(m^3/kg) = (Q/C) \times \frac{(3.14 \times D_A \times T)^{1/2}}{(2 \times \rho_b \times D_A)} \times 10^{-4}(m^2/cm^2)$$

where:

$$D_A = \frac{[(\Theta_a^{10/3} D_i H' + \Theta_w^{10/3} D_w)/n^2]}{\rho_B K_d + \Theta_w + \Theta_a H'}$$

Parameter	Definition (units)	Default
VF_s	Volatilization factor (m^3/kg)	--
D_A	Apparent diffusivity (cm^2/s)	--
Q/C	Inverse of the mean conc. at the center of a 0.5-acre square source ($g/^{M2}$-s per kg/m^3)	68.81
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-Θ_w
n	Total soil porosity (L_{pore}/L_{soil})	0.43 or 1 - (ρ_b/ρ_s)
Θ_w	Water-filled soil porosity (L_{water}/L_{soil})	0.15
ρ_s	Soil particle density (g/cm^3)	2.65
Di	Diffusivity in air (cm^2/s)	Chemical-specific
H	Henry's Law constant (atm-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) = $K_{oc}f_{oc}$	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%)

SOIL SATURATION CONCENTRATION (sat)

Equation 4-10: Derivation of the Soil Saturation Limit

$$sat = \frac{S}{\rho_b} (K_d \rho_b + \Theta_w + H' \Theta_a)$$

Parameter	Definition (units)	Default
sat	Soil saturation concentration (mg/kg)	--
S	Solubility in water (mg/L-water)	Chemical-specific
ρ_b	Dry soil bulk density (kg/L)	1.5
n	Total soil porosity (L_{pore}/L_{soil})	0.43 or 1 - (ρ_b/ρ_s)
ρ_s	Soil particle density (kg/L)	2.65
K_d	Soil-water partition coefficient (L/kg)	K_{oc} x f_{oc} (chemical-specific)
k_{oc}	Soil organic carbon/water partition coefficient (L/kg)	Chemical-specific
f_{oc}	Fraction organic carbon content of soil (g/g)	0.006 or site-specific
Θ_w	Water-filled soil porosity (L_{water}/L_{soil})	0.15
Θ_a	Air filled soil porosity (L_{air}/L_{soil})	0.28 or n-Θ_w
w	Average soil moisture content (kg_{water}/kg_{soil} or L_{water}/kg_{soil})	0.1
H	Henry's Law constant (atm-m^3/mol)	Chemical-specific
H'	Dimensionless Henry's Law constant	H x 41, where 41 is a units conversion factor

SOIL-TO-AIR PARTICULATE EMISSION FACTOR (PEF)

Equation 4-11: Derivation of the Particulate Emission Factor

$$PEF(m^3/kg) = Q/C \times \frac{3600s/h}{0.036 \times (1-V) \times (U_m/U_t)^3 \times F(x)}$$

Parameter	Definition (units)	Default
PEF	Particulate emission factor (m^3/kg)	1.316×10^9
Q/C	Inverse of the mean concentration at the center of a 0.5-acre-square source ($g/^{M2}$-s per kg/m^3)	90.80
V	Fraction of vegetative cover (unitless)	0.5
U_m	Mean annual windspeed (m/s)	4.69
U_t	Equivalent threshold value of windspeed at 7 m (m/s)	11.32
F(x)	Function dependent on U_m/U_t derived using Cowherd (1985) (unitless)	0.194

REFERENCES

ASTM. 1995. *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites.* Designation E 1739 - 95. Philadelphia, Pennsylvania.

Calabrese, E.J., H. Pastides, R. Barnes, et al. 1989. How much soil do young children ingest: an epidemiologic study. In: *Petroleum Contaminated Soils*, Vol. 2. E.J. Calabrese and P.T. Kostecki, eds. pp. 363-417. Chelsea, MI, Lewis Publishers.

California EPA. 1994. *Preliminary Endangerment Assessment Guidance Manual.* (PEA) Department of Toxic Substances Control, Sacramento, California.

California EPA. 1996. *Guidance for Ecological Risk Assessment at Hazardous Waste Sites and Permitted Facilities, Part A: Overview.* Department of Toxic Substances Control, Sacramento, California.

Cowherd, C., G. Muleski, P. Engelhart, and D. Gillette. 1985. *Rapid Assessment of Exposure to Particulate Emission from Surface Contamination.* EPA/600/8-85/002. Prepared for Office of Health and Environmental Assessment, U.S. Environmental Protection Agency, Washington, DC. NTIS PB85-1922197AS.

Davis, S., P. Waller, R. Buschom, J. Ballou, and P. White. 1990. Quantitative estimates of soil ingestion in normal children between the ages of 2 and 7 years: population-based estimates using Al, Si, and Ti as soil tracer elements. *Archives of Environmental Health* 45:112-122.

Howard, P.H. 1990. *Handbook of Environmental Fate and Exposure Data for Organic Chemicals.* Lewis Publishers, Chelsea Michigan.

U.S. EPA. 1988. *Superfund Exposure Assessment Manual.* EPA/540/1-88/001. Office of Emergency and Remedial Response, Washington, DC.

U.S. EPA. 1990a. *Subsurface Contamination Reference Guide.* EPA/540/2-90/011. Office of Emergency and Remedial Response, Washington, DC.

U.S. EPA 1990b. *Exposure Factors Handbook.* EPA/600/8089/043. Office of Health and Environmental Assessment, Washington, DC.

U.S. EPA. 1991a. *Risk Assessment Guidance for Superfund Volume 1: Human Health Evaluation Manual (Part B, Development of Risk-Based Preliminary Remediation Goals).* Publication 9285.7-01B. Office of Emergency and Remedial Response, Washington, DC. NTIS PB92-963333.

U.S. EPA. 1991b. *Human Health Evaluation Manual, Supplemental Guidance: Standard Default Exposure Factors.* Publication 9285.6-03. Office of Emergency and Remedial Response, Washington, DC. NTIS PB91-921314.

U.S. EPA. 1992a *Technical Support Document for Land Application of Sewage Sludge; Volumes I and II.* Office of Water, Washington, DC. 822/R-93-001a,b.

U.S. EPA. 1992b *Dermal Exposure Assessment: Principles and Applications.* EPA/600/8-91/011B. Office of Health and Environmental Assessment, Washington, DC.

U.S. EPA 1994a. *Estimating Exposure to Dioxin-Like Compounds.* U.S. EPA Office of Research and Development, EPA/600/6-88/005B.

U.S. EPA 1994b. *Role of Ecological Assessment in the Baseline Risk Assessment.* OSWER Directive No. 9285.7-17. Office of Solid Waste and Emergency Response, Washington, DC.

U.S. EPA. 1996a. *Soil Screening Guidance: Technical Background Document.* EPA/540/R-95/128. Office of Emergency and Remedial Response, Washington, DC. PB96-963502.

U.S. EPA. 1996b. *Soil Screening Guidance: User's Guide.* EPA/540/R-96/018. Office of Emergency and Remedial Response, Washington, DC. PB96-963505.

U.S. EPA 1996c. *Superfund Chemical Data Matrix*. EPA/540/R-96/028. Office of Solid Waste and Emergency Response, Washington, DC. PB94-963506.

U.S. EPA. 1997a. *Health Effects Assessment Summary Tables* (HEAST): Annual Update, FY 1997. National Center For Environmental Assessment (NCEA), Office of Research and Development and Office of Emergency and Remedial Response, Washington, DC.

U.S. EPA. 1997b. *Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessments, Interim Final*. EPA/540/R-97/006. Office of Solid Waste and Emergency Response, Washington, DC. PB97-963211.

U.S. EPA. 2001a. *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites, Interim Guidance*. OSWER 9355.4-24.

U.S. EPA. 2001b. *Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment), Interim Guidance*. EPA/540/R-99/005. Office of Solid Waste and Emergency Response, Washington, DC. PB99-963312.

U.S. EPA. 2001c. *Guidance for Characterizing Background Chemicals in Soil at Superfund Sites* (Draft) June 2001, EPA/540/R-01/003. Office of Solid Waste and Emergency Response, Washington, DC.

U.S. EPA. 2002. *Integrated Risk Information System* (IRIS). Duluth, MN.

Van Wijnen, J.H., P. Clausing and B. Brunekreef. 1990. Estimated soil ingestion by children. *Environmental Research*, 51:147-162.

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 THE JOHNSON AND ETTINGER (1991) MODEL FOR 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

E.H. Pechan & Associates, Inc.
5537-C Hempstead way
Springfield, Virginia 22151

Contract No. 68-D30035
Work Assignment No. III-106
PN 5099-6

For Submittal to

Janine Dinan, Work Assignment Manager

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF EMERGENCY AND REMEDIAL RESPONSE
TOXICS INTEGRATION BRANCH (5202G)
401 M STREET, S.W.
WASHINGTON, D.C. 20450

September 1997

DISCLAIMER

The contents of this document are reproduced herein as received from the contractor. The opinions, findings, and conclusions expressed are those of the author and not necessarily those of the U.S. Environmental Protection Agency.

CONTENTS

Figures		v
Tables		vi
Acknowledgment		vii
1.	Introduction	1
2.	Model Theory	3
	Model Setting	3
	Vapor Concentration at the Source of Contamination	5
	Diffusion Through the Capillary Zone	9
	Diffusion Through the Unsaturated Zone	14
	The Infinite Source Solution to Convective and Diffusive Transport	17
	The Finite Source Solution to Convective and Diffusive Transport	21
	Soil Vapor Permeability	23
	Calculation of a Risk-Based Soil or Groundwater Concentration	26
	Calculation of Incremental Risks	27
	Major Model Assumptions/Limitations	28
3.	Model Application	30
	Running the Models	30
	The Data Entry Sheet (DATENTER)	32
4.	The Results Sheet and Ancillary Sheets	47
	The Results Sheet (RESULTS)	47
	The Chemical Properties Sheet (CHEMPROPS)	47
	The Intermediate Calculations Sheet (INTERCALCS)	48
	The Lookup Tables (VLOOKUP)	48

CONTENTS (continued)

5. Model Assumptions and Limitations 49

Source Vapor Concentration 49
Soil Vapor Permeability 50
Rise of and Diffusion Across the Capillary Zone 50
Diffusive and Convective Transport into the Structure 52

6. Values for Input Variables 54

7. Interpretation of Results 57

References 59

Appendices

A. Example Worksheets for the Tier-2 Soil Contamination Model A-1
B. Sample Data Entry Sheets for Each Model B-1
C. Chemical Properties Lookup Table and References C-1

FIGURES

Number		Page
1	Conceptual diagram of soil contamination	4
2	Conceptual diagram of groundwater contamination	6
3	U.S. Soil Conservation Service classification chart showing centroid compositions (solid circles)	15
4	GWSCREEN data entry sheet	33
5	GWTIER2 data entry sheet	34
6	Example error message on data entry sheet	35
7	Example error messages on results sheet	35
8	Average shallow groundwater temperature in the United States	37
9	Floor slab and foundation	45

TABLES

Number		Page
1	Values of Exponent n as a Function of T_B/T_C	9
2	Mean Values of the Van Genuchten Soil Water Retention Parameters for the 12 SCS Soil Types	11
3	Centroid Compositions and Mean Particle Diameters of the 12 SCS Soil Classifications	16
4	Mean Values of Saturated Hydraulic Conductivity for the 12 SCS Soil Textural Classifications	25
5	Range of Values, Sensitivity, and Uncertainty of Model Input Parameters	55
6	Effect on Building Concentration from an Increase in Input Parameter Values	56

ACKNOWLEDGMENT

This document and the accompanying spreadsheets were prepared for the U.S. Environmental Protection Agency by Environmental Quality Management, Inc. under Contract No. 68-D30035, Work Assignment III-106. Mr. Craig Mann (Project Manager) and Ms. Janine Dinan (Work Assignment Manager) managed the project. The principal author was Mr. Craig Mann of Environmental Quality Management, Inc.

SECTION 1

INTRODUCTION

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 (1991) introduced a screening-level model which 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 or in close proximity to the source of contamination. In their article, Johnson and Ettinger reported that the results of the model were in qualitative agreement with published experimental case histories and in good qualitative and quantitative agreement with detailed three-dimensional numerical modeling of radon transport into houses (Loureiro, et al., 1990).

The Johnson and Ettinger 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 nondiminishing 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 Johnson and Ettinger model as provided in the accompanying spreadsheets. The infinite source model and the finite source model are provided in both MICROSOFT EXCEL and LOTUS 1-2-3 formats for soil contamination and the infinite source model for contamination occurring below the water table. Model results (both screening and tier-2) 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.

Second-tier 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 second-tier 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.

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 of input parameters and to explore and quantity 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 6).

SECTION 2

MODEL THEORY

Chemical fate and transport within soils and between the soil column and enclosed spaces is determined by a number of physical and chemical processes. This section presents the theoretical framework on which the Johnson and Ettinger 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 Johnson and Ettinger (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 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 towards 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.

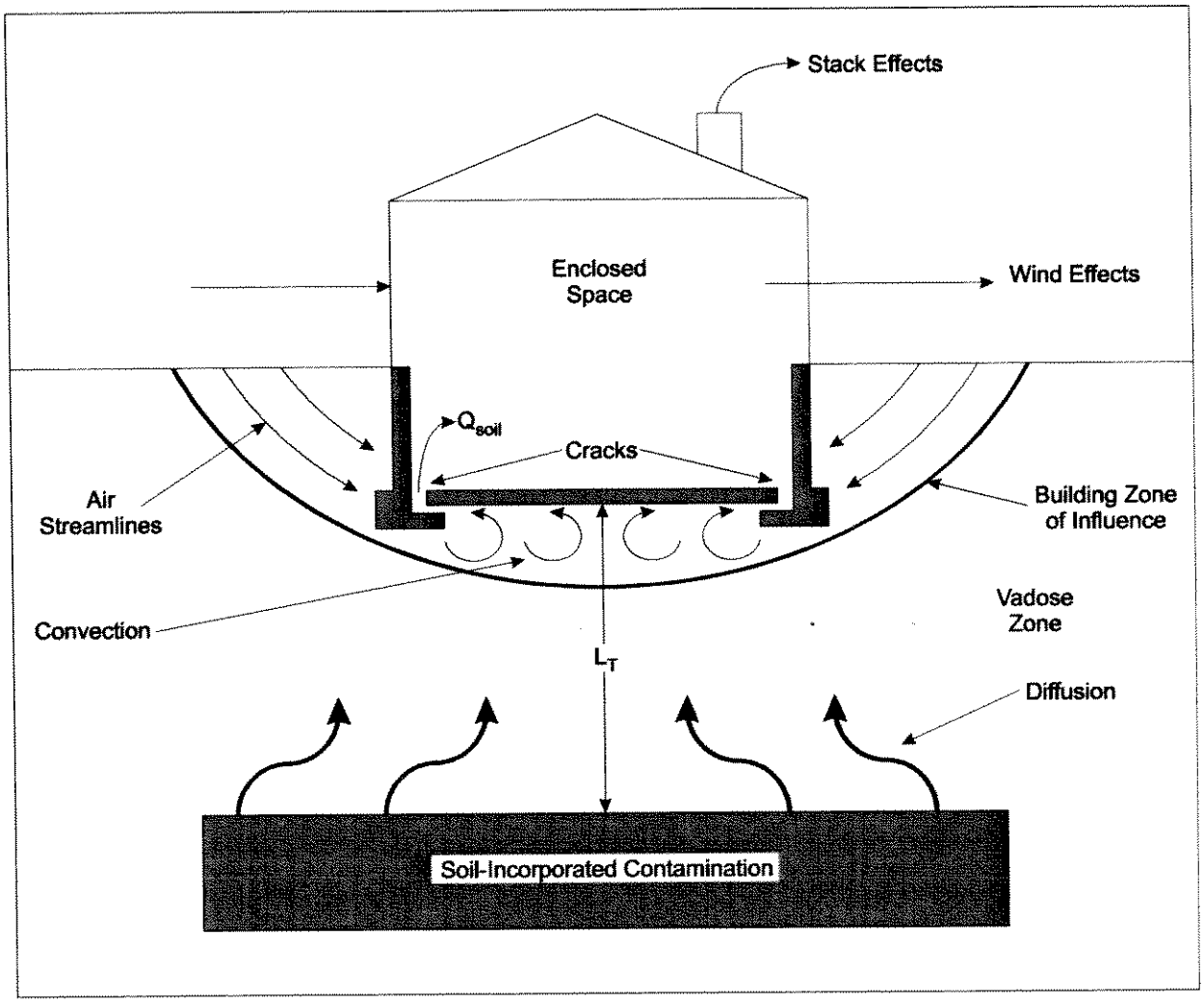


Figure 1. Conceptual Diagram of Soil Contamination

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 rate of soil gas entry (Q_{soil}) 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:

$$C_{source} = \frac{H'_{TS}\, C_R\, \rho_b}{\theta_w + K_d \rho_b + H'_{TS}\, \theta_a} \tag{1}$$

where C_{source} = Vapor concentration at the source of contamination, g/cm^3-v

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

C_R = Initial soil concentration, g/g

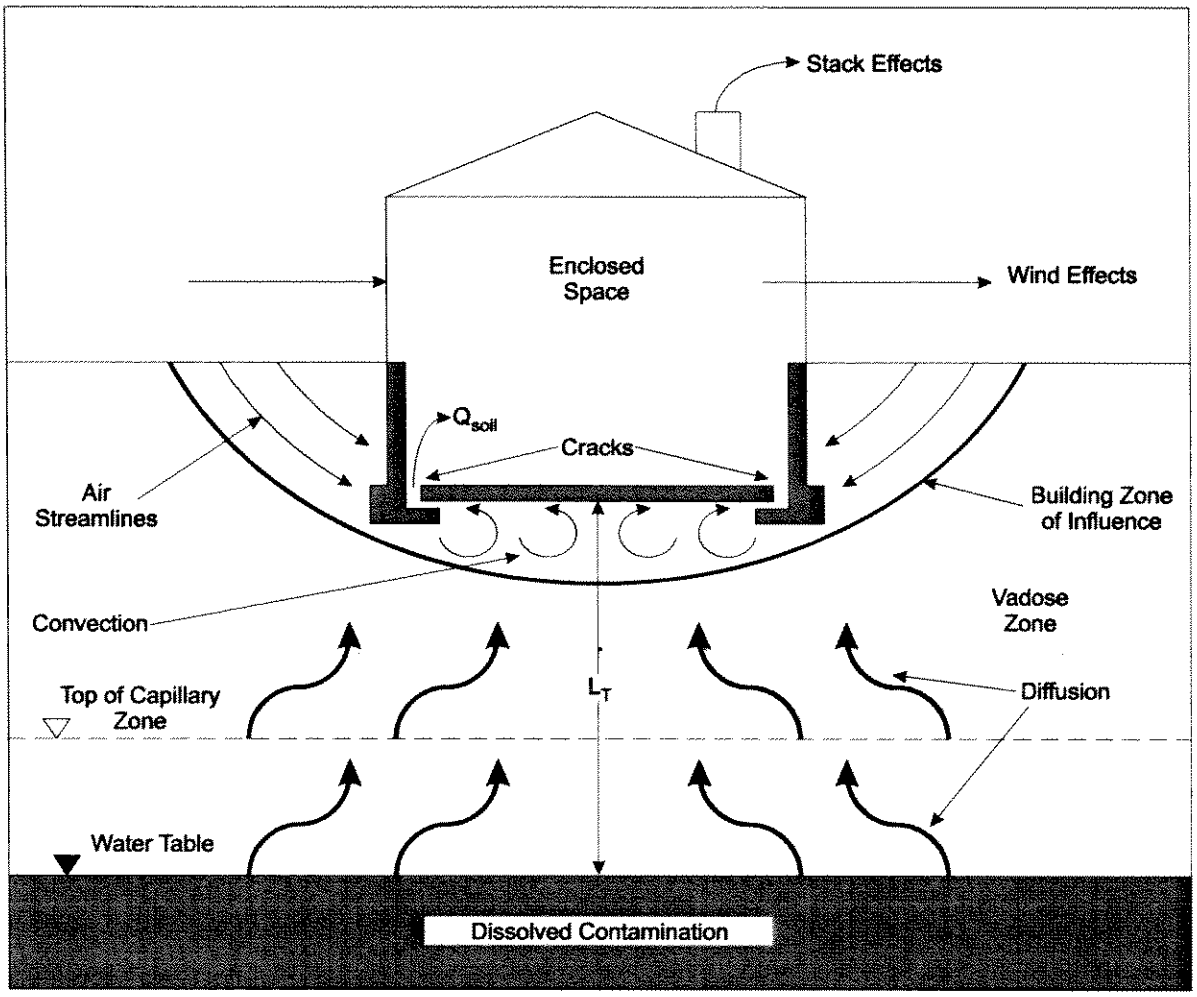


Figure 2. Conceptual Diagram of Groundwater Contamination

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} x 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.

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:

$$C_{source} = H'_{TS} C_w \tag{2}$$

where C_{source} = Vapor concentration at the source of contamination, g/cm^3-v

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

C_w = Groundwater concentration, g/cm^3-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:

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

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-m^3/mol

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

R = Gas constant (= 8.206 E-05 atm-m^3/mol-°K).

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

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

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 1 gives the value of n as a function of the ratio T_B/T_C.

TABLE 1. 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

Chemical properties are included in the accompanying spreadsheets for the 93 volatile chemicals listed in the U.S. Environmental Protection Agency (EPA) Soil Screening Guidance (EPA 1996a and b) and for four PCB aroclors. See Appendix C for the complete list of references by chemical.

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 implying 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 which corresponded to the air-entry pressure head. The air-entry pressure head corresponds with the top of the saturated capillary zone. Therefore, to account for the variation in the air content of the capillary zone, and 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:

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

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

h = Air-entry pressure head, cm (= $1/\alpha$ 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 $\theta_{w,cz}$.

Carsel and Parrish (1988) computed mean values of the van Genuchten soil water retention curve parameters for the 12 Soil Conservation Service (SCS) soil textural classifications. The data base used to develop the mean values presented in Table 2 was developed from sampling data representing 42 States and ranged from sample population sizes of 46 to 1,183. With these data, a general estimate can be made of the values of $\theta_{w,cz}$ and $\theta_{a,cz}$ for each soil 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:

TABLE 2. MEAN VALUES OF THE VAN GENUCHTEN SOIL WATER RETENTION PARAMETERS FOR THE 12 SCS SOIL TYPES

Soil texture (USDA)	Saturated water content, θ_s	Residual water Content, θ_r	Van Genuchten parameters			Number of samples[a]
			α (1/cm)	N	M	
Clayey soil[b]	0.38	0.068	0.008	1.09	0.083	400
Clay loam	0.41	0.095	0.019	1.31	0.237	364
Loam	0.43	0.078	0.036	1.56	0.359	735
Loamy sand	0.41	0.057	0.124	2.28	0.561	315
Silt	0.46	0.034	0.016	1.37	0.270	82
Silt loam	0.45	0.067	0.020	1.41	0.291	1093
Silty clay	0.26	0.070	0.005	1.09	0.083	374
Silty clay loam	0.43	0.089	0.010	1.23	0.187	641
Sand	0.43	0.045	0.145	2.68	0.627	246
Sandy clay	0.38	0.100	0.027	1.23	0.187	46
Sandy clay loam	0.39	0.100	0.059	1.48	0.324	214
Sandy loam	0.41	0.065	0.075	1.89	0.471	1183

[a]Number of samples as indicated with minor exceptions; see Carsel and Parrish (1988).
[b]Clay soil refers to agricultural soil with < 60 percent clay.

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

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:

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

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.

The value of C_{source} is calculated using Equation 2; the value of A is assumed to be one cm^2; and the value of D_{cz}^{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 capillarity 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:

$$L_{cz} = \frac{2 \ \alpha \ COS \ \lambda}{\rho_w \ g \ R} \tag{8}$$

where L_{cz} = Mean rise of the capillary zone, cm

σ = 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/cm^3 (= 0.999)

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

R = Mean interparticle pore radius, cm

and,

$$R = 0.2D \tag{9}$$

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 10° and 20°C, Equation 8 reduces to:

$$L_{cz} = \frac{0.15}{R} \quad . \tag{10}$$

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

Given the mean particle diameter data in Table 3, 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:

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

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.

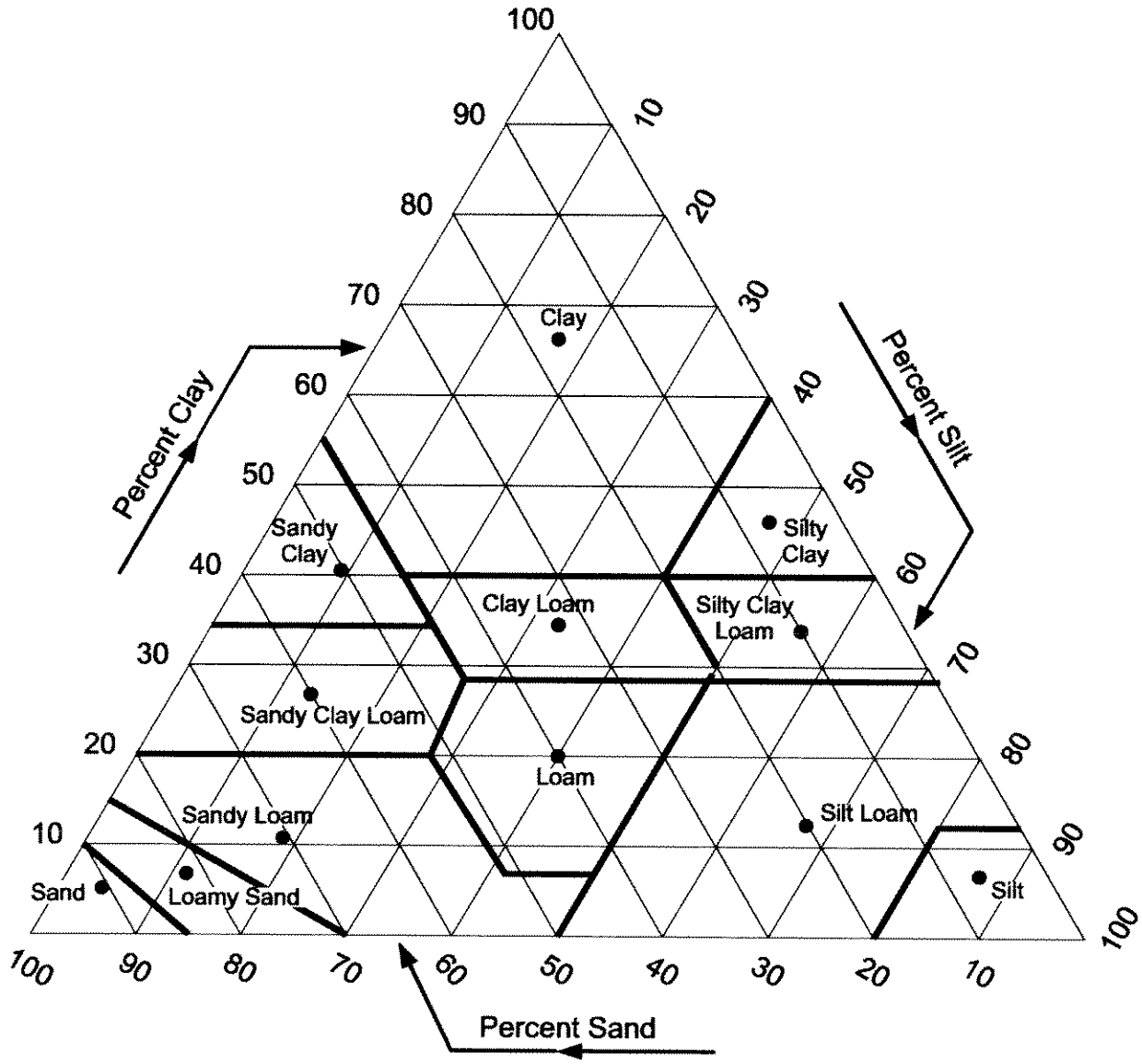


Figure 3. U.S. Soil Conservation Service Classification Chart Showing Centroid Compostions (Solid Circles)

TABLE 3. CENTROID COMPOSITIONS AND MEAN PARTICLE DIAMETERS OF THE 12 SCS SOIL CLASSIFICATIONS

Textural class	% clay	% silt	% sand	Arithmetic mean particle diameter, cm
Sand	3.33	5.00	91.67	0.044
Loamy sand	6.25	11.25	82.50	0.040
Sandy loam	10.81	27.22	61.97	0.030
Sandy clay loam	26.73	12.56	60.71	0.029
Sandy clay	41.67	6.67	51.66	0.025
Loam	18.83	41.01	40.16	0.020
Clay loam	33.50	34.00	32.50	0.016
Silt loam	12.57	65.69	21.74	0.011
Clay	64.83	16.55	18.62	0.0092
Silty clay loam	33.50	56.50	10.00	0.0056
Silt	6.00	87.00	7.00	0.0046
Silty clay	46.67	46.67	6.66	0.0039

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

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

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 (infinite source), Johnson and Ettinger (1991) give the solution for the attenuation coefficient (α) as:

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

where

α = Infinite source 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:

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

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:

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

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 Johnson and Ettinger (1991) as:

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

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 following dimensionless group:

$$\left(\frac{Q_{soil}\, L_{crack}}{D^{crack}\, A_{crack}} \right) \quad . \tag{17}$$

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:

$$\frac{\left(\dfrac{D_T^{eff}\, A_B}{Q_{building}\, L_T} \right)}{\left(\dfrac{D_T^{eff}\, A_B}{Q_{soil}\, L_T} \right) + 1} \quad . \tag{18}$$

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:

$$C_{building} = \alpha\, C_{source} \quad . \tag{19}$$

2.6 THE FINITE SOURCE SOLUTION TO CONVECTIVE AND DIFFUSIVE TRANSPORT

If the thickness of soil contamination is known, the finite source solution of Johnson and Ettinger (1991) can be employed such that the time-averaged attenuation coefficient (<α>) may be calculated as:

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

where <α> = Time-averaged finite source attenuation coefficient, unitless

ρ_b = Soil dry bulk density at the source of contamination, g/cm^3

C_R = Initial soil concentration, g/g

ΔH_c = Initial thickness of contamination, cm

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

$Q_{building}$ = Building ventilation rate, cm^3/s

C_{source} = Vapor concentration at the source of contamination, g/cm^3-v

τ = Exposure interval, s

L_T^o = Source-building separation at time = 0, cm

and,

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

and,

$$\Psi = \frac{D_T^{eff}\, C_{source}}{\left(L_T^O\right)^2\, \rho_b\, C_R} \quad . \tag{22}$$

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) which 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:

$$C_{building} = \langle\alpha\rangle\, C_{source} \quad . \tag{23}$$

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:

$$\tau_D = \frac{\left[\Delta H_c / L_T^O + \beta\right]^2 - \beta^2}{2\,\Psi} \quad . \tag{24}$$

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:

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

where $C_{building}$ = Time-averaged vapor concentration in the building, g/cm^3-v

ρ_b = Soil dry bulk density at the source of contamination, g/cm^3

C_R = Initial soil concentration, g/g

ΔH_c = Initial thickness of contamination, cm

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

$Q_{building}$ = Building ventilation rate, cm^3/s

τ = Exposure interval, s.

2.7 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 hydraulic conductivity:

$$k_i = \frac{K_s \mu_w}{\rho_w g} \tag{26}$$

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).

Carsel and Parrish (1988) estimated the mean saturated hydraulic conductivity (K_s) of the 12 SCS soil textural classifications (Table 4). With these values, a general estimate of the value of k_i can be made by soil type.

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.

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:

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

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

S_{te} = Effective total fluid saturation, unitless

M = van Genuchten shape parameter, unitless.

TABLE 4. MEAN VALUES OF SATURATED HYDRAULIC CONDUCTIVITY FOR THE 12 SCS SOIL TEXTURAL CLASSIFICATIONS

Soil texture , USDA	Saturated hydraulic conductivity, cm/h
Sand	29.70
Loamy sand	14.59
Sandy loam	4.42
Sandy clay loam	1.31
Sandy clay	0.12
Loam	1.04
Clay loam	0.26
Silt loam	0.45
Clay	0.20
Silty clay loam	0.07
Silt	0.25
Silty clay	0.02

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

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

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.

Mean values for the parameters θ_r and M by SCS soil type may be obtained from Table 2.

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 fixed soil water-filled porosity θ_w.

2.8 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:

$$C_C = \frac{TR \, x \, AT_C \, x 365 \, days / yr}{URF \, x \, EF \, x \, ED \, x \, C_{building}} \tag{29}$$

where C_c = Risk-based media concentration for carcinogens, µg/kg-soil, or µg/L-water

TR = Target risk level, unitless

AT_c = Averaging time for carcinogens, yr

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

EF = Exposure frequency, days/yr

ED = Exposure duration, yr

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

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

$$C_{NC} = \frac{THQ\, x\, AT_{NC}\, x 365\, days / yr}{EF\, x\, ED\, x \frac{1}{RfC}\, x\, C_{building}} \tag{30}$$

where C_{NC} = Risk-based media concentration for noncarcinogens, µg/kg-soil, or µg/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 µg/kg-soil, or mg/m^3 per µg/L-water.

The accompanying 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 µg/kg-soil, while for groundwater the initial hypothetical concentration is 1 µg/L-water.

2.9 CALCULATION OF INCREMENTAL RISKS

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

$$Risk = \frac{URF\, x\, EF\, x\, ED\, x\, C_{building}}{AT_C\, x 365\, days / yr} \tag{31}$$

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

$$HQ = \frac{EF \ x \ ED \ x \frac{1}{RfC} \ x \ C_{building}}{AT_{NC} \ x \ 365 \ days/yr} \quad . \tag{32}$$

2.10 MAJOR MODEL ASSUMPTIONS/LIMITATIONS

The following represent the major assumptions/limitations of the Johnson and Ettinger model. Additional assumptions specific to the application of the model as applied in the accompanying spreadsheets are contained in Section 5.

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.

SECTION 3

MODEL APPLICATION

This section provides step-by-step instructions on how to implement the Johnson and Ettinger model using the accompanying spreadsheets. 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, out of range, or outside of permitted limits.

3.1 RUNNING THE MODELS

Four different models are provided as both MICROSOFT EXCEL and LOTUS 1-2-3 spreadsheets.

1. Screening-Level Models for Soil Contamination:

    - SLSCREEN.XLS (EXCEL)
    - SLSCREEN.WK4 (1-2-3)

2. Screening-Level Models for Groundwater Contamination:

    - GWSCREEN.XLS (EXCEL)
    - GWSCREEN.WK4 (1-2-3)

3. Tier-2 Models for Soil Contamination:

    - SLTIER2.XLS (EXCEL)
    - SLTIER2.WK4 (1-2-3)

4. Tier-2 Models for Groundwater Contamination:

- GWTIER2.XLS (EXCEL)
- GWTIER2.WK4 (1-2-3).

Both the screening-level models and the tier-2 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 tier-2 models provide the user with the ability to enter data for all of the model parameters and also incorporates 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 either MICROSOFT EXCEL or LOTUS 1-2-3. 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, data entry conventions, how to interpret model results, and how to add/revise the chemical properties data found in the VLOOKUP Tables. As an example, Appendix A contains all the worksheets for the tier-2 soil contamination model SLTIER2.

<u>Note</u>: Because of the limitations of LOTUS 1-2-3, variable names (e.g., ΔH_c) appear in alphanumeric characters. Subscripts are preceded by the symbol "_" and superscripts are preceded by the symbol "^." Upper case greek characters are spelled with an initial capital letter and lower case greek characters are spelled in lower case. For example, the variable ΔH_c would appear as "Delta H_c" while the variable D_T^{eff} would appear as "D_T^eff."

3.2 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 (GWSCREEN). Figure 5 is an example of a tier-2 model data entry sheet (GWTIER2). Note that the screening-level model sheet requires entry of considerably less data than does the tier-2 sheet. To enter data, simply position the cursor within the appropriate box and type the value; all other cells are protected.

3.2.1 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 tier-2 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.

Figure 6 is an example of an error message appearing on the data entry sheet. Figure 7 illustrates error messages appearing within the error summary section on the results sheet (tier-2 models only).

3.2.2 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 tier-2 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

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 ($\mu g/L$)	Chemical
56235		Carbon tetrachloride

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 (°C)
200	400	SC	10

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 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			1.5	0.43	0.3

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. GWSCREEN Data Entry Sheet

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 (µg/L)	Chemical
56235		Carbon tetrachloride

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 Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
			Totals must add up to value of L_{WT} (cell D28)							
10	200	400	300	50	50	C	SC	C		

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 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 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)
1.5	0.43	0.2	1.7	0.42	0.27	1.7	0.43	0.3

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)
15	40	961	961	488	0.1	0.45

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	1
				Used to calculate risk-based groundwater concentration.	

Figure 5. GWTIER2 Data Entry Sheet

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 [X]

ENTER Chemical CAS No. (numbers only, no dashes)	**ENTER** Initial groundwater conc., C_w (µg/L)	Cannot calculate risk-based concentration and incremental risk simultaneously.
		Chemical

Figure 6. Example Error Message on Data Entry Sheet

RISK-BASED SOIL CONCENTRATION CALCULATIONS:

Indoor exposure soil conc., carcinogen (µg/kg)	Indoor exposure soil conc., noncarcinogen (µg/kg)	Risk-based indoor exposure soil conc., (µg/kg)	Soil saturation conc., C_{sat} (µg/kg)	Final indoor exposure soil conc., (µg/kg)
NA	NA	NA	4.81E+05	NA

INCREMENTAL RISK CALCULATIONS:

Incremental risk from vapor intrusion to indoor air, carcinogen (unitless)	Hazard quotient from vapor intrusion to indoor air, noncarcinogen (unitless)
2.9E-05	NA

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

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

Figure 7. Example Error Message on Results Sheet

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 B.

1. *Calculate Risk-Based Concentration* OR *Calculate Incremental Risks from Actual Concentration* (All 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 97 chemicals and their associated properties are included with each model; see Section 4.4 for instructions on adding/revising chemicals.

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

   Enter a value only if incremental risks are to be calculated. Be sure to enter the concentration in units of µg/kg (soil) or µg/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)

   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. Another source of information may be your State groundwater protection regulatory agency.

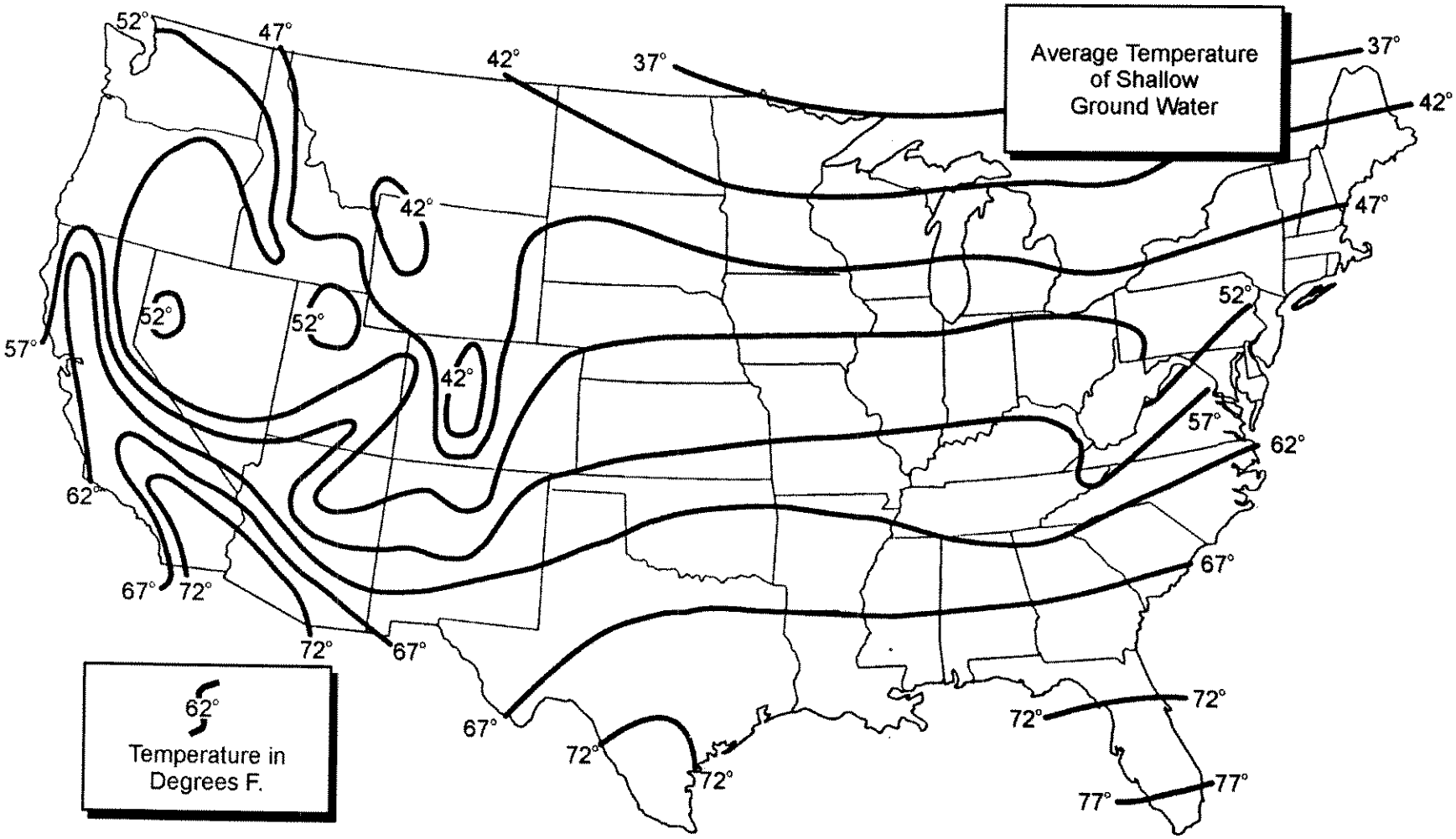


Figure 8. Average Shallow Groundwater Temperature in the United States

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

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)

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.

7. *Depth Below Grade to Water Table* (Groundwater Models Only)

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 type 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* (Soil Tier-2 Model Only)

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"* (Tier-2 Models Only)

In the tier-2 models, the user can define up to three soil strata between the soil surface and the top of contamination. 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 top of the water table, 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* (Tier-2 Models Only)

Enter one of the following SCS soil type abbreviations:

Abbreviation	SCS Soil Type
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	Silt loam
SL	Sandy loam

To determine the correct soil type, see the SCS soil textural classification triangle in Figure 3.

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* (Tier-2 Models Only)

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:

Soil type	Soil vapor permeability, cm^2
Medium sand	1.0×10^{-7} to 1.0×10^{-6}
Fine sand	1.0×10^{-8} to 1.0×10^{-7}
Silty sand	1.0×10^{-9} to 1.0×10^{-8}
Clayey silts	1.0×10^{-10} to 1.0×10^{-9}

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

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

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

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* (Groundwater Tier-2 Models Only)

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)

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* (Tier-2 Models Only)

Enter the average soil dry bulk density for the appropriate soil stratum. 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* (Tier-2 Models Only)

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* (Tier-2 Models Only)

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 as they may not be representative of long-term conditions.

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 rainfall 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 2 and 4 (i.e., θ_s, θ_r, N, α, and K_s). The HYDRUS model is available from the U.S. Department of Agriculture - Agricultural Research Service in Riverside, California via their internet website at http://www.ussl.ars.usda.gov/MODELS/HYDRUS.HTM.
Schapp et al. (1997) recently developed a hierarchical neural network approach to predict van Genuchten (1980) soil hydraulic properties from

basic soil properties. They concluded that of all the published models with which they compared their results, only the models of Vereecken et al. (1989) compared favorably. Vereecken et al. (1989) and Vereecken et al. (1990) developed a series of nonlinear regression equations to predict the soil hydraulic parameters of van Genuchten (1980) using simple soil properties such as particle size distribution, dry bulk density, and carbon content. With estimates of these values, the HYDRUS model may be employed to calculate long-term average soil moisture contents by soil stratum.

19. *Stratum "X" Soil Organic Carbon Fraction* (Soil Tier-2 Models Only)

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 (Nelson and Sommers, 1982). 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)

Because the screening-level models accommodate only one soil stratum above the top of contamination, enter the depth-averaged soil dry bulk density. The default value is 1.5 g/cm^3 which is consistent with U.S. EPA (1996a and b) for subsurface soils.

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

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)

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)

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* (Tier-2 Models Only)

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 15 cm which is consistent with Johnson and Ettinger (1991).

25. *Soil-Building Pressure Differential* (Tier-2 Models Only)

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 (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-s^2).

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* (Tier-2 Models Only)

The default value is 961 cm (see Variable No. 28).

27. *Enclosed Space Floor Width* (Tier-2 Models Only)

The default value is 961 cm (see Variable No. 28).

28. *Enclosed Space Height* (Tier-2 Models Only)

The default values of the enclosed space length, width, and height were derived from the average estimated volume of both owner-occupied and rental single-family detached residences in the U.S. (U.S. DOE, 1995). These dimensions assume a living space volume of 451 m^3 divided into two stories of equal volume with ceiling heights of 8 ft (2.44 m). Each floor is assumed to be a square with a total floor area of 92.42 m^2 and equal lengths and widths of 9.61 m. The total height of the living space is 2 x 2.44 m or 4.88 m.

29. *Floor-Wall Seam Crack Width* (Tier-2 Models Only)

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-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 joints between wall and floor slabs of residential structures in Canada of approximately 300 cm^2. Therefore, given the default floor length and width of 961 cm, a gap width (w) of 0.1 cm equates to a total gap area of 384 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* (Tier-2 Models Only)

The indoor air exchange rate is used, along with the building dimensions, to calculate the building ventilation rate. The default value of the indoor air exchange rate is 0.45/h. This value is consistent with both the geometric mean and the 50th percentile of houses in all regions of the U.S. as reported in Koontz and Rector (1995). This value is also consistent with the average 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.

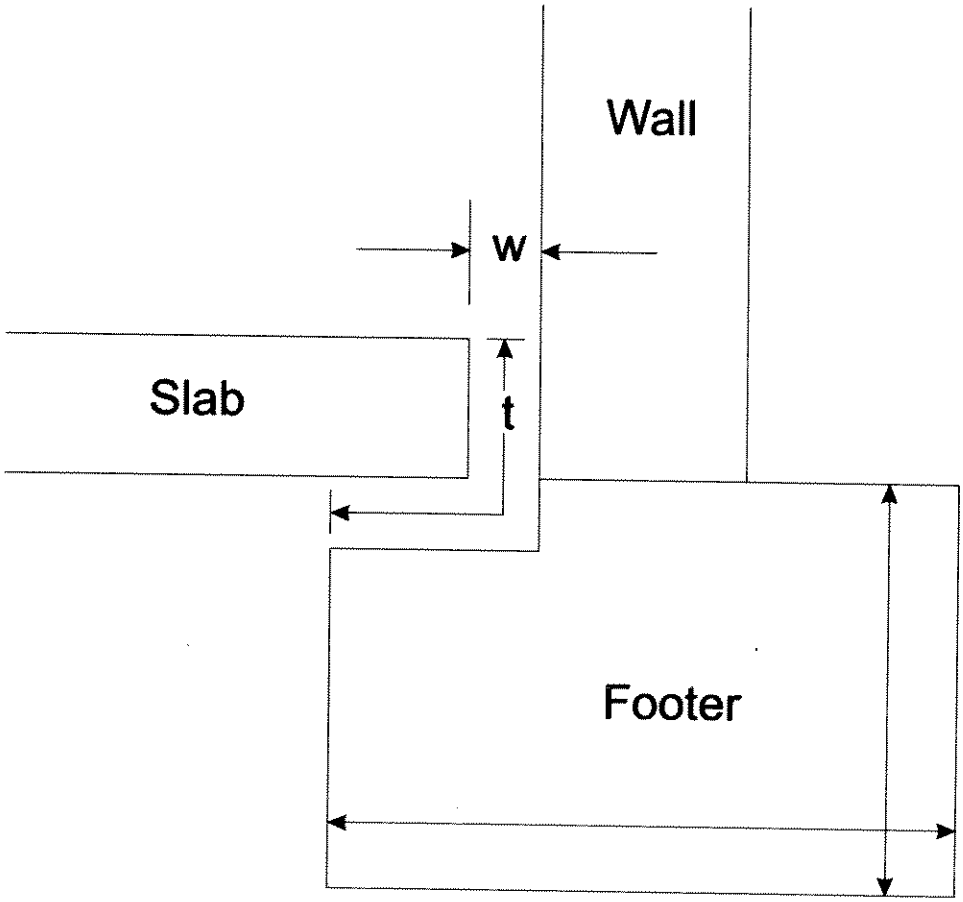


Figure 9. Floor Slab and Foundation

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

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

32. *Averaging Time for Noncarcinogens* (All Models)

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)

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)

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 Models)

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 Models)

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

SECTION 4

THE RESULTS SHEET AND ANCILLARY SHEETS

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).

4.1 THE RESULTS SHEET (RESULTS)

Once all data are entered in the data entry sheet, the model results may be viewed on the RESULTS sheet. Model 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 tier-2 models, the user should check the 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. All data in the results sheet are protected.

4.2 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.

4.3 THE INTERMEDIATE CALCULATIONS SHEET (INTERCALCS)

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.

4.4 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 Carsel and Parrish (1988) (see Tables 2 and 4) and the mean grain diameter data of Nielson and Rogers (1990) (see Table 3) by SCS soil type. The second table contains all of the chemical and toxicological data for all of the chemicals included with each model.

Data for any chemical may be edited, new chemicals added, or existing chemicals deleted from the Chemical Properties Lookup Table. To begin an editing session, the user must unprotect (unseal) the worksheet (the password is "ABC" in capital letters); editing of individual elements or deletion of chemicals may then proceed. Space has been allocated for up to 150 chemicals in the lookup table. Row number 171 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 5

MODEL ASSUMPTIONS AND LIMITATIONS

The following is a discussion of the major assumptions and limitations of the Johnson and Ettinger vapor intrusion model as well as the ancillary models for estimating the vapor concentration at the source of contamination, soil vapor permeability, the rise of the capillary zone, and the effective diffusion coefficient across the capillary zone.

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 is 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) and will overpredict vapor concentrations in such cases. 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. Therefore, use of these models to calculate incremental risks under inappropriate conditions will cause erroneous results.

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, the final soil concentration will be set equal to the soil saturation concentration. This tends to eliminate the possibility of allowing a residual phase to exist within the soil column.

Likewise, the groundwater models will compare the calculated risk-based groundwater concentration to the aqueous solubility limit of the compound and will limit the allowed concentration to a value less than or equal to the solubility limit.

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 pump 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.

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 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 is 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 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 episodic rises 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 Johnson and Ettinger 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 differential (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 transport by convection (e.g., water infiltration) and by mechanical dispersion are neglected. Transformation processes (e.g., biodegradation, hydrolysis, etc.) are also neglected.

A recent empirical field study (Fitzpatrick and Fitzgerald, 1997) indicates that the model may be overly conservative for nonchlorinated species (e.g., benzene, toluene, ethybenzene 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 Johnson and Ettinger 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

VALUES FOR INPUT VARIABLES

The Johnson and Ettinger model as constructed within the accompanying spreadsheets requires a range of input variables depending on whether a screening-level or tier-2 model is chosen.

Table 5 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 5 also includes references for each value or range of values.

Table 6 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.

TABLE 5. RANGE OF VALUES, SENSITIVITY, AND UNCERTAINTY OF MODEL INPUT PARAMETERS

Input parameter	Practical range of values	Default value	Relative model sensitivity	Relative uncertainty
Soil water-filled porosity (θ_w)	0.02 -0.43 cm^3/cm^3[a]	0.30 cm^3/cm^3[a]	High	High
Soil vapor permeability (k_v)	10^{-6} - 10^{-12} cm^2[b,c]	10^{-8} cm^2[d]	High	High
Soil-building pressure differential (ΔP)	0 - 20 Pa[e]	4 Pa[f]	High	High
Media initial concentration (C_R, C_w)	User-defined	NA	High	Moderate
Depth to bottom of soil contamination (L_b)	User-defined	NA	High	Moderate
Depth to top of contamination (L_T)	User-defined	NA	High	Low
Floor-wall seam gap (w)	0.05 - 1.0 cm[e]	0.1 cm[e]	Moderate	High
Soil organic carbon fraction (f_{oc})	0.001 - 0.006[a]	0.002[a]	Moderate	Moderate
Building air exchange rate (ER)	0.18 - 1.26 (h^{-1})[g]	0.45 (h^{-1})[g,h]	Moderate	Moderate
Building volume	147 - 672 m^3[a]	451 m^3[i]	Moderate	Low
Soil total porosity (n)	0.34 - 0.53 cm^3/cm^3[a]	0.43 cm^3/cm^3[a]	Moderate	Low
Soil dry bulk density (ρ_b)	1.25 - 1.75 g/cm^3[a]	1.5 g/cm^3[a]	Low	Low

[a]U.S. EPA (1996a and b).
[b]Johnson and Ettinger (1991).
[c]Nazaroff (1988).
[d]Based on transition point between diffusion and convection dominated transport from Johnson and Ettinger (1991).
[e]Eaton and Scott (1984); Loureiro et al. (1990).
[f]Loureiro et al. (1990); Grimsrud et al. (1983).
[g]Koontz and Rector (1995).
[h]Parker et al. (1990).
[i]U.S. DOE (1995).

TABLE 6. 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 contamination (L_t)	Increase	Decrease
Floor-wall seam gap (w)	Increase	Increase
Soil organic carbon fraction (f_{oc})	Increase	Decrease
Building air exchange rate (ER)	Increase	Decrease
Building volume[c]	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 tier-2 model for soil contamination.
[c]Used with building air exchange rate to calculate building ventilation rate.

SECTION 7

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 Johnson and Ettinger 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 monitoring 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 an actual or hypothetical structure. Once a representative average concentration is determined, all vapor directly below the areal extent of the building is presumed to enter the structure. This concentration, along with the building ventilation rate, will determine the indoor concentration. When using soil gas measurements, it must be remembered that no analysis has been made concerning the source of contamination. Therefore, the calculated indoor concentration must be assumed to be steady-state. Soil gas monitoring may also be used to help calibrate the theoretical equilibrium partitioning and diffusion transport considerations of the model. The reader is 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 has been limited to radon studies 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.

REFERENCES

1. 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.

2. Carsel, R. F., and R. S. Parrish. 1988. Developing joint probability distributions of soil water retention characteristics. Water Resources Research, 24(5):755-769.

3. Eaton, R. S., and A. G. Scott. 1984. Understanding radon transport into houses. Radiation Protection Dosimetry, 7:251-253.

4. Fetter, C. W. 1994. Applied Hydrogeology, 3rd Ed., Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

5. 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.

6. Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

7. Freijer, J. I. 1994. Calibration of jointed tube model for the gas diffusion coefficient in soils. Soil Sci. Soc. Am. J., 58:1067-1076.

8. Gillham, R. W. 1984. The capillary fringe and its effect on water table response. Journal of Hydrology, 67:307-324.

9. 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., ASHRNE. SP38, pp. 422-452, Atlanta, Georgia.

10. Johnson, P. C., and R. A. Ettinger. 1991. Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. Environ. Sci. Technology, 25:1445-1452.

11. 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.

12. Koontz, M. D., and H. E. Rector. 1995. Estimation of Distributions for Residential Air Exchange Rates. EPA Contract No. 68-D9-0166, Work Assignment No. 3-19, U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington, D.C.

13. Lohman, S. W. 1972. Ground-Water Hydraulics. Geological Survey Professional Paper 708, U.S. Department of the Interior, Washington, D.C.

14. 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.

15. Lyman, W. J., W. F. Reehl, and D. H. Rosenblatt. 1990. Handbook of Chemical Property Estimation Methods. American Chemical Society, Washington, D.C.

16. McCarthy, K. A., and R. L. Johnson. 1993. Transport of volatile organic compounds across the capillary fringe. Water Resources Research, 29(6):1675-1683.

17. Millington, R. J., and J. M. Quirk. 1961. Permeability of porous solids. Trans. Faraday Soc., 57:1200-1207.

18. Nazaroff, W. W. 1988. Predicting the rate of ^{222}Rn entry from soil into the basement of a dwelling due to pressure-driven air flow. Radiation Protection Dosimetry, 24:199-202.

19. 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.

20. 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.

21. 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.

22. 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.

23. 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.

24. 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.

25. Put, L. W., and R. J. Meijer. 1989. Luchtdrukverschillen in en rond een woning; implicaties voor het transport van radon. Kernfysisch Versneller Instituut, Groningen University, The Netherlands.

26. Schaap, M. G., F. J. Leij, and M. Th. van Genuchten. 1997. Neural network analysis for hierachical 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.

27. U.S. Department of Energy (DOE). Housing Characteristics 1995, Report No. DOE/EIA-0314(93). U.S. Department of Energy, Energy Information Administration, Washington, D.C.

28. U.S. Environmental Protection Agency (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.

29. U.S. Environmental Protection Agency (EPA). 1995. Review of Mathematical Modeling for Evaluating Soil Vapor Extraction Systems. Office of Research and Development, Washington, D.C. EPA/540/R-95-513.

30. U.S. Environmental Protection Agency (EPA). 1996a. Soil Screening Guidance: User's Guide. Office of Solid Waste and Emergency Response, Washington, D.C. EPA/540/R-96/018.

31. U.S. Environmental Protection Agency (EPA). 1996b. Soil Screening Guidance: Technical Background Document. Office of Solid Waste and Emergency Response, Washington, D.C. EPA/540/R-95/128.

32. 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.

33. 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.

34. Vereecken, H., J. Maes, and J. Feyen. 1990. Estimating unsaturated hydraulic conductivity from easily measured soil properties. Soil Sci., 149:1-12.

35. 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.

36. Waitz, M. F. W., J. Freijer, P. Kreule, and F. Swartjes. 1996. The VOLASOIL Risk Assessment Model Based on CSOIL for Soils Contaminated with Volatile Compounds. Report No. 715810014. National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

APPENDIX A

EXAMPLE WORKSHEETS FOR THE TIER-2 SOIL CONTAMINATION MODEL

DATA ENTRY SHEET

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

YES [X]

OR

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

YES [ ]

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial soil conc., C_a (µg/kg)	Chemical
71432		Benzene

ENTER Average soil temperature, T_s (°C)	ENTER Depth below grade to bottom of enclosed space floor, L_F (cm)	ENTER Depth below grade to top of contamination, L_t (cm)	ENTER Depth below grade to bottom of contamination, (enter value of 0 if value is unknown) L_b (cm)	ENTER Totals must add up to value of L_t (cell D28) Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	ENTER Soil stratum A SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined stratum A soil vapor permeability, k_v (cm²)
10	200	400	600	200	100	100	SCL		

ENTER Stratum A soil dry bulk density, ρ_b^A (g/cm³)	ENTER Stratum A soil total porosity, n^A (unitless)	ENTER Stratum A soil water-filled porosity, θ_w^A (cm³/cm³)	ENTER Stratum A soil organic carbon fraction, f_{oc}^A (unitless)	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm³)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm³/cm³)	ENTER Stratum B soil organic carbon fraction, f_{oc}^B (unitless)	ENTER Stratum C soil dry bulk density, ρ_b^C (g/cm³)	ENTER Stratum C soil total porosity, n^C (unitless)	ENTER Stratum C soil water-filled porosity, θ_w^C (cm³/cm³)	ENTER Stratum C soil organic carbon fraction, f_{oc}^C (unitless)
1.5	0.43	0.15	0.006	1.5	0.43	0.25	0.003	1.7	0.34	0.26	0.002

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP (g/cm-s²)	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)
15	40	961	961	488	0.1	0.45

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	1
				Used to calculate risk-based soil concentration	

CHEMICAL PROPERTIES 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 (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Enthalpy of vaporization at the normal boiling point, ΔH_{vb} (cal/mol)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
8.80E-02	9.80E-06	5.56E-03	25	7,342	353.24	562.16	5.89E+01	1.75E+03	8.3E-06	0.0E+00

INTERMEDIATE CALCULATIONS 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_w (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)	Floor-wall seam perimeter, X_{crack} (cm)	Initial soil concentration used, C_R (µg/kg)	Bldg. ventilation rate, $Q_{building}$ (cm^3/s)
9.46E+08	200	0.280	0.180	0.080	0.152	4.85E-09	0.919	4.46E-09	3.844	1	5.63E+04

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} (atm-m^3/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^{eff}_A (cm^2/s)	Stratum B effective diffusion coefficient, D^{eff}_B (cm^2/s)	Stratum C effective diffusion coefficient, D^{eff}_C (cm^2/s)	Total overall effective diffusion coefficient, D^{eff}_T (cm^2/s)	Diffusion path length, L_d (cm)	Convection path length, L_p (cm)
1.69E+06	2.27E-04	200	8.122	2.69E-03	1.16E-01	1.75E-04	6.86E-03	1.58E-03	1.78E-04	3.19E-04	200	200

Soil-water partition coefficient, K_d (cm^3/g)	Source vapor conc., C_{source} (µg/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(Pe^f) (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ (µg/m^3)	Finite source β term (unitless)	Finite source ψ term $(sec)^{-1}$	Time for source depletion, τ_D (sec)	Exposure duration > time for source depletion (YES/NO)
1.18E-01	4.19E+02	0.10	2.96E+00	6.86E-03	3.84E+02	2.07E+07	NA	NA	1.91E+00	1.97E-09	1.23E+09	NO

Finite source indoor attenuation coefficient, <α> (unitless)	Mass limit bldg. conc., $C_{building}$ (µg/m^3)	Finite source bldg. conc., $C_{building}$ (µg/m^3)	Final finite source bldg. conc., $C_{building}$ (µg/m^3)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
2.07E-05	NA	8.69E-03	8.69E-03	8.3E-06	NA

RESULTS SHEET

RISK-BASED SOIL CONCENTRATION CALCULATIONS:

Indoor exposure soil conc., carcinogen (µg/kg)	Indoor exposure soil conc., noncarcinogen (µg/kg)	Risk-based indoor exposure soil conc., (µg/kg)	Soil saturation conc., C_{sat} (µg/kg)	Final indoor exposure soil conc., (µg/kg)
3.37E+01	NA	3.37E+01	4.83E+05	3.37E+01

ERROR SUMMARY BELOW. (DO NOT USE RESULTS IF ERRORS ARE PRESENT)

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

VLOOKUP TABLES

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.20	0.008	1.09	0.083	0.38	0.068	0.0092
CL	0.26	0.019	1.31	0.237	0.41	0.095	0.016
L	1.04	0.036	1.56	0.359	0.43	0.078	0.020
LS	14.59	0.124	2.28	0.561	0.41	0.057	0.040
S	29.70	0.145	2.68	0.627	0.43	0.045	0.044
SC	0.12	0.027	1.23	0.187	0.38	0.100	0.025
SCL	1.31	0.059	1.48	0.324	0.39	0.100	0.029
SI	0.25	0.016	1.37	0.270	0.46	0.034	0.0046
SIC	0.02	0.005	1.09	0.083	0.26	0.070	0.0039
SICL	0.07	0.010	1.23	0.187	0.43	0.089	0.0056
SIL	0.45	0.020	1.41	0.291	0.45	0.067	0.011
SL	4.42	0.075	1.89	0.471	0.41	0.065	0.030

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H^c (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_H (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, ΔH_v (cal/mol)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
50293	DDT	2.63E+06	1.37E-02	4.95E-06	2.50E-02	3.32E-04	8.10E-06	25	533.15	720.75	11,000	9.7E-05	0.0E+00
50328	Benzo(a)pyrene	1.02E+06	4.30E-02	9.00E-06	1.62E-03	4.63E-05	1.13E-06	25	715.90	969.27	15,000	2.1E-03	0.0E+00
51285	2,4-Dinitrophenol	1.00E-02	2.73E-02	9.06E-06	2.79E+03	1.82E-05	4.44E-07	25	605.28	827.85	15,000	0.0E+00	7.0E-03
53703	Dibenz(a,h)anthracene	3.80E+06	2.02E-02	5.18E-06	2.49E-03	6.03E-07	1.47E-08	25	743.24	990.41	16,000	2.1E-03	0.0E+00
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.05E-02	25	349.90	556.60	7,127	1.5E-05	0.0E+00
56553	Benz(a)anthracene	3.98E+05	5.10E-02	9.00E-06	9.40E-03	1.37E-04	3.34E-06	25	708.15	1004.79	15,000	2.1E-04	0.0E+00
57749	Chlordane	1.20E+05	1.18E-02	4.37E-06	5.60E-02	1.99E-03	4.85E-05	25	624.24	885.73	13,000	3.7E-04	0.0E+00
58899	gamma-HCH (Lindane)	1.07E+03	1.42E-02	7.34E-06	6.80E+00	5.74E-04	1.40E-05	25	596.55	839.36	13,000	3.7E-04	0.0E+00
60571	Dieldrin	2.14E+04	1.25E-02	4.74E-06	1.95E-01	6.19E-04	1.51E-05	25	613.32	842.25	13,000	4.6E-03	0.0E+00
65850	Benzoic Acid	6.00E-01	5.36E-02	7.97E-06	3.50E+03	6.31E-05	1.54E-06	25	720.00	751.00	10,000	0.0E+00	1.4E+01
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.66E-03	25	334.32	536.40	6,988	2.3E-05	0.0E+00
67721	Hexachloroethane	1.78E+03	2.50E-03	6.80E-06	5.00E+01	1.59E-01	3.88E-03	25	458.00	695.00	9,510	4.0E-06	0.0E+00
71363	Butanol	6.92E+00	8.00E-02	9.30E-06	7.40E+04	3.61E-04	8.80E-06	25	390.88	563.05	10,346	0.0E+00	3.5E-01
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.56E-03	25	353.24	562.16	7,342	8.3E-06	0.0E+00
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	1.0E+00
72208	Endrin	1.23E+04	1.25E-02	4.74E-06	2.50E-01	3.08E-04	7.51E-06	25	718.15	986.20	12,000	0.0E+00	1.1E-03
72435	Methoxychlor	9.77E+04	1.56E-02	4.46E-06	4.50E-02	6.48E-04	1.58E-05	25	651.02	848.49	14,000	0.0E+00	1.8E-02
72548	DDD	1.00E+06	1.69E-02	4.76E-06	9.00E-02	1.64E-04	4.00E-06	25	639.90	863.77	14,000	6.9E-05	0.0E+00
72559	DDE	4.47E+06	1.44E-02	5.87E-06	1.20E-01	8.61E-04	2.10E-05	25	636.44	860.38	13,000	9.7E-05	0.0E+00
74839	Methyl bromide	1.05E+01	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-06	2.76E+03	1.11E+00	2.71E-02	25	259.25	432.00	5,250	8.4E-05	0.0E+00
75092	Methylene chloride	1.17E+01	1.01E-01	1.17E-05	1.30E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00
75150	Carbon disulfide	4.57E+01	1.04E-01	1.00E-05	1.19E+03	1.24E+00	3.02E-02	25	319.00	552.00	6,391	0.0E+00	7.0E-01
75252	Bromoform	8.71E+01	1.49E-02	1.03E-05	3.10E+03	2.19E-02	5.34E-04	25	422.35	696.00	9,479	1.1E-06	0.0E+00
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	0.0E+00
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.61E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	0.0E+00
76448	Heptachlor	1.41E+06	1.12E-02	5.69E-06	1.80E-01	4.47E-02	1.09E-03	25	603.69	846.31	13,000	1.3E-03	0.0E+00
77474	Hexachlorocyclopentadiene	2.00E+05	1.61E-02	7.21E-06	1.80E+00	1.11E+00	2.71E-02	25	512.15	746.00	10,931	0.0E+00	7.0E-05
78591	Isophorone	4.68E+01	6.23E-02	6.76E-06	1.20E+04	2.72E-04	6.63E-06	25	488.35	715.00	10,271	2.7E-07	0.0E+00
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	0.0E+00	4.0E-03
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.12E-04	25	386.15	602.00	8,322	1.6E-05	0.0E+00
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.7E-06	0.0E+00
79345	1,1,2,2-Tetrachloroethane	9.33E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.44E-04	25	419.60	661.15	8,996	5.8E-05	0.0E+00
83329	Acenaphthene	7.08E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01
84662	Diethylphthalate	2.88E+02	2.56E-02	6.35E-06	1.08E+03	1.85E-05	4.51E-07	25	567.15	757.00	13,733	0.0E+00	2.8E+00
84742	Di-n-butyl phthalate	3.39E+04	4.38E-02	7.86E-06	1.12E+01	3.85E-08	9.39E-10	25	613.15	798.67	14,751	0.0E+00	3.5E-01
85687	Butyl benzyl phthalate	5.75E+04	1.74E-02	4.83E-06	2.69E+00	5.17E-05	1.26E-06	25	660.60	839.68	13,000	0.0E+00	7.0E-01
86306	N-Nitrosodiphenylamine	1.29E+03	3.12E-02	6.35E-06	3.51E+01	2.05E-04	5.00E-06	25	632.28	890.45	13,000	1.4E-06	0.0E+00
86737	Fluorene	1.38E+04	3.63E-02	7.88E-06	1.98E+00	2.61E-03	6.37E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01
86748	Carbazole	3.39E+03	3.90E-02	7.03E-06	7.48E+00	6.26E-07	1.53E-08	25	627.87	899.00	13,977	5.7E-06	0.0E+00

87683	Hexachloro-1,3-butadiene	5.37E+04	5.61E-02	6.16E-06	3.23E+00	3.34E-01	8.15E-03	25	486.15	738.00	10,206	2.2E-05	0.0E+00
87865	Pentachlorophenol	5.92E+02	5.60E-02	6.10E-06	1.95E+03	1.00E-06	2.44E-08	25	582.15	813.20	14,000	3.4E-05	0.0E+00
88062	2,4,6-Trichlorophenol	3.81E+02	3.18E-02	6.25E-06	8.00E+02	3.19E-04	7.78E-06	25	519.15	749.03	12,000	3.1E-06	0.0E+00
91203	Naphthalene	2.00E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	1.4E-01
91941	3,3-Dichlorobenzidine	7.24E+02	1.94E-02	6.74E-06	3.11E+00	1.64E-07	4.00E-09	25	560.26	754.03	13,000	1.3E-04	0.0E+00
95476	o-Xylene	3.63E+02	8.70E-02	1.00E-05	1.78E+02	2.13E-01	5.20E-03	25	417.60	630.30	8,661	0.0E+00	7.0E+00
95487	2-Methylphenol (o-cresol)	9.12E+01	7.40E-02	8.30E-06	2.60E+04	4.92E-05	1.20E-06	25	464.19	697.60	10,800	0.0E+00	1.8E-01
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	2.0E-01	0.0E+00
95578	2-Chlorophenol	3.88E+02	5.01E-02	9.46E-06	2.20E+04	1.60E-02	3.90E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02
95954	2,4,5-Trichlorophenol	1.60E+03	2.91E-02	7.03E-06	1.20E+03	1.78E-04	4.34E-06	25	526.15	759.13	13,000	0.0E+00	3.5E-01
98953	Nitrobenzene	6.46E+01	7.60E-02	8.60E-06	2.09E+03	9.84E-04	2.40E-05	25	483.95	719.00	10,566	0.0E+00	2.0E-03
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	0.0E+00	1.0E+00
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.76E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00
105679	2,4-Dimethylphenol	2.09E+02	5.84E-02	8.69E-06	7.87E+03	8.20E-05	2.00E-06	25	484.13	707.60	11,329	0.0E+00	7.0E-02
106423	p-Xylene	3.89E+02	7.69E-02	8.44E-06	1.85E+02	3.14E-01	7.66E-03	26	411.52	616.20	8,525	0.0E+00	7.0E+00
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	8.0E-01	0.0E+00
106478	p-Chloroaniline	6.61E+01	4.83E-02	1.01E-05	5.30E+03	1.36E-05	3.32E-07	25	503.65	754.00	11,689	0.0E+00	1.4E-02
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.78E-04	25	356.65	561.00	7,643	2.6E-05	0.0E+00
108054	Vinyl acetate	5.25E+00	8.50E-02	9.20E-06	2.00E+04	2.10E-02	5.12E-04	25	345.65	519.13	7,800	0.0E+00	2.0E-01
108383	m-Xylene	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	7.0E+00
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.63E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.71E-03	25	404.87	632.40	8,410	0.0E+00	2.0E-02
108952	Phenol	2.88E+01	8.20E-02	9.10E-06	8.28E+04	1.63E-05	3.98E-07	25	455.02	694.20	10,920	0.0E+00	2.1E+00
111444	Bis(2-chloroethyl)ether	1.55E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00
115297	Endosulfan	2.14E+03	1.15E-02	4.55E-06	5.10E-01	4.59E-04	1.12E-05	25	674.43	942.94	14,000	0.0E+00	2.1E-02
117817	Bis(2-ethylhexyl)phthalate	1.51E+07	3.51E-02	3.66E-06	3.40E-01	4.18E-06	1.02E-07	25	657.15	806.00	15,999	4.0E-06	0.0E+00
117840	Di-n-octyl phthalate	8.32E+07	1.51E-02	3.58E-06	2.00E-02	2.74E-03	6.68E-05	25	704.09	862.22	15,000	0.0E+00	7.0E-02
118741	Hexachlorobenzene	5.50E+04	5.42E-02	5.91E-06	6.20E+00	5.41E-02	1.32E-03	25	582.55	825.00	14,447	4.6E-04	0.0E+00
120127	Anthracene	2.95E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.51E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01
120832	2,4-Dichlorophenol	1.47E+02	3.46E-02	8.77E-06	4.50E+03	1.30E-04	3.17E-06	25	482.15	708.17	11,000	0.0E+00	1.1E-02
121142	2,4-Dinitrotoluene	9.55E+01	2.03E-01	7.06E-06	2.70E+02	3.80E-06	9.27E-08	25	590.00	814.00	13,467	1.9E-04	0.0E+00
124481	Chlorodibromomethane	6.31E+01	1.96E-02	1.05E-05	2.60E+03	3.21E-02	7.83E-04	25	416.14	678.20	8,000	2.4E-05	0.0E+00
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	5.8E-07	0.0E+00
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.07E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.39E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02
193395	Indeno(1,2,3-cd)pyrene	3.47E+06	1.90E-02	5.66E-06	2.20E-05	6.56E-05	1.60E-06	25	809.15	1078.24	17,000	2.1E-04	0.0E+00
205992	Benzo(b)fluoranthene	1.23E+06	2.26E-02	5.56E-06	1.50E-03	4.55E-03	1.11E-04	25	715.90	969.27	15,000	2.1E-04	0.0E+00
206440	Fluoranthene	1.07E+05	3.02E-02	6.35E-06	2.06E-01	6.60E-04	1.61E-05	25	655.95	905.00	13,815	0.0E+00	1.4E-01
207089	Benzo(k)fluoranthene	1.23E+06	2.26E-02	5.56E-06	8.00E-04	3.40E-05	8.29E-07	25	753.15	1019.70	16,000	2.1E-05	0.0E+00
218019	Chrysene	3.98E+05	2.48E-02	6.21E-06	1.60E-03	3.88E-03	9.46E-05	25	714.15	979.00	16,455	2.1E-06	0.0E+00
309002	Aldrin	2.45E+06	1.32E-02	4.86E-06	1.80E-01	6.97E-03	1.70E-04	25	603.01	839.37	13,000	4.9E-03	0.0E+00
319846	alpha-HCH (alpha-BHC)	1.23E+03	1.42E-02	7.34E-06	2.00E+00	4.35E-04	1.06E-05	25	596.55	839.36	13,000	1.8E-03	0.0E+00
319857	beta-HCH (beta-BHC)	1.26E+03	1.42E-02	7.34E-06	2.40E-01	3.05E-05	7.44E-07	25	596.55	839.36	13,000	5.3E-04	0.0E+00
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	3.7E-05	2.0E-02
606202	2,6-Dinitrotoluene	6.92E+01	3.27E-02	7.26E-06	1.82E+02	3.06E-05	7.46E-07	25	558.00	770.00	12,938	1.9E-04	0.0E+00
621647	N-Nitrosodi-n-propylamine	2.40E+01	5.45E-02	8.17E-06	9.89E+03	9.23E-05	2.25E-06	25	509.60	746.87	11,000	2.0E-03	0.0E+00
1024573	Heptachlor epoxide	8.32E+04	1.32E-02	4.23E-06	2.00E-01	3.90E-04	9.51E-06	25	613.96	848.76	13,000	2.6E-03	0.0E+00
7439976	Mercury (elemental)	5.20E+01	3.07E-02	6.30E-06	5.62E-02	4.67E-01	1.14E-02	25	629.88	1750.00	14,127	0.0E+00	3.0E-04
8001352	Toxaphene	2.57E+05	1.16E-02	4.34E-06	7.40E-01	2.46E-04	6.00E-06	25	657.15	873.31	14,000	3.2E-04	0.0E+00
11096825	Aroclor 1260 (PCB-1260)	2.90E+05	1.38E-02	4.32E-06	8.00E-02	1.89E-01	4.60E-03	25	402.50	539.37	19,000	1.0E-04	0.0E+00
11097691	Aroclor 1254 (PCB-1254)	2.00E+05	1.56E-02	5.00E-06	5.70E-02	8.20E-02	2.00E-03	25	377.50	512.27	19,000	1.0E-04	0.0E+00
12674112	Aroclor 1016 (PCB-1016)	3.30E+04	2.22E-02	5.42E-06	4.20E-01	1.19E-02	2.90E-04	25	340.50	475.22	18,000	1.0E-04	0.0E+00
53469219	Aroclor 1242 (PCB-1242)	3.30E+04	2.14E-02	5.31E-06	3.40E-01	2.13E-02	5.20E-04	25	345.50	482.20	18,000	1.0E-04	0.0E+00

APPENDIX B

SAMPLE DATA ENTRY SHEETS FOR EACH MODEL

DATA ENTRY SHEET (SLSCREEN)

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

YES [X]

OR

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

YES [ ]

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial soil conc., C_n (µg/kg)	Chemical
71432		Benzene

ENTER Depth below grade to bottom of enclosed space floor, L_F (15 or 200 cm)	ENTER Depth below grade to top of contamination, L_s (cm)	ENTER Average soil temperature, T_S (°C)	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)
200	400	10	SCL		

ENTER Vadose zone soil dry bulk density, ρ_b^A (g/cm³)	ENTER Vadose zone soil total porosity, n^V (unitless)	ENTER Vadose zone soil water-filled porosity, θ_w^V (cm^3/cm^3)	ENTER Vadose zone soil organic carbon fraction, f_{oc}^V (unitless)
1.5	0.43	0.3	0.002

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	1
				Used to calculate risk-based soil concentration.	

DATA ENTRY SHEET (GWSCREEN)

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 (µg/L)	Chemical
71432		Benzene

ENTER Depth below grade to bottom of enclosed space floor, L_f (15 or 200 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 (°C)
200	400	SC	10

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 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)
SCL			1.5	0.43	0.3

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.

DATA ENTRY SHEET (SLTIER2)

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

YES [X]

OR

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

YES [ ]

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial soil conc., C_{si} (µg/kg)	Chemical
71432		Benzene

ENTER Average soil temperature, T_s (°C)	ENTER Depth below grade to bottom of enclosed space floor, L_f (cm)	ENTER Depth below grade to top of contamination, L_t (cm)	ENTER Depth below grade to bottom of contamination, (enter value of 0 if value is unknown) L_b (cm)	ENTER Totals must add up to value of L_t (cell D28) Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	ENTER Soil stratum A SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined stratum A soil vapor permeability, k, (cm^2)
10	200	400	600	200	100	100	SCL		

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 A soil organic carbon fraction, f_{oc}^A (unitless)	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 B soil organic carbon fraction, f_{oc}^B (unitless)	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)	ENTER Stratum C soil organic carbon fraction, f_{oc}^C (unitless)
1.5	0.43	0.15	0.006	1.5	0.43	0.25	0.003	1.7	0.34	0.26	0.002

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	488	0.1	0.45

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	1

Used to calculate risk-based soil concentration.

DATA ENTRY SHEET (GWTIER2)

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 (µg/L)	Chemical
71432		Benzene

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 Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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, (cm^2)
			Totals must add up to value of L_{WT} (cell D28)							
10	200	400	300	50	50	C	SC	L		

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 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 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)
1.5	0.43	0.2	1.7	0.42	0.27	1.7	0.43	0.3

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	488	0.1	0.45

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	1
				Used to calculate risk-based groundwater concentration.	

APPENDIX C

CHEMICAL PROPERTIES LOOKUP TABLE AND REFERENCES

CHEMICAL PROPERTIES AND REFERENCES

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)		Diffusivity in air, D_a (cm^2/s)		Diffusivity in water, D_w (cm^2/s)		Pure component water solubility, S (mg/L)		Henry's law constant H' (unitless)		Henry's law constant at reference temperature, H (atm-m^3/mol)		Henry's law constant reference temperature, T_h (°C)		Normal boiling point, T_B (°K)		Critical temperature, T_C (°K)		Enthalpy of vaporization at the normal boiling point, ΔH_{vb} (cal/mol)		Unit risk factor, URF ($\mu g/m^3)^{-1}$		Reference conc., RfC (mg/m^3)	
50293	DDT	2.63E+06	1	1.37E-02	1	4.95E-06	1	2.50E-02	1	3.32E-04	1	8.10E-06	5	25	1	533.15	7	720.75	11	11,000	12	9.7E-05	1		
50328	Benzo(a)pyrene	1.02E+06	1	4.30E-02	1	9.00E-06	1	1.62E-03	1	4.63E-05	1	1.13E-06	5	25	1	715.90	8	969.27	11	15,000	12	2.1E-03	13		
51285	2,4-Dinitrophenol	1.00E-02	1	2.73E-02	1	9.06E-06	1	2.79E+03	1	1.82E-05	1	4.44E-07	5	25	1	605.28	8	827.85	11	15,000	12			7.0E-03	13
53703	Dibenz(a,h)anthracene	3.80E+06	1	2.02E-02	1	5.18E-06	1	2.49E-03	1	6.03E-07	1	1.47E-08	5	25	1	743.24	8	990.41	11	16,000	12	2.1E-03	13		
56235	Carbon tetrachloride	1.74E+02	1	7.80E-02	1	8.80E-06	1	7.93E+02	1	1.25E+00	1	3.05E-02	5	25	1	349.90	9	556.60	9	7,127	9	1.5E-05	1		
56553	Benz(a)anthracene	3.98E+05	1	5.10E-02	1	9.00E-06	1	9.40E-03	1	1.37E-04	1	3.34E-06	5	25	1	708.15	8	1004.79	11	15,000	12	2.1E-04	13		
57749	Chlordane	1.20E+05	1	1.18E-02	1	4.37E-06	1	5.60E-02	1	1.99E-03	1	4.85E-05	5	25	1	624.24	8	885.73	11	13,000	12	3.7E-04	1		
58899	gamma-HCH (Lindane)	1.07E+03	1	1.42E-02	1	7.34E-06	1	6.80E+00	1	5.74E-04	1	1.40E-05	5	25	1	596.55	7	839.36	11	13,000	12	3.7E-04	13		
60571	Dieldrin	2.14E+04	1	1.25E-02	1	4.74E-06	1	1.95E-01	1	6.19E-04	1	1.51E-05	5	25	1	613.32	8	842.25	11	13,000	12	4.6E-03	1		
65850	Benzoic Acid	6.00E-01	1	5.36E-02	1	7.97E-06	1	3.50E+03	1	6.31E-05	1	1.54E-06	5	25	1	720.00	10	751.00	10	10,000	12			1.4E+01	13
67641	Acetone	5.75E-01	1	1.24E-01	1	1.14E-05	1	1.00E+06	1	1.59E-03	1	3.88E-05	5	25	1	329.20	9	508.10	9	6,955	9			3.5E-01	13
67663	Chloroform	3.98E+01	1	1.04E-01	1	1.00E-05	1	7.92E+03	1	1.50E-01	1	3.66E-03	5	25	1	334.32	9	536.40	9	6,988	9	2.3E-05	1		
67721	Hexachloroethane	1.78E+03	1	2.50E-03	1	6.80E-06	1	5.00E+01	1	1.59E-01	1	3.88E-03	5	25	1	458.00	10	695.00	10	9,510	10	4.0E-06	1		
71363	Butanol	6.92E+00	1	8.00E-02	1	9.30E-06	1	7.40E+04	1	3.61E-04	1	8.80E-06	5	25	1	390.88	9	563.05	9	10,346	9			3.5E-01	13
71432	Benzene	5.89E+01	1	8.80E-02	1	9.80E-06	1	1.75E+03	1	2.28E-01	1	5.56E-03	5	25	1	353.24	9	562.16	9	7,342	9	8.3E-06	1		
71556	1,1,1-Trichloroethane	1.10E+02	1	7.80E-02	1	8.80E-06	1	1.33E+03	1	7.05E-01	1	1.72E-02	5	25	1	347.24	9	545.00	9	7,136	9			1.0E+00	1
72208	Endrin	1.23E+04	1	1.25E-02	1	4.74E-06	1	2.50E-01	1	3.08E-04	1	7.51E-06	5	25	1	718.15	9	986.20	11	12,000	12			1.1E-03	13
72435	Methoxychlor	9.77E+04	1	1.56E-02	1	4.46E-06	1	4.50E-02	1	6.48E-04	1	1.58E-05	5	25	1	651.02	8	848.49	11	14,000	12			1.8E-02	13
72548	DDD	1.00E+06	1	1.69E-02	1	4.76E-06	1	9.00E-02	1	1.64E-04	1	4.00E-06	5	25	1	639.90	8	863.77	11	14,000	12	6.9E-05	13		
72559	DDE	4.47E+06	1	1.44E-02	1	5.87E-06	1	1.20E-01	1	8.61E-04	1	2.10E-05	5	25	1	636.44	8	860.38	11	13,000	12	9.7E-05	13		
74839	Methyl bromide	1.05E+01	1	7.28E-02	1	1.21E-05	1	1.52E+04	1	2.56E-01	1	6.24E-03	5	25	1	276.71	9	467.00	10	5,714	9			5.0E-03	1
75014	Vinyl chloride (chloroethene)	1.86E+01	1	1.06E-01	1	1.23E-06	1	2.76E+03	1	1.11E+00	1	2.71E-02	5	25	1	259.25	10	432.00	10	5,250	10	8.4E-05	1		
75092	Methylene chloride	1.17E+01	1	1.01E-01	1	1.17E-05	1	1.30E+04	1	8.98E-02	1	2.19E-03	5	25	1	313.00	9	510.00	9	6,706	9	4.7E-07	1	3.0E+00	1
75150	Carbon disulfide	4.57E+01	1	1.04E-01	1	1.00E-05	1	1.19E+03	1	1.24E+00	1	3.02E-02	5	25	1	319.00	9	552.00	9	6,391	9			7.0E-01	1
75252	Bromoform	8.71E+01	1	1.49E-02	1	1.03E-05	1	3.10E+03	1	2.19E-02	1	5.34E-04	5	25	1	422.35	10	696.00	10	9,479	9	1.1E-06	1		
75274	Bromodichloromethane	5.50E+01	1	2.98E-02	1	1.06E-05	1	6.74E+03	1	6.56E-02	1	1.60E-03	5	25	1	363.15	7	585.85	11	7,000	12	1.8E-05	13		
75343	1,1-Dichloroethane	3.16E+01	1	7.42E-02	1	1.05E-05	1	5.06E+03	1	2.30E-01	1	5.61E-03	5	25	1	330.55	9	523.00	9	6,895	9			5.0E-01	1
75354	1,1-Dichloroethylene	5.89E+01	1	9.00E-02	1	1.04E-05	1	2.25E+03	1	1.07E+00	1	2.61E-02	5	25	1	304.75	9	576.05	9	6,247	9	5.0E-05	1		
76448	Heptachlor	1.41E+06	1	1.12E-02	1	5.69E-06	1	1.80E-01	1	4.47E-02	1	1.09E-03	5	25	1	603.69	8	846.31	11	13,000	12	1.3E-03	1		
77474	Hexachlorocyclopentadiene	2.00E+05	1	1.61E-02	1	7.21E-06	1	1.80E+00	1	1.11E+00	1	2.71E-02	5	25	1	512.15	10	746.00	10	10,931	10			7.0E-05	1
78591	Isophorone	4.68E+01	1	6.23E-02	1	6.76E-06	1	1.20E+04	1	2.72E-04	1	6.63E-06	5	25	1	488.35	10	715.00	10	10,271	10	2.7E-07	13		
78875	1,2-Dichloropropane	4.37E+01	1	7.82E-02	1	8.73E-06	1	2.80E+03	1	1.15E-01	1	2.80E-03	5	25	1	369.52	10	572.00	10	7,590	10			4.0E-03	1
79005	1,1,2-Trichloroethane	5.01E+01	1	7.80E-02	1	8.80E-06	1	4.42E+03	1	3.74E-02	1	9.12E-04	5	25	1	386.15	9	602.00	10	8,322	9	1.6E-05	1		
79016	Trichloroethylene	1.66E+02	1	7.90E-02	1	9.10E-06	1	1.10E+03	1	4.22E-01	1	1.03E-02	5	25	1	360.36	9	544.20	9	7,505	9	1.7E-06	1		
79345	1,1,2,2-Tetrachloroethane	9.33E+01	1	7.10E-02	1	7.90E-06	1	2.97E+03	1	1.41E-02	1	3.44E-04	5	25	1	419.60	9	661.15	9	8,996	9	5.8E-05	1		
83329	Acenaphthene	7.08E+03	1	4.21E-02	1	7.69E-06	1	4.24E+00	1	6.36E-03	1	1.55E-04	5	25	1	550.54	10	803.15	10	12,155	10			2.1E-01	13
84662	Diethylphthalate	2.88E+02	1	2.56E-02	1	6.35E-06	1	1.08E+03	1	1.85E-05	1	4.51E-07	5	25	1	567.15	10	757.00	10	13,733	10			2.8E+00	13
84742	Di-n-butyl phthalate	3.39E+04	1	4.38E-02	1	7.86E-06	1	1.12E+01	1	3.85E-08	1	9.39E-10	5	25	1	613.15	9	798.67	11	14,751	9			3.5E-01	13
85687	Butyl benzyl phthalate	5.75E+04	1	1.74E-02	1	4.83E-06	1	2.69E+00	1	5.17E-05	1	1.26E-06	5	25	1	660.60	8	839.68	11	13,000	12			7.0E-01	13
86306	N-Nitrosodiphenylamine	1.29E+03	1	3.12E-02	1	6.35E-06	1	3.51E+01	1	2.05E-04	1	5.00E-06	5	25	1	632.28	8	890.45	11	13,000	12	1.4E-06	13		
86737	Fluorene	1.38E+04	1	3.63E-02	1	7.88E-06	1	1.98E+00	1	2.61E-03	1	6.37E-05	5	25	1	570.44	10	870.00	10	12,666	10			1.4E-01	13
86748	Carbazole	3.39E+03	1	3.90E-02	1	7.03E-06	1	7.48E+00	1	6.26E-07	1	1.53E-08	5	25	1	627.87	10	899.00	10	13,977	10	5.7E-06	13		
87683	Hexachloro-1,3-butadiene	5.37E+04	1	5.61E-02	1	6.16E-06	1	3.23E+00	1	3.34E-01	1	8.15E-03	5	25	1	486.15	10	738.00	10	10,206	10	2.2E-05	1		
87865	Pentachlorophenol	5.92E+02	1	5.60E-02	1	6.10E-06	1	1.95E+03	1	1.00E-06	1	2.44E-08	5	25	1	582.15	9	813.20	11	14,000	12	3.4E-05	13		
88062	2,4,6-Trichlorophenol	3.81E+02	1	3.18E-02	1	6.25E-06	1	8.00E+02	1	3.19E-04	1	7.78E-06	5	25	1	519.15	9	749.03	11	12,000	12	3.1E-06	1		
91203	Naphthalene	2.00E+03	1	5.90E-02	1	7.50E-06	1	3.10E+01	1	1.98E-02	1	4.83E-04	5	25	1	491.14	10	748.40	10	10,373	10			1.4E-01	13
91941	3,3-Dichlorobenzidine	7.24E+02	1	1.94E-02	1	6.74E-06	1	3.11E+00	1	1.64E-07	1	4.00E-09	5	25	1	560.26	8	754.03	11	13,000	12	1.3E-04	13		
95476	o-Xylene	3.63E+02	1	8.70E-02	1	1.00E-05	1	1.78E+02	1	2.13E-01	1	5.20E-03	5	25	1	417.60	9	630.30	9	8,661	9			7.0E+00	13
95487	2-Methylphenol (o-cresol)	9.12E+01	1	7.40E-02	1	8.30E-06	1	2.60E+04	1	4.92E-05	1	1.20E-06	5	25	1	464.19	9	697.60	9	10,800	9			1.8E-01	13
95501	1,2-Dichlorobenzene	6.17E+02	1	6.90E-02	1	7.90E-06	1	1.56E+02	1	7.79E-02	1	1.90E-03	5	25	1	453.57	10	705.00	10	9,700	10	2.0E-01	1		
95578	2-Chlorophenol	3.88E+02	1	5.01E-02	1	9.46E-06	1	2.20E+04	1	1.60E-02	1	3.90E-04	5	25	1	447.53	10	675.00	10	9,572	10			1.8E-02	13
95954	2,4,5-Trichlorophenol	1.60E+03	1	2.91E-02	1	7.03E-06	1	1.20E+03	1	1.78E-04	1	4.34E-06	5	25	1	526.15	9	759.13	11	13,000	12			3.5E-01	13
98953	Nitrobenzene	6.46E+01	1	7.60E-02	1	8.60E-06	1	2.09E+03	1	9.84E-04	1	2.40E-05	5	25	1	483.95	10	719.00	10	10,566	10			2.0E-03	1
100414	Ethylbenzene	3.63E+02	1	7.50E-02	1	7.80E-06	1	1.69E+02	1	3.23E-01	1	7.88E-03	5	25	1	409.34	9	617.20	9	8,501	9			1.0E+00	1
100425	Styrene	7.76E+02	1	7.10E-02	1	8.00E-06	1	3.10E+02	1	1.13E-01	1	2.76E-03	5	25	1	418.31	10	636.00	10	8,737	10			1.0E+00	1
105679	2,4-Dimethylphenol	2.09E+02	1	5.84E-02	1	8.69E-06	1	7.87E+03	1	8.20E-05	1	2.00E-06	5	25	1	484.13	10	707.60	10	11,329	10			7.0E-02	13
106423	p-Xylene	3.89E+02	1	7.69E-02	1	8.44E-06	1	1.85E+02	1	3.14E-01	1	7.66E-03	5	26	1	411.52	9	616.20	9	8,525	9			7.0E+00	13
106467	1,4-Dichlorobenzene	6.17E+02	1	6.90E-02	1	7.90E-06	1	7.38E+01	1	9.96E-02	1	2.43E-03	5	25	1	447.21	10	684.75	10	9,271	10	8.0E-01	1		

CHEMICAL PROPERTIES AND REFERENCES

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)		Diffusivity in air, D_a (cm^2/s)		Diffusivity in water, D_w (cm^2/s)		Pure component water solubility, S (mg/L)		Henry's law constant H' (unitless)		Henry's law constant at reference temperature, H (atm-m^3/mol)		Henry's law constant reference temperature, T_R (°C)		Normal boiling point, T_B (°K)		Critical temperature, T_C (°K)		Enthalpy of vaporization at the normal boiling point, ΔH_{vb} (cal/mol)		Unit risk factor, URF ($\mu g/m^3)^{-1}$		Reference conc., RfC (mg/m^3)	
106478	p-Chloroaniline	6.61E+01	1	4.83E-02	1	1.01E-05	1	5.30E+03	1	1.36E-05	1	3.32E-07	5	25	1	503.65	10	754.00	10	11,689	10			1.4E-02	13
107062	1,2-Dichloroethane	1.74E+01	1	1.04E-01	1	9.90E-06	1	8.52E+03	1	4.01E-02	1	9.78E-04	5	25	1	356.65	9	561.00	9	7,643	9	2.6E-05	1		
108054	Vinyl acetate	5.25E+00	1	8.50E-02	1	9.20E-06	1	2.00E+04	1	2.10E-02	1	5.12E-04	5	25	1	345.65	10	519.13	10	7,800	10			2.0E-01	1
108383	m-Xylene	4.07E+02	1	7.00E-02	1	7.80E-06	1	1.61E+02	1	3.01E-01	1	7.34E-03	5	25	1	412.27	9	617.05	9	8,523	9			7.0E+00	13
108883	Toluene	1.82E+02	1	8.70E-02	1	8.60E-06	1	5.26E+02	1	2.72E-01	1	6.63E-03	5	25	1	383.78	9	591.79	9	7,930	9			4.0E-01	1
108907	Chlorobenzene	2.19E+02	1	7.30E-02	1	8.70E-06	1	4.72E+02	1	1.52E-01	1	3.71E-03	5	25	1	404.87	9	632.40	9	8,410	9			2.0E-02	1
108952	Phenol	2.88E+01	1	8.20E-02	1	9.10E-06	1	8.28E+04	1	1.63E-05	1	3.98E-07	5	25	1	455.02	9	694.20	9	10,920	9			2.1E+00	13
111444	Bis(2-chloroethyl)ether	1.55E+01	1	6.92E-02	1	7.53E-06	1	1.72E+04	1	7.38E-04	1	1.80E-05	5	25	1	451.15	9	659.79	11	9,000	12	3.3E-04	1		
115297	Endosulfan	2.14E+03	1	1.15E-02	1	4.55E-06	1	5.10E-01	1	4.59E-04	1	1.12E-05	5	25	1	674.43	8	942.94	11	14,000	12			2.1E-02	13
117817	Bis(2-ethylhexyl)phthalate	1.51E+07	1	3.51E-02	1	3.66E-06	1	3.40E-01	1	4.18E-06	1	1.02E-07	5	25	1	657.15	10	806.00	10	15,999	10	4.0E-06	13		
117840	Di-n-octyl phthalate	8.32E+07	1	1.51E-02	1	3.58E-06	1	2.00E-02	1	2.74E-03	1	6.68E-05	5	25	1	704.09	8	862.22	11	15,000	12			7.0E-02	13
118741	Hexachlorobenzene	5.50E+04	1	5.42E-02	1	5.91E-06	1	6.20E+00	1	5.41E-02	1	1.32E-03	5	25	1	582.55	10	825.00	10	14,447	10	4.6E-04	1		
120127	Anthracene	2.95E+04	1	3.24E-02	1	7.74E-06	1	4.34E-02	1	2.67E-03	1	6.51E-05	5	25	1	615.18	10	873.00	10	13,121	10			1.1E+00	13
120821	1,2,4-Trichlorobenzene	1.78E+03	1	3.00E-02	1	8.23E-06	1	3.00E+02	1	5.82E-02	1	1.42E-03	5	25	1	486.15	10	725.00	10	10,471	10			2.0E-01	1
120832	2,4-Dichlorophenol	1.47E+02	1	3.46E-02	1	8.77E-06	1	4.50E+03	1	1.30E-04	1	3.17E-06	5	25	1	482.15	9	708.17	11	11,000	12			1.1E-02	13
121142	2,4-Dinitrotoluene	9.55E+01	1	2.03E-01	1	7.06E-06	1	2.70E+02	1	3.80E-06	1	9.27E-08	5	25	1	590.00	10	814.00	10	13,467	10	1.9E-04	13		
124481	Chlorodibromomethane	6.31E+01	1	1.96E-02	1	1.05E-05	1	2.60E+03	1	3.21E-02	1	7.83E-04	5	25	1	416.14	8	678.20	11	8,000	12	2.4E-05	13		
127184	Tetrachloroethylene	1.55E+02	1	7.20E-02	1	8.20E-06	1	2.00E+02	1	7.54E-01	1	1.84E-02	5	25	1	394.40	9	620.20	9	8,288	9	5.8E-07	1		
129000	Pyrene	1.05E+05	1	2.72E-02	1	7.24E-06	1	1.35E-01	1	4.51E-04	1	1.10E-05	5	25	1	667.95	10	936.00	10	14,370	10			1.1E-01	13
156592	cis-1,2-Dichloroethylene	3.55E+01	1	7.36E-02	1	1.13E-05	1	3.50E+03	1	1.67E-01	1	4.07E-03	5	25	1	333.65	10	544.00	10	7,192	10			3.5E-02	13
156605	trans-1,2-Dichloroethylene	5.25E+01	1	7.07E-02	1	1.19E-05	1	6.30E+03	1	3.85E-01	1	9.39E-03	5	25	1	320.85	10	516.50	10	6,717	10			7.0E-02	13
193395	Indeno(1,2,3-cd)pyrene	3.47E+06	1	1.90E-02	1	5.66E-06	1	2.20E-05	1	6.56E-05	1	1.60E-06	5	25	1	809.15	7	1078.24	11	17,000	12	2.1E-04	13		
205992	Benzo(b)fluoranthene	1.23E+06	1	2.26E-02	1	5.56E-06	1	1.50E-03	1	4.55E-03	1	1.11E-04	5	25	1	715.90	8	969.27	11	15,000	12	2.1E-04	13		
206440	Fluoranthene	1.07E+05	1	3.02E-02	1	6.35E-06	1	2.06E-01	1	6.60E-04	1	1.61E-05	5	25	1	655.95	10	905.00	10	13,815	10			1.4E-01	13
207089	Benzo(k)fluoranthene	1.23E+06	1	2.26E-02	1	5.56E-06	1	8.00E-04	1	3.40E-05	1	8.29E-07	5	25	1	753.15	7	1019.70	11	16,000	12	2.1E-05	13		
218019	Chrysene	3.98E+05	1	2.48E-02	1	6.21E-06	1	1.60E-03	1	3.88E-03	1	9.46E-05	5	25	1	714.15	10	979.00	10	16,455	10	2.1E-06	13		
309002	Aldrin	2.45E+06	1	1.32E-02	1	4.86E-06	1	1.80E-01	1	6.97E-03	1	1.70E-04	5	25	1	603.01	8	839.37	11	13,000	12	4.9E-03	1		
319846	alpha-HCH (alpha-BHC)	1.23E+03	1	1.42E-02	1	7.34E-06	1	2.00E+00	1	4.35E-04	1	1.06E-05	5	25	1	596.55	7	839.36	11	13,000	12	1.8E-03	1		
319857	beta-HCH (beta-BHC)	1.26E+03	1	1.42E-02	1	7.34E-06	1	2.40E-01	1	3.05E-05	1	7.44E-07	5	25	1	596.55	7	839.36	11	13,000	12	5.3E-04	1		
542756	1,3-Dichloropropene	4.57E+01	1	6.26E-02	1	1.00E-05	1	2.80E+03	1	7.26E-01	1	1.77E-02	5	25	1	381.15	9	587.38	11	7,000	12	3.7E-05	1	2.0E-02	1
606202	2,6-Dinitrotoluene	6.92E+01	1	3.27E-02	1	7.26E-06	1	1.82E+02	1	3.06E-05	1	7.46E-07	5	25	1	558.00	10	770.00	10	12,938	10	1.9E-04	13		
621647	N-Nitrosodi-n-propylamine	2.40E+01	1	5.45E-02	1	8.17E-06	1	9.89E+03	1	9.23E-05	1	2.25E-06	5	25	1	509.60	8	746.87	11	11,000	12	2.0E-03	13		
1024573	Heptachlor epoxide	8.32E+04	1	1.32E-02	1	4.23E-06	1	2.00E-01	1	3.90E-04	1	9.51E-06	5	25	1	613.96	8	848.76	11	13,000	12	2.6E-03	1		
7439976	Mercury (elemental)	5.20E+01	2	3.07E-02	1	6.30E-06	1	5.62E-02	14	4.67E-01	1	1.14E-02	5	25	1	629.88	9	1750.00	9	14,127	9			3.0E-04	1
8001352	Toxaphene	2.57E+05	1	1.16E-02	1	4.34E-06	1	7.40E-01	1	2.46E-04	1	6.00E-06	5	25	1	657.15	9	873.31	11	14,000	12	3.2E-04	1		
11096825	Aroclor 1260 (PCB-1260)	2.90E+05	3	1.38E-02	4	4.32E-06	4	8.00E-02	3	1.89E-01	6	4.60E-03	3	25	3	402.50	3	539.37	11	19,000	12	1.0E-04	3		
11097691	Aroclor 1254 (PCB-1254)	2.00E+05	3	1.56E-02	4	5.00E-06	4	5.70E-02	3	8.20E-02	6	2.00E-03	3	25	3	377.50	3	512.27	11	19,000	12	1.0E-04	3		
12674112	Aroclor 1016 (PCB-1016)	3.30E+04	3	2.22E-02	4	5.42E-06	4	4.20E-01	3	1.19E-02	6	2.90E-04	3	25	3	340.50	3	475.22	11	18,000	12	1.0E-04	3		
53469219	Aroclor 1242 (PCB-1242)	3.30E+04	3	2.14E-02	4	5.31E-06	4	3.40E-01	3	2.13E-02	6	5.20E-04	3	25	3	345.50	3	482.20	11	18,000	12	1.0E-04	3		

LEGEND:

1 = Soil Screening Level (SSL) Guidance Documents, U. S. EPA (1996a and b).
2 = SSL Guidance Documents (U. S. EPA, 1996a and b); value is the soil-water partition coefficient (K_d) at pH = 6.8.
3 = ATSDR draft Toxicity Profile for PCBs, August 1995.
4 = Estimation using the U. S. EPA WATER8 model.
5 = Unitless Henry's law constant divided by 41.
6 = Henry's law constant in units of atm-m^3/mol multiplied by 41.
7 = U. S. EPA Superfund Chemical Data Matrix.
8 = Estimation based on the Quantitative Structure Activity Relationship method of Stein and Brown (1994).
9 = CRC Handbook of Chemistry and Physics, CRC Press (1994).
10 = Design Institute for Physical Property Data, The American Institute for Chemical Engineers, on-line data search, 1997.
11 = Estimation based on Lyman et al. (1990), Equations 12-4 and 12-5.
12 = Estimation based on Lyman et al. (1990), Equation 13-16; Antoine coefficients estimated by boiling point using the U. S. EPA CHEMDAT8 model.
13 = Route-to-Route extrapolation based on the procedures in U. S. EPA (1996b).
14 = The Merck Index, Eleventh Edition, Merck & Co., Inc. 1989.

Ground Water Monitoring & Remediation

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 ~1×10^{-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 sulpher 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

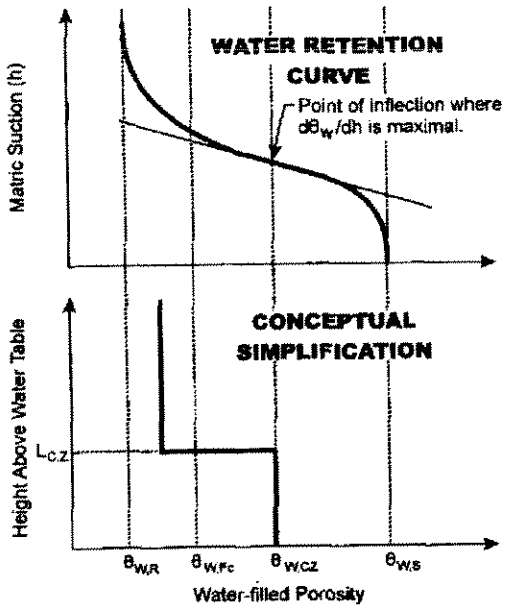


Figure 1. Conceptual simplification of water retention curve for purposes of estimating moisture contents and capillary rise ($\theta_{W,R}$, $\theta_{W,FC}$, $\theta_{W,CZ}$, $\theta_{W,S}$ are the residual, field capacity, capillary zone, and saturated water contents).

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 Quirck (1961) relationship to estimate the effective diffusion coefficient (D_T^{eff}), as follows:

$$D^T_{eff} = (\theta_a^{(10/3)} / \theta^2) * D_{air} + 1/H' * (\theta_w^{(10/3)} / \theta^2) * D_{water}$$

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' 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:

$$Q_{soil} = \frac{2\,\pi\, k_a\, \Delta P\, X_{crack}}{\mu \ln\left(\frac{2\, z_{crack}}{r_{crack}}\right)} \qquad (2)$$

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 ($M\,L^{-1}\,T^{-1}$), 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

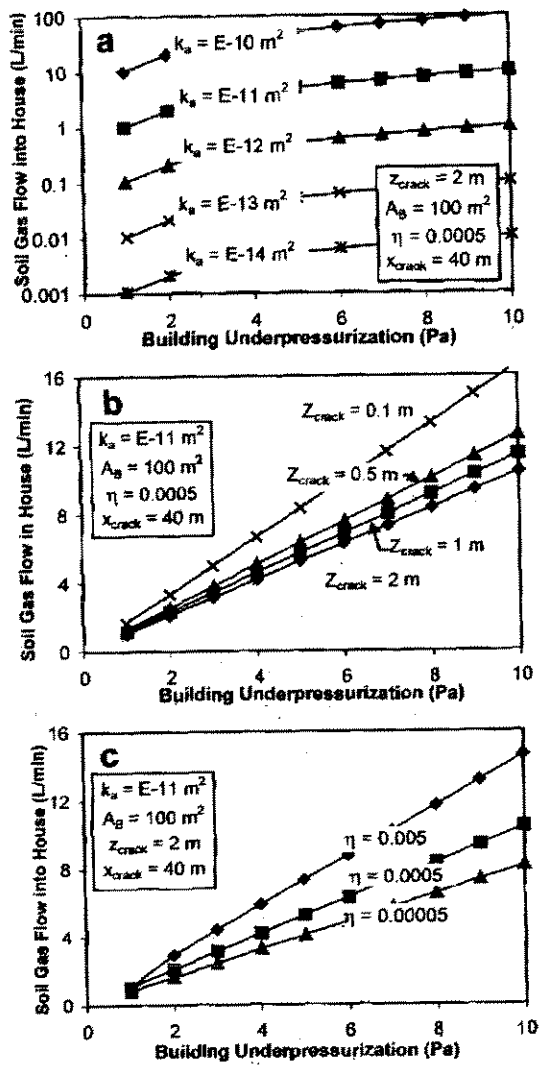


Figure 2. Sensitivity of soil gas flow to perimeter crack model (used in J&E model) to (a) soil-air permeability (k_a), (b) depth to perimeter crack (z_{crack}), and (c) crack ratio (η). X_{crack} = perimeter crack length, A_b = subsurface foundation area.

$$\eta = \frac{r_{crack} X_{crack}}{A_B} \tag{3}$$

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; (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.

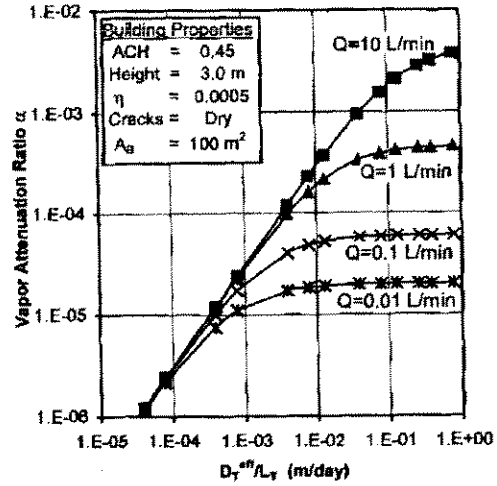


Figure 3. Sensitivity of vapor attenuation ratio (benzene) to soil-gas flow rate (Q) into building using perimeter crack model with dry dust-filled concrete cracks with total porosity = 0.3 Height = building height, Q = Q_{soil} ACH = air exchanges per hour (other symbols previously defined).

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 Quirck (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)	$k_{soil-air}$ (Darcy)	Soil Gas Flow Rates: Measured Tracer (L/min)	Soil Gas Flow Rates: Predicted 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.

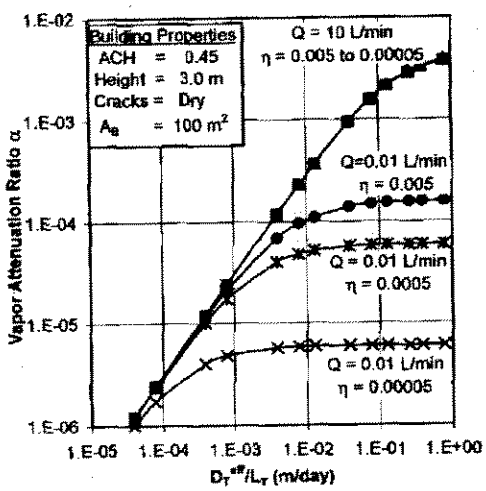


Figure 4. Sensitivity of vapor attenuation ratio (benzene) to soil-gas flow rate (Q) using perimeter crack model and foundation crack ratio (η) (other symbols previously defined).

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_{soil} = 10 L/min, α_p is not sensitive to η. When Q_{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_{soil} = 0). The crack ratio is of little importance for smaller D_T^{eff}/L_T or Q_{soil} >~1 L/min, which means that for the majority of sites crack ratio will not be important.

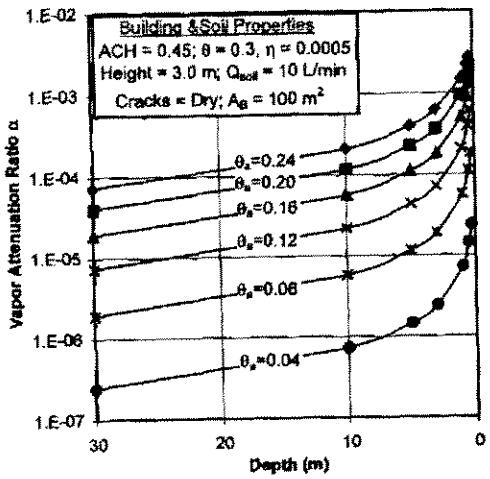


Figure 5. Sensitivity of vapor attenuation ratio (benzene) to water-filled porosity (θa). Other symbols previously defined.

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 backfill) 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 subsurface 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

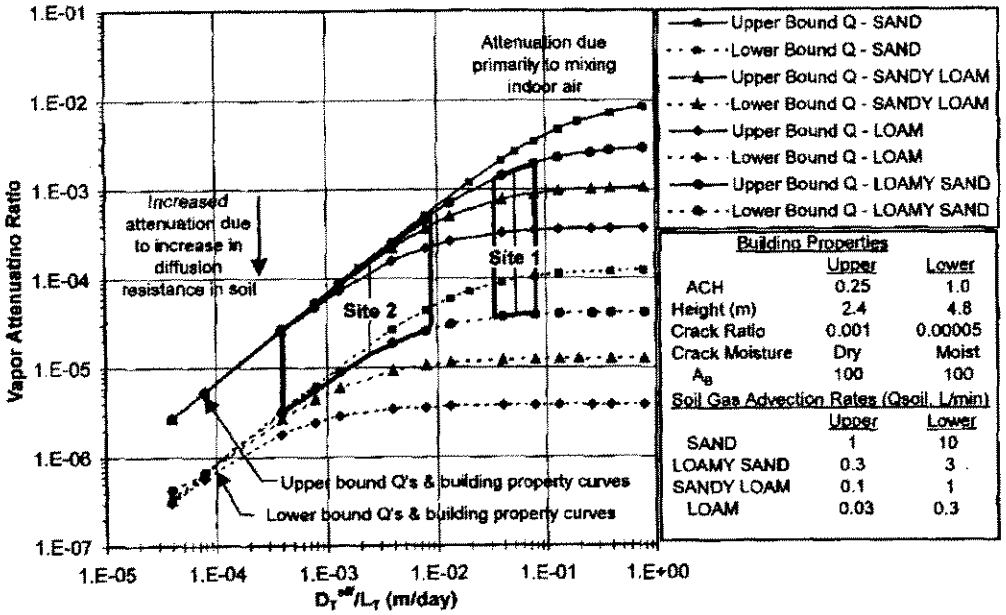


Figure 6. Predicted vapor attenuation ratio (benzene) for vapor concentrations at source and indoor air using Johnson and Ettinger (1991) model. Figure adapted from Johnson et al. (1998). Dry dust-filled cracks: Total porosity = 0.3; moist dust-filled cracks: water-filled porosity = 0.1, and total porosity = 0.3.

Table 3
Uncertainty Analysis for Normalized Effective Diffusion Coefficient

Parameters	Best Estimate Values Site 1	Site 2	Uncertainty
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 (θ_w/θ) above CZ (S)	0.265	0.265	+/– 25%
Height of CZ (L_{cz}) (m)	N/A	0.250	+/– 25%
S_R (θ_w/θ) 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 (SF_6), 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 Statistic	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 Hers et al. (1998) Hers et al.(2000a)	BTX petro-chemical plant, NAPL above water table	research greenhouse slab-on-grade poured concrete 2 mm edge crack	surface silt to f. sand, under-lain by m.sand with k ~ 10 darcies	1.4	benzene	V: 15,000	3-4	Avg	< 5.3E-7	1.3E-05	C1: ΔP= 0 Pa, η = 3.3E-4
					toluene	V: 20,000	3-4	Avg	< 1.9E-6	1.3E-05	C1: ΔP= 0 Pa, η = 3.3E-4
					benzene	V: 15,000	3-4	Avg	4.0E-07	5.9E-05	C2: ΔP= 2.5 Pa, η = 1E-4
					toluene	V: 20,000	3-4	Avg	5.9E-07	5.9E-05	C2: ΔP= 2.5 Pa, η = 1E-4
					benzene	V: 15,000	3-4	Avg	9.9E-05	7.8E-05	C3: ΔP= 10 Pa, η = 1E-4
					toluene	V: 20,000	3-4	Avg	1.3E-04	7.8E-05	C3: ΔP= 10 Pa, η = 1E-4
					benzene	V: 15,000	3-4	Avg	7.2E-06	8.0E-05	C4: ΔP= 10 Pa, η = 3.3E-4
					toluene	V: 20,000	3-4	Avg	3.4E-05	8.0E-05	C4: ΔP= 10 Pa, η = 3.3E-4
					benzene	V: 15,000	3-4	Avg	5.8E-06	2.9E-05	C5: ΔP= 30 Pa, η = 3.3E-4
					toluene	V: 20,000	3-4	Avg	2.2E-05	2.9E-05	C5: ΔP= 30 Pa, η = 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 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/m³, Total HC ~ 500 mg/m³
"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 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	115-150 115-150 115-150 115-150 115-150	Geom 90th Geom 90th Geom 90th Geom 90th	4.8E-06 2.0E-05 1.4E-05 7.0E-05 1.7E-05 6.6E-05 1.2E-05 5.2E-05	8.6E-05 2.4E-04[4]	a_m values for houses above plume with DCE groundwater concentration > 10 ug/L 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	a_m values for houses above plume with DCE groundwater concentration > 10 ug/L
Hamilton Site Colorado, USA (2001), unpublished	chlorinated solvents, dis-solved plume	SFRs built 50's most basements	primarily sand & & gravel, some clay & silt layers	9.7 to 11	1,1 DCE	G: 15-30 G: 15-30	32 32	50th 90th	6.80E-05 1.40E-04	INS	Gravel at water table
"Lowry (Air Force Base) Site" Colorado, USA Verzar (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 a_m = 6.2E-04 max G a_m = 1.2E-03 max V_{SS} a_m = 8.3E-03 max V_{SS} a_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 V: 84 G: 735 G: 735	14 14 14 14	Max 2nd[6] Max 2nd	2.80E-04 <1.3E-5 7.80E-05 <3.6E-5	INS	a_m shallow vapour a_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 to 1E-1	INS	high a_m associated with highly permeable building envelopes (earthern 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	ΔP = 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	ΔP ~ 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[7]	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 to 4.5E-2	N/A	winter conditions, mean house volume = 500 m³, ACH = 0.5/hr

Notes: [1]Depth to contamination from underside of foundation slab; [2]N = Number of indoor air samples tested; [3]Best estimate unless otherwise noted; [4]Upper range; [5]Contamination likely in unsaturated zone; [6]2nd highest α_m value; [7]Alpha (α) estimated using mean radon content of soil combined with appropriate constant divided by radon concentration in U.S. homes (55 Bq m-3); [8]N/A = not available or applicable, SFR = single family residence, SF_6 = 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) Model[1]

Parameter	Virginia Site	Chatterton Site	Paulsboro Site	Alameda Site	Midwest Site	CDOT HDQ Site	Redfields Site	Hamilton Site	Lowry Site	Mountain West Site
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	Sand	Loamy Sand	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] 6.1[3]	1.5[2] 10.7[3]
Total porosity unsaturated zone (θ)	0.43	0.36	0.39	0.36	0.4	0.4	0.39	0.375	0.39	0.41
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	0.2
Height of capillary zone (L_c) (m)	N/A	N/A	N/A	N/A	N/A	0.2	0.25		0.17	0.25
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] 0.050[5]	0.016[6]	3.4E-3[6]	2.4E-3[7]	8.4E-3[7]	0.49[8] 2.4E-3[9]	0.013[10] 1.5E-3[11]
Soil-air permeability k_a (10^{-12} m^2)	0.01	10	10	3	—	N/A[12]	—	—	—	—
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: [1]Depth to sub-slab soil gas probes; [2]Depth to shallow gas probes; [3]Depth to ground water; [4]Benzene; [5]Iso-pentene; [6]Average 1, 1 DCE, TCE and 1,1,1 TCA; [7]1,1,DCE; [8]DCE for sub-slab vapor source (TCE value is 0.43); [9]DCE for ground water source (value for TCE is 2.2E-03); [10]TCE for shallow vapor source; [11]TCE for ground water source; [12]Q_{soil} is estimated directly; therefore x_{crack}, z_{crack}, ΔP and k_a not needed; [13]Building 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 Virgina site) and

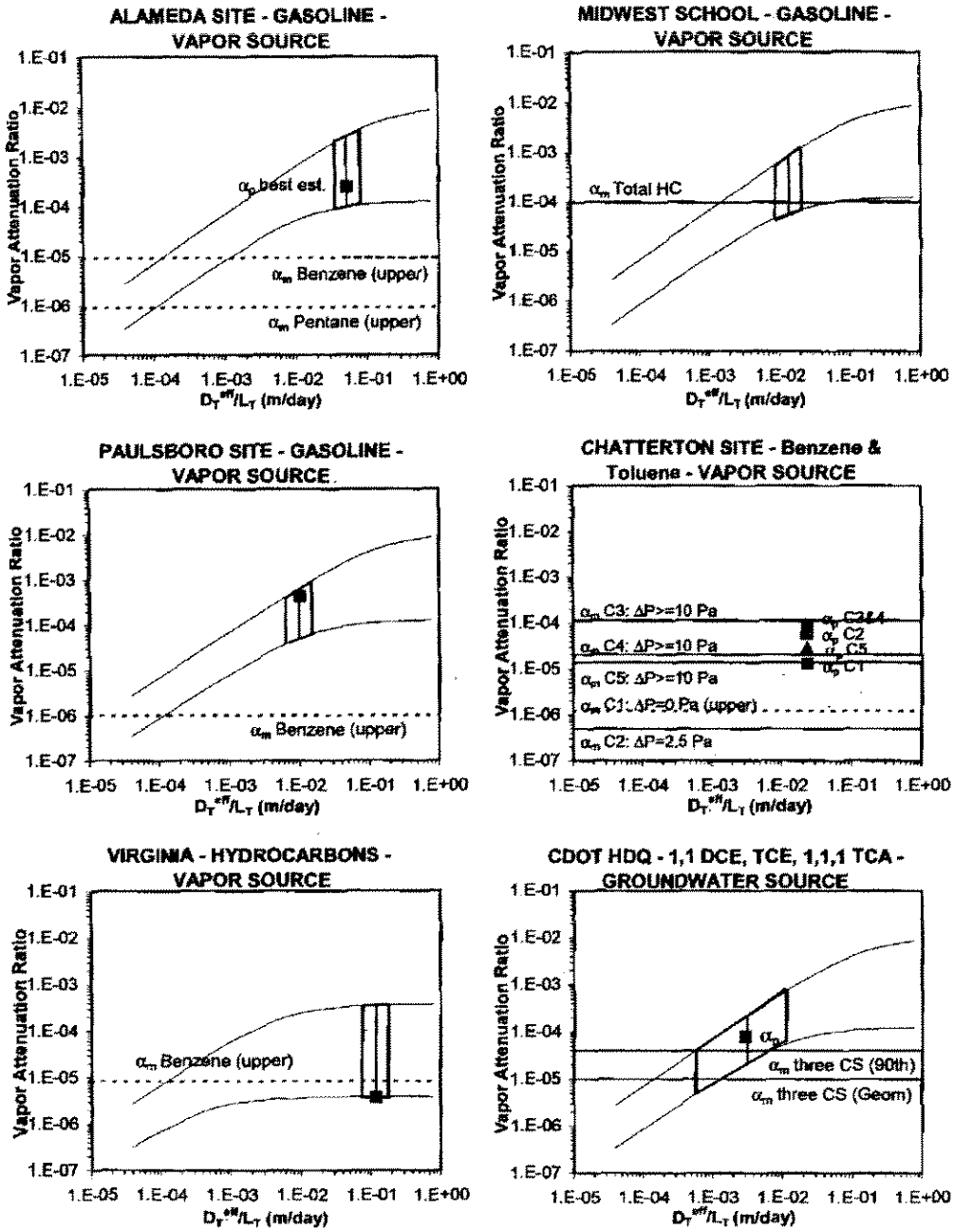


Figure 7a. Comparison between measured and J&E model-predicted vapor attenuation ratio (benzene). Upper and lower bound curves from Figure 6 are included. Dashed lines indicate that α_m is upper bound value. Symbols are best estimate α_p values.

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_p 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

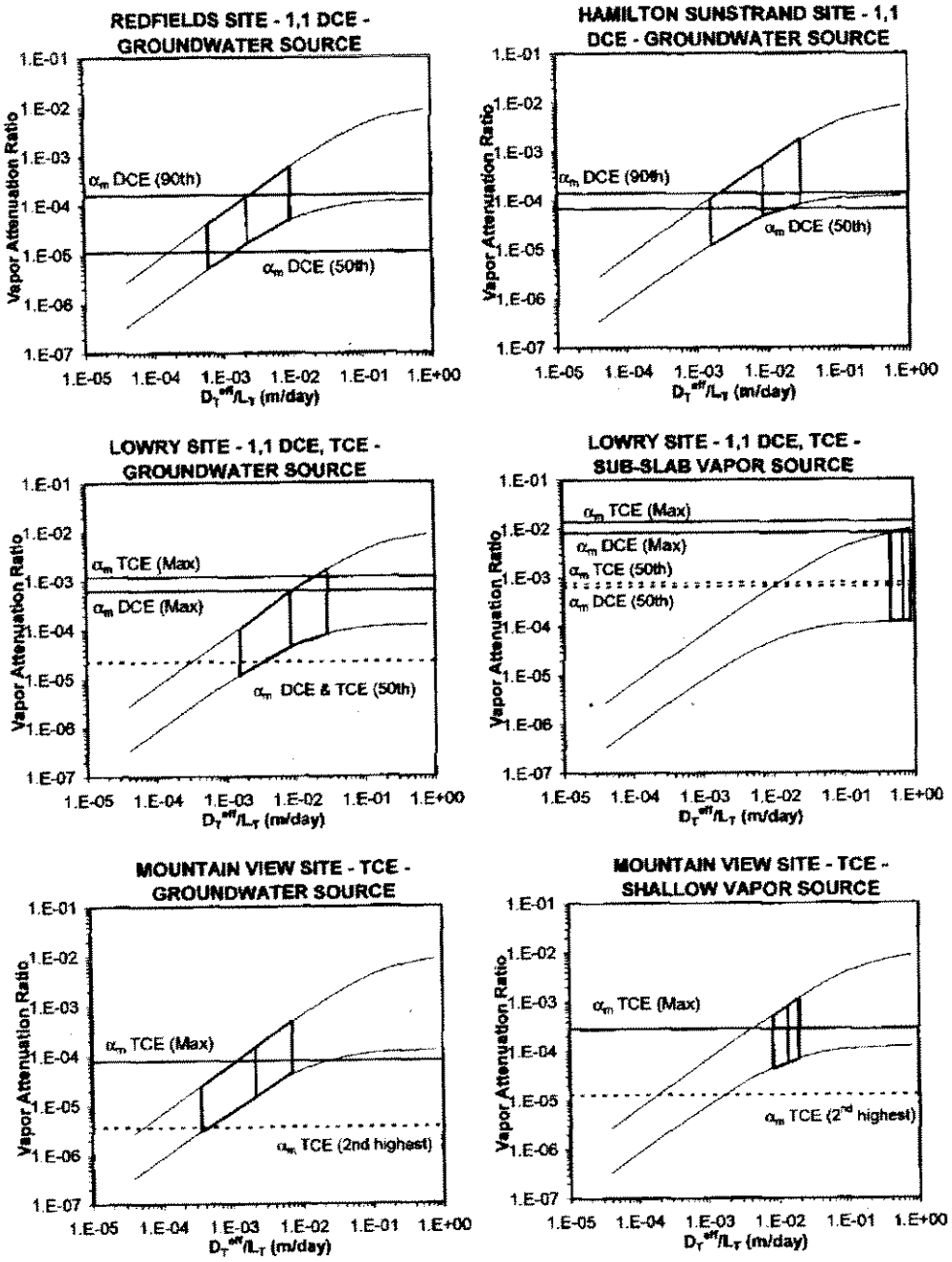


Figure 7b. Comparison between measured and J&E model-predicted vapor attenuation ratio (benzene). Upper and lower bound curves from Figure 6 are included. Dashed lines indicate that α_m is upper bound.

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 indicated 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 µg/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 µg/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 µg/m^3 and 0.91 µg/m^3, suggesting significant vapor intrusion. At three other houses, the TCE concentrations in indoor air were mostly between 5 and 15 µg/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 µg/m^3, but exceeded 5 µg/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 µg/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 µg/m^3 and/or subslab TCE concentrations exceeded 1000 µg/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 $\mu g/m^3$, whereas the TCE concentrations in remaining houses were at background levels (0.26 to 1.1 $\mu g/m^3$) (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 nonconservative 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). Semigeneric 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 semigeneric 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 lessor 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 underpressurization).

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 ~1×10^{-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 family 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 ~ 5×10^{-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 ~ 1×10^{-3} while the maximum subslab vapor α_m was ~ 1×10^{-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 semigeneric 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.

Acknowledgments

The authors thank those persons that contributed data to this study, and acknowledge the constructive comments by the reviewers of this paper.

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. Ettinger. 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. Kemblowski, 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 mitration 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. Quirck. 1961. Permeability of porous solids. *Trans. Farady 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 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: Batelle 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 pedotranfer 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 chamber. 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 conductivy 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.*

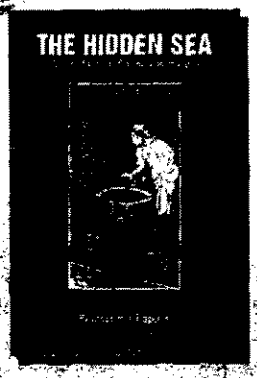
national ground water association

Order these new National Ground Water publications today!

The Hidden Sea: Ground Water, Springs, and Wells, 2nd Edition

by Francis H. Chapelle
NGWA (2000)

The Hidden Sea tells the story of human interaction with ground water throughout history. Chapelle divides the book into three sections: the folklore of ground water, the geology of aquifers, and the environmental problems occurring as the result of ground water contamination. The 238-page book also includes tables and illustrations. Written for the general reader, *The Hidden Sea* offers an entertaining examination of the ground water resource that will be meaningful to anyone who has ever drilled a well, soaked in a mineral spring, or just wondered why the tap water smelled funny.



238 pages/ 2000
Reference/ #T852
Member price/ $20.00
Prospective Member price/ $25.00

The Compendium of Hydrogeology

by Robert Porges and Matthew Hammer

Written by practicing hydrogeologists, this inclusive handbook provides a concise, easy-to-use reference for hydrologic terms, equations, pertinent physical parameters, and acronyms.

303 pages/ 2001
Reference/ #T947
Member price/ $25.00
Prospective Member price/ $31.25

For additional information on these titles, or any of the other titles offered through the NGWA Bookstore, call our Customer Service Department at 1 800 551 7379, or visit us on the web at www.NGWA.org.

APPENDIX 4

EXAMPLE PRINTOUTS OF INDOOR AIR IMPACT MODELS

1. Groundwater to indoor air, high-permeability soils, residential exposure scenario.
2. Groundwater to indoor air, low-permeability soils, residential exposure scenario.
3. Groundwater to indoor air, high-permeability soils, commercial/industrial exposure scenario.
4. Groundwater to indoor air, low-permeability soils, commercial/industrial exposure scenario.
5. Soil to indoor air, high-permeability soils, residential exposure scenario.
6. Soil to indoor air, high-permeability soils, commercial/industrial exposure scenario.
7. Soil Gas to indoor air, high-permeability soils, residential exposure scenario.
8. Soil Gas to indoor air, high-permeability soils, commercial/industrial exposure scenario.

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

GW-ADV
Version 2.3; 03/01

YES [X]

OR

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

YES

GROUNDWATER VOC EMISSIONS TO INDOOR AIR COMMERCIAL/INDUSTRIAL EXPOSURE SCENARIO HIGH-PERMEABILITY (SANDY) SOILS

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_W (µg/L)	Chemical
127184		Tetrachloroethylene

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 Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
			Totals must add up to value of L_{WT} (cell D28)							
15	15	300	100	200		B	CL	S		

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 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 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)
1.5	0.43	0.15	1.5	0.43	0.3			

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	244	0.1	2

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	25	25	250	1.0E-06	1
				Used to calculate risk-based groundwater concentration.	

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (^oC)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	1.55E+02	2.00E+02	6.9E-06	6.0E-01

END

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_{te} (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)
7.88E+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} (atm-m^3/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^{eff}_A (cm^2/s)	Stratum B effective diffusion coefficient, D^{eff}_B (cm^2/s)	Stratum C effective diffusion coefficient, D^{eff}_C (cm^2/s)	Capillary zone effective diffusion coefficient, D^{eff}_{cz} (cm^2/s)	Total overall effective diffusion coefficient, D^{eff}_T (cm^2/s)	Diffusion path length, L_d (cm)
1.25E+05	9.24E+05	4.16E-04	15	9,502	1.05E-02	4.46E-01	1.77E-04	5.62E-03	4.38E-04	0.00E+00	2.85E-05	1.42E-04	285

Convection path length, L_p (cm)	Source vapor conc., C_{source} ($\mu g/m^3$)	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(Pe^f) (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
15	4.46E+02	0.10	6.74E+01	5.62E-03	3.84E+02	2.22E+203	3.65E-06	1.63E-03	6.9E-06	6.0E-01

END

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)
3.64E+02	5.39E+05	3.64E+02	2.00E+05	3.64E+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

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	26.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0046
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,988	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	248.94	416.80	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-06	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.9E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01	98.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	535.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.16E-03	7.70E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.46E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	98.96		
108101	Methyl isobutyl Ketone	1.34E+02	7.50E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	6.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	416.14	678.20	8,000	2.4E-05	7.0E-02	208.28	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	6.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	98.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

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

GW-ADV
Version 2.3; 03/01

YES [X]

OR

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

YES

GROUNDWATER VOC EMISSIONS TO INDOOR AIR
COMMERCIAL/INDUSTRIAL EXPOSURE SCENARIO
LOW-PERMEABILITY (SILTY) SOILS

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_W (µg/L)	Chemical
127184		Tetrachloroethylene

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 Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
			Totals must add up to value of L_{WT} (cell D28)							
15	15	300	100	200		B	SI	LS		

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 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 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)
1.5	0.43	0.15	1.5	0.43	0.3			

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	244	0.1	2

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	25	25	250	1.0E-06	0.2
				Used to calculate risk-based groundwater concentration.	

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (^oC)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	1.55E+02	2.00E+02	6.9E-06	6.0E-01

END

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_{te} (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)
7.88E+08	285	0.280	0.130	ERROR	0.265	1.64E-08	0.824	1.35E-08	163.04	0.43	0.048	0.382	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} (atm-m^3/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^{eff}_A (cm^2/s)	Stratum B effective diffusion coefficient, D^{eff}_B (cm^2/s)	Stratum C effective diffusion coefficient, D^{eff}_C (cm^2/s)	Capillary zone effective diffusion coefficient, D^{eff}_{cz} (cm^2/s)	Total overall effective diffusion coefficient, D^{eff}_T (cm^2/s)	Diffusion path length, L_d (cm)
1.25E+05	9.24E+05	4.16E-04	15	9,502	1.05E-02	4.46E-01	1.77E-04	5.62E-03	4.38E-04	0.00E+00	2.02E-05	3.48E-05	285

Convection path length, L_p (cm)	Source vapor conc., C_{source} ($\mu g/m^3$)	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(Pe^f) (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
15	4.46E+02	0.10	1.29E+01	5.62E-03	3.84E+02	9.74E+38	8.94E-07	3.99E-04	6.9E-06	6.0E-01

END

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)
1.49E+03	4.39E+05	1.49E+03	2.00E+05	1.49E+03

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

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	26.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0046
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,989	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	249.94	416.80	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-06	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.8E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01	98.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	535.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.16E-03	7.70E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.46E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	98.96		
108101	Methyl Isobutyl Ketone	1.34E+02	7.50E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	6.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	416.14	678.20	8,000	2.4E-05	7.0E-02	208.28	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	6.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	98.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

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

GW-ADV
Version 2.3; 03/01

YES [X]

OR

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

YES

GROUNDWATER VOC EMISSIONS TO INDOOR AIR
RESIDENTIAL EXPOSURE SCENARIO
HIGH-PERMEABILITY (SANDY) SOILS

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_W (µg/L)	Chemical
127184		Tetrachloroethylene

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 Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
			Totals must add up to value of L_{WT} (cell D28)							
15	15	300	100	200		B	CL	S		

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 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 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)
1.5	0.43	0.15	1.5	0.43	0.3			

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	244	0.1	1

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
				Used to calculate risk-based groundwater concentration.	

ND

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (^oC)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	1.55E+02	2.00E+02	6.9E-06	6.0E-01

END

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_{te} (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} (atm-m^3/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^{eff}_A (cm^2/s)	Stratum B effective diffusion coefficient, D^{eff}_B (cm^2/s)	Stratum C effective diffusion coefficient, D^{eff}_C (cm^2/s)	Capillary zone effective diffusion coefficient, D^{eff}_{cz} (cm^2/s)	Total overall effective diffusion coefficient, D^{eff}_T (cm^2/s)	Diffusion path length, L_d (cm)
6.26E+04	9.24E+05	4.16E-04	15	9,502	1.05E-02	4.46E-01	1.77E-04	5.62E-03	4.38E-04	0.00E+00	2.85E-05	1.42E-04	285

Convection path length, L_p (cm)	Source vapor conc., C_{source} ($\mu g/m^3$)	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, $\exp(Pe^f)$ (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
15	4.46E+02	0.10	6.74E+01	5.62E-03	3.84E+02	2.22E+203	7.29E-06	3.25E-03	6.9E-06	6.0E-01

END

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)
1.08E+02	3.85E+04	1.08E+02	2.00E+05	1.08E+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

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	26.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0046
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,988	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	6.20E+03	9.84E-01	2.40E-02	25	248.94	416.80	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-06	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.9E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01	98.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	535.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.15E-03	7.70E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.46E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	98.96		
108101	Methyl Isobutyl Ketone	1.34E+02	7.50E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	6.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	416.14	678.20	8,000	2.4E-05	7.0E-02	208.28	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	6.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	98.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

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

GW-ADV
Version 2.3; 03/01

YES [X]

OR

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

YES

GROUNDWATER VOC EMISSIONS TO INDOOR AIR
RESIDENTIAL EXPOSURE SCENARIO
LOW-PERMEABILITY (SILTY) SOILS

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_W (µg/L)	Chemical
127184		Tetrachloroethylene

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 Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
			Totals must add up to value of L_{WT} (cell D28)							
15	15	300	100	200		B	SI	LS		

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 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 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)
1.5	0.43	0.15	1.5	0.43	0.3			

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	244	0.1	1

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
				Used to calculate risk-based groundwater concentration.	

ND

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H ($atm\text{-}m^3/mol$)	Henry's law constant reference temperature, T_R (^oC)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	1.55E+02	2.00E+02	6.9E-06	6.0E-01

END

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_{te} (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	0.265	1.64E-08	0.824	1.35E-08	163.04	0.43	0.048	0.382	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} (atm-m^3/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^{eff}_A (cm^2/s)	Stratum B effective diffusion coefficient, D^{eff}_B (cm^2/s)	Stratum C effective diffusion coefficient, D^{eff}_C (cm^2/s)	Capillary zone effective diffusion coefficient, D^{eff}_{cz} (cm^2/s)	Total overall effective diffusion coefficient, D^{eff}_T (cm^2/s)	Diffusion path length, L_d (cm)
6.26E+04	9.24E+05	4.16E-04	15	9,502	1.05E-02	4.46E-01	1.77E-04	5.62E-03	4.38E-04	0.00E+00	2.02E-05	3.48E-05	285

Convection path length, L_p (cm)	Source vapor conc., C_{source} ($\mu g/m^3$)	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, $exp(Pe^f)$ (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
15	4.46E+02	0.10	1.29E+01	5.62E-03	3.84E+02	9.74E+38	1.79E-06	7.98E-04	6.9E-06	6.0E-01

END

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)
4.42E+02	1.57E+05	4.42E+02	2.00E+05	4.42E+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

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	26.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0046
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, ΔH_{vb} (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,988	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	6.20E+03	9.84E-01	2.40E-02	25	248.94	416.80	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-06	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.9E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.99E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01	98.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	535.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.16E-03	7.70E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.46E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	98.96		
108101	Methyl Isobutyl Ketone	1.34E+02	7.50E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	6.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	416.14	678.20	8,000	2.4E-05	7.0E-02	208.28	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	6.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	88.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

SG-ADV
Version 1.0; 03/01

SOIL VOC EMISSIONS TO INDOOR AIR
COMMERCIAL/INDUSTRIAL EXPOSURE SCENARIO
HIGH-PERMEABILITY (SANDY) SOILS
SOIL GAS:INDOOR AIR ATTENUATION FACTOR = 0.0005

Soil Gas Concentration Data

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Soil gas conc., C_g ($\mu g/m^3$)	OR	ENTER Soil gas conc., C_g (ppmv)	Chemical
127184	1.30E+03			Tetrachloroethylene

Enter soil gas concentration in only one set of units.

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 Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
			Totals must add up to value of Ls (cell C24)					
15	15	10	15			S		

MORE ↓

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 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 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)
1.5	0.43	0.15						

MORE ↓

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	244	0.1	2

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	25	25	250

END

Diffusivity in air, Da (cm2/s)	Diffusivity in water, Dw (cm2/s)	Henry's law constant at reference temperature, H (atm-m3/mol)	Henry's law constant reference temperature, TR (oC)	Enthalpy of vaporization at the normal boiling point, ΔHϖ,β (cal/mol)	Normal boiling point, TB (oK)	Critical temperature, TC (oK)	Molecular weight, MW (g/mol)	Unit risk factor, URF (mg/m3)-1	Reference conc., RfC (mg/m3)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	165.83	6.9E-06	6.0E-01

END

Exposure duration, t (sec)	Source-building separation, LT (cm)	Stratum A air-filled porosity, qaA (cm3/cm3)	Stratum B soil air-filled porosity, qaB (cm3/cm3)	Stratum C air-filled porosity, qaC (cm3/cm3)	Stratum A effective total fluid saturation, Ste (cm3/cm3)	Stratum A soil intrinsic permeability, ki (cm2)	Stratum A soil relative air permeability, krg (cm2)	Stratum A soil effective vapor permeability, kv (cm2)	Floor-wall seam perimeter, Xcrack (cm)	Soil gas conc. (mg/m3)	Bldg. ventilation rate, Qbuilding (cm3/s)
7.88E+08	1	0.28	ERROR	ERROR	0.25729443	9.92425E-08	0.703228129	6.97901E-08	3844	1304	125188.4022

Area of enclosed space below grade, AB (cm2)	Crack-to-total area ratio, h (unitless)	Crack depth below grade, Zcrack (cm)	Enthalpy of vaporization at ave. soil temperature, DHv,TS (cal/mol)	Henry's law constant at ave. soil temperature, HTS (atm-m3/mol)	Henry's law constant at ave. soil temperature, H'TS (unitless)	Vapor viscosity at ave. soil temperature, mTS (g/cm-s)	Stratum A effective diffusion coefficient, DeffA (cm2/s)	Stratum B effective diffusion coefficient, DeffB (cm2/s)	Stratum C effective diffusion coefficient, DeffC (cm2/s)	Total overall effective diffusion coefficient, DeffT (cm2/s)	Diffusion path length, Ld (cm)
923521	0.000416233	15	9552.934617	7.83E-03	0.337067044	0.000175414	5.62E-03	0	0	0.005616299	1

Convection path length, Lp (cm)	Source vapor conc., Csource (mg/m3)	Crack radius, rcrack (cm)	Average vapor flow rate into bldg., Qsoil (cm3/s)	Crack effective diffusion coefficient, Dcrack (cm2/s)	Area of crack, Acrack (cm2)	Exponent of equivalent foundation Peclet number, exp(Pef) (unitless)	Infinite source indoor attenuation coefficient, a (unitless)	Infinite source bldg. conc., Cbuilding (mg/m3)	Unit risk factor, URF (mg/m3)-1	Reference conc., RfC (mg/m3)
15	1304	0.1	67.38925148	0.005616299	384.4	2.211E+203	0.000531398	0.692943596	0.0000069	0.6

END

Qsoil (L/min)
4.0

INCREMENTAL RISK CALCULATIONS:

Incremental risk from vapor intrusion to indoor air, carcinogen (unitless)	Hazard quotient from vapor intrusion to indoor air, noncarcinogen (unitless)
1.2E-06	7.9E-04

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

SCROLL DOWN TO "END"

END

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	26.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0046
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, ΔH_{vb} (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,988	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	248.94	416.90	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-06	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.9E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01	98.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	536.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.16E-03	7.70E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.46E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.53E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	9.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	98.96		
108101	Methyl Isobutyl Ketone	1.34E+02	7.50E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	6.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	416.14	678.20	8,000	2.4E-05	7.0E-02	208.26	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	6.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	98.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

SG-ADV
Version 1.0; 03/01

SOIL VOC EMISSIONS TO INDOOR AIR
RESIDENTIAL EXPOSURE SCENARIO
HIGH-PERMEABILITY (SANDY) SOILS
SOIL GAS:INDOOR AIR ATTENUATION FACTOR = 0.001

Soil Gas Concentration Data

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Soil gas conc., C_g ($\mu g/m^3$)	OR	ENTER Soil gas conc., C_g (ppmv)	Chemical
127184	3.88E+02			Tetrachloroethylene

Enter soil gas concentration in only one set of units.

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 Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
			Totals must add up to value of Ls (cell C24)					
15	15	10	15			S		

MORE ↓

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 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 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)
1.5	0.43	0.15						

MORE ↓

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	244	0.1	1

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

END

Diffusivity in air, Da (cm2/s)	Diffusivity in water, Dw (cm2/s)	Henry's law constant at reference temperature, H (atm-m3/mol)	Henry's law constant reference temperature, TR (oC)	Enthalpy of vaporization at the normal boiling point, ΔHϖ,β (cal/mol)	Normal boiling point, TB (oK)	Critical temperature, TC (oK)	Molecular weight, MW (g/mol)	Unit risk factor, URF (mg/m3)-1	Reference conc., RfC (mg/m3)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	165.83	6.9E-06	6.0E-01

END

Exposure duration, t (sec)	Source-building separation, LT (cm)	Stratum A air-filled porosity, qaA (cm3/cm3)	Stratum B soil air-filled porosity, qaB (cm3/cm3)	Stratum C air-filled porosity, qaC (cm3/cm3)	Stratum A effective total fluid saturation, Ste (cm3/cm3)	Stratum A soil intrinsic permeability, ki (cm2)	Stratum A soil relative air permeability, krg (cm2)	Stratum A soil effective vapor permeability, kv (cm2)	Floor-wall seam perimeter, Xcrack (cm)	Soil gas conc. (mg/m3)	Bldg. ventilation rate, Qbuilding (cm3/s)
9.46E+08	1	0.28	ERROR	ERROR	0.25729443	9.92425E-08	0.703228129	6.97901E-08	3844	388.1	62594.20111

Area of enclosed space below grade, AB (cm2)	Crack-to-total area ratio, h (unitless)	Crack depth below grade, Zcrack (cm)	Enthalpy of vaporization at ave. soil temperature, DHv,TS (cal/mol)	Henry's law constant at ave. soil temperature, HTS (atm-m3/mol)	Henry's law constant at ave. soil temperature, H'TS (unitless)	Vapor viscosity at ave. soil temperature, mTS (g/cm-s)	Stratum A effective diffusion coefficient, DeffA (cm2/s)	Stratum B effective diffusion coefficient, DeffB (cm2/s)	Stratum C effective diffusion coefficient, DeffC (cm2/s)	Total overall effective diffusion coefficient, DeffT (cm2/s)	Diffusion path length, Ld (cm)
923521	0.000416233	15	9552.934617	7.83E-03	0.337067044	0.000175414	5.62E-03	0	0	0.005616299	1

Convection path length, Lp (cm)	Source vapor conc., Csource (mg/m3)	Crack radius, rcrack (cm)	Average vapor flow rate into bldg., Qsoil (cm3/s)	Crack effective diffusion coefficient, Dcrack (cm2/s)	Area of crack, Acrack (cm2)	Exponent of equivalent foundation Peclet number, exp(Pef) (unitless)	Infinite source indoor attenuation coefficient, a (unitless)	Infinite source bldg. conc., Cbuilding (mg/m3)	Unit risk factor, URF (mg/m3)-1	Reference conc., RfC (mg/m3)
15	388.1	0.1	67.38925148	0.005616299	384.4	2.211E+203	0.001062797	0.412471487	0.0000069	0.6

END

Qsoil (L/min)
4.0

INCREMENTAL RISK CALCULATIONS:

Incremental risk from vapor intrusion to indoor air, carcinogen (unitless)	Hazard quotient from vapor intrusion to indoor air, noncarcinogen (unitless)
1.2E-06	6.6E-04

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

SCROLL DOWN TO "END"

END

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	26.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0046
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,988	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	248.94	416.80	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-05	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.9E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01	98.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	535.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.16E-03	7.70E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.46E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	98.96		
108101	Methyl Isobutyl Ketone	1.34E+02	7.50E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	5.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	416.14	678.20	8,000	2.4E-05	7.0E-02	208.28	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	8.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	8.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	96.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

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

YES [X]

OR

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

YES

SL-ADV
Version 2.3; 03/01

SOIL VOC EMISSIONS TO INDOOR AIR
COMMERCIAL/INDUSTRIAL EXPOSURE SCENARIO
HIGH-PERMEABILITY (SANDY) SOILS

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial soil conc., C_R (µg/kg)	Chemical
127184		Tetrachloroethylene

MORE ↓

ENTER Average soil temperature, T_S (°C)	ENTER Depth below grade to bottom of enclosed space floor, L_F (cm)	ENTER Depth below grade to top of contamination, L_t (cm)	ENTER Depth below grade to bottom of contamination, (enter value of 0 if value is unknown) L_b (cm)	ENTER Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	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)
				Totals must add up to value of L_t (cell D28)					
20	15	15	215	15			S		

MORE ↓

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 A soil organic carbon fraction, f_{oc}^A (unitless)	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 B soil organic carbon fraction, f_{oc}^B (unitless)	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)	ENTER Stratum C soil organic carbon fraction, f_{oc}^C (unitless)
1.5	0.43	0.15	0.006								

MORE ↓

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP ($g/cm\text{-}s^2$)	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)
15	40	961	961	244	0.1	2

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	25	25	250	1.0E-06	0.2
				Used to calculate risk-based soil concentration.	

END

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (^oC)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Physical state at soil temperature, (S,L,G)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	1.55E+02	2.00E+02	6.9E-06	6.0E-01	1.7E+02

END

Exposure duration, τ (sec)	Source-building separation, LT (cm)	Stratum A soil air-filled porosity, θαA (cm3/cm3)	Stratum B soil air-filled porosity, θαB (cm3/cm3)	Stratum C soil air-filled porosity, θαX (cm3/cm3)	Stratum A effective total fluid saturation, Ste (cm3/cm3)	Stratum A soil intrinsic permeability, ki (cm2)	Stratum A soil relative air permeability, krg (cm2)	Stratum A soil effective vapor permeability, kv (cm2)	Floor-wall seam perimeter, Xcrack (cm)	Initial soil concentration used, CR (mg/kg)	Bldg. ventilation rate, Qbuilding (cm3/s)
7.88E+08	1	0.280	ERROR	ERROR	0.257	1.01E-07	0.703	7.10E-08	3,844	1.00E+00	1.25E+05

Area of enclosed space below grade, AB (cm2)	Crack-to-total area ratio, η (unitless)	Crack depth below grade, Zcrack (cm)	Enthalpy of vaporization at ave. soil temperature, ΔHϖ,TΣ (cal/mol)	Henry's law constant at ave. soil temperature, HTS (atm-m3/mol)	Henry's law constant at ave. soil temperature, H'TS (unitless)	Vapor viscosity at ave. soil temperature, μTΣ (g/cm-s)	Stratum A effective diffusion coefficient, DeffA (cm2/s)	Stratum B effective diffusion coefficient, DeffB (cm2/s)	Stratum C effective diffusion coefficient, DeffC (cm2/s)	Total overall effective diffusion coefficient, DeffT (cm2/s)	Diffusion path length, Ld (cm)	Convection path length, Lp (cm)
9.24E+05	4.16E-04	15	9,451	1.40E-02	5.83E-01	1.78E-04	5.62E-03	0.00E+00	0.00E+00	5.62E-03	1	15

Soil-water partition coefficient, Kd (cm3/g)	Source vapor conc., Csource (mg/m3)	Crack radius, rcrack (cm)	Average vapor flow rate into bldg., Qsoil (cm3/s)	Crack effective diffusion coefficient, Dcrack (cm2/s)	Area of crack, Acrack (cm2)	Exponent of equivalent foundation Peclet number, exp(Pef) (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., Cbuilding (mg/m3)	Finite source β τερμ (unitless)	Finite source ψ τερμ (sec)-1	Time for source depletion, τΔ (sec)	Exposure duration > time for source depletion (YES/NO)
9.30E-01	5.12E+02	0.10	6.74E+01	5.62E-03	3.84E+02	2.23E+203	NA	NA	7.80E+01	1.92E-03	1.86E+07	YES

Finite source indoor attenuation coefficient, <a> (unitless)	Mass limit bldg. conc., Cbuilding (mg/m3)	Finite source bldg. conc., Cbuilding (mg/m3)	Final finite source bldg. conc., Cbuilding (mg/m3)	Unit risk factor, URF (mg/m3)-1	Reference conc., RfC (mg/m3)
NA	2.81E-03	NA	2.81E-03	6.9E-06	6.0E-01

END

RISK-BASED SOIL CONCENTRATION CALCULATIONS:

Indoor exposure soil conc., carcinogen (µg/kg)	Indoor exposure soil conc., noncarcinogen (µg/kg)	Risk-based indoor exposure soil conc., (µg/kg)	Soil saturation conc., C_{sat} (µg/kg)	Final indoor exposure soil conc., (µg/kg)
2.11E+02	6.24E+04	2.11E+02	2.28E+05	2.11E+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

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	28.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0048
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,988	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.94E-01	2.40E-02	25	249.94	416.80	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-05	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.9E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,695	0.0E+00	5.0E-01	98.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	6.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	535.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.36	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.16E-03	7.70E-05	25	570.44	870.00	12,656	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.46E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.8E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	98.96		
108101	Methyl isobutyl Ketone	1.34E+02	7.50E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	6.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	486.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	416.14	678.20	8,000	2.4E-05	7.0E-02	208.26	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	6.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	98.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

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

SL-ADV
Version 2.3; 03/01

YES [X]

OR

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

YES

SOIL VOC EMISSIONS TO INDOOR AIR
RESIDENTIAL EXPOSURE SCENARIO
HIGH-PERMEABILITY (SANDY) SOILS

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial soil conc., C_R (µg/kg)	Chemical
127184		Tetrachloroethylene

MORE ↓

ENTER Average soil temperature, T_S (°C)	ENTER Depth below grade to bottom of enclosed space floor, L_F (cm)	ENTER Depth below grade to top of contamination, L_1 (cm)	ENTER Depth below grade to bottom of contamination, (enter value of 0 if value is unknown) L_b (cm)	ENTER Totals must add up to value of L_1 (cell D28) Thickness of soil stratum A, h_A (cm)	ENTER Thickness of soil stratum B, (Enter value or 0) h_B (cm)	ENTER Thickness of soil stratum C, (Enter value or 0) h_C (cm)	ENTER Soil stratum A SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined stratum A soil vapor permeability, k_v (cm²)
20	15	15	215	15			S		

MORE ↓

ENTER Stratum A soil dry bulk density, ρ_b^A (g/cm³)	ENTER Stratum A soil total porosity, n^A (unitless)	ENTER Stratum A soil water-filled porosity, θ_w^A (cm³/cm³)	ENTER Stratum A soil organic carbon fraction, f_{oc}^A (unitless)	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm³)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm³/cm³)	ENTER Stratum B soil organic carbon fraction, f_{oc}^B (unitless)	ENTER Stratum C soil dry bulk density, ρ_b^C (g/cm³)	ENTER Stratum C soil total porosity, n^C (unitless)	ENTER Stratum C soil water-filled porosity, θ_w^C (cm³/cm³)	ENTER Stratum C soil organic carbon fraction, f_{oc}^C (unitless)
1.5	0.43	0.15	0.006								

MORE ↓

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP (g/cm-s²)	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)
15	40	961	961	244	0.1	1

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

Used to calculate risk-based soil concentration.

END

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H ($atm\text{-}m^3/mol$)	Henry's law constant reference temperature, T_R (^oC)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Pure component water solubility, S (mg/L)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)	Physical state at soil temperature, (S,L,G)
7.20E-02	8.20E-06	1.84E-02	25	8,288	394.40	620.20	1.55E+02	2.00E+02	6.9E-06	6.0E-01	1.7E+02

END

Exposure duration, τ (sec)	Source-building separation, LT (cm)	Stratum A soil air-filled porosity, θαA (cm3/cm3)	Stratum B soil air-filled porosity, θαB (cm3/cm3)	Stratum C soil air-filled porosity, θαX (cm3/cm3)	Stratum A effective total fluid saturation, Ste (cm3/cm3)	Stratum A soil intrinsic permeability, ki (cm2)	Stratum A soil relative air permeability, krg (cm2)	Stratum A soil effective vapor permeability, kv (cm2)	Floor-wall seam perimeter, Xcrack (cm)	Initial soil concentration used, CR (mg/kg)	Bldg. ventilation rate, Qbuilding (cm3/s)
9.46E+08	1	0.280	ERROR	ERROR	0.257	1.01E-07	0.703	7.10E-08	3,844	1.00E+00	6.26E+04

Area of enclosed space below grade, AB (cm2)	Crack-to-total area ratio, η (unitless)	Crack depth below grade, Zcrack (cm)	Enthalpy of vaporization at ave. soil temperature, ΔHϖ,TΣ (cal/mol)	Henry's law constant at ave. soil temperature, HTS (atm-m3/mol)	Henry's law constant at ave. soil temperature, H'TS (unitless)	Vapor viscosity at ave. soil temperature, μTΣ (g/cm-s)	Stratum A effective diffusion coefficient, DeffA (cm2/s)	Stratum B effective diffusion coefficient, DeffB (cm2/s)	Stratum C effective diffusion coefficient, DeffC (cm2/s)	Total overall effective diffusion coefficient, DeffT (cm2/s)	Diffusion path length, Ld (cm)	Convection path length, Lp (cm)
9.24E+05	4.16E-04	15	9,451	1.40E-02	5.83E-01	1.78E-04	5.62E-03	0.00E+00	0.00E+00	5.62E-03	1	15

Soil-water partition coefficient, Kd (cm3/g)	Source vapor conc., Csource (mg/m3)	Crack radius, rcrack (cm)	Average vapor flow rate into bldg., Qsoil (cm3/s)	Crack effective diffusion coefficient, Dcrack (cm2/s)	Area of crack, Acrack (cm2)	Exponent of equivalent foundation Peclet number, exp(Pef) (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., Cbuilding (mg/m3)	Finite source β τερμ (unitless)	Finite source ψ τερμ (sec)-1	Time for source depletion, τΔ (sec)	Exposure duration > time for source depletion (YES/NO)
9.30E-01	5.12E+02	0.10	6.74E+01	5.62E-03	3.84E+02	2.23E+203	NA	NA	7.80E+01	1.92E-03	1.86E+07	YES

Finite source indoor attenuation coefficient, <a> (unitless)	Mass limit bldg. conc., Cbuilding (mg/m3)	Finite source bldg. conc., Cbuilding (mg/m3)	Final finite source bldg. conc., Cbuilding (mg/m3)	Unit risk factor, URF (mg/m3)-1	Reference conc., RfC (mg/m3)
NA	4.68E-03	NA	4.68E-03	6.9E-06	6.0E-01

END

RISK-BASED SOIL CONCENTRATION CALCULATIONS:

Indoor exposure soil conc., carcinogen (µg/kg)	Indoor exposure soil conc., noncarcinogen (µg/kg)	Risk-based indoor exposure soil conc., (µg/kg)	Soil saturation conc., C_{sat} (µg/kg)	Final indoor exposure soil conc., (µg/kg)
7.54E+01	2.67E+04	7.54E+01	2.28E+05	7.54E+01

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

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α (1/cm)	N (unitless)	M (unitless)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)
C	0.61	0.0150	1.253	0.2019	0.459	0.098	0.0092
CL	0.34	0.0158	1.416	0.2938	0.442	0.079	0.016
L	0.50	0.0111	1.472	0.3207	0.399	0.061	0.02
LS	4.38	0.0348	1.746	0.4273	0.39	0.049	0.04
S	26.78	0.0352	3.177	0.6852	0.375	0.053	0.044
SC	0.47	0.0334	1.208	0.1722	0.385	0.117	0.025
SCL	0.55	0.0211	1.33	0.2481	0.384	0.063	0.029
SI	1.82	0.0066	1.679	0.4044	0.489	0.05	0.0046
SIC	0.40	0.0162	1.321	0.243	0.481	0.111	0.0039
SICL	0.46	0.0084	1.521	0.3425	0.482	0.09	0.0056
SIL	0.76	0.0051	1.663	0.3987	0.439	0.065	0.011
SL	1.60	0.0267	1.449	0.3099	0.387	0.039	0.03

Chemical Properties Lookup Table

CAS No.	Chemical	Organic carbon partition coefficient, K_{oc} (cm^3/g)	Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Pure component water solubility, S (mg/L)	Henry's law constant H' (unitless)	Henry's law constant at reference temperature, H (atm-m^3/mol)	Henry's law constant reference temperature, T_R (°C)	Normal boiling point, T_B (°K)	Critical temperature, T_C (°K)	Enthalpy of vaporization at the normal boiling point, $\Delta H_{v,b}$ (cal/mol)	Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RIC (mg/m^3)	Molecular weight, MW (g/mol)	URF extrapolated (X)	RfC extrapolated (X)
56235	Carbon tetrachloride	1.74E+02	7.80E-02	8.80E-06	7.93E+02	1.25E+00	3.04E-02	25	349.90	556.60	7,127	1.5E-05	2.5E-03	153.82		+
67641	Acetone	5.75E-01	1.24E-01	1.14E-05	1.00E+06	1.59E-03	3.88E-05	25	329.20	508.10	6,955	0.0E+00	3.5E-01	58.08		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	334.32	536.40	6,988	0.0E+00	3.0E-03	119.38		+
71432	Benzene	5.89E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.55E-03	25	353.24	562.16	7,342	7.8E-06	6.0E-03	78.11		+
71556	1,1,1-Trichloroethane	1.10E+02	7.80E-02	8.80E-06	1.33E+03	7.05E-01	1.72E-02	25	347.24	545.00	7,136	0.0E+00	2.2E+00	133.41		
74839	Methyl bromide (bromomethane)	9.00E+00	7.28E-02	1.21E-05	1.52E+04	2.56E-01	6.24E-03	25	276.71	467.00	5,714	0.0E+00	5.0E-03	94.94		
74873	Chloromethane	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	248.94	416.80	5,147	1.8E-06	3.0E-01	51.00		X
75003	Chloroethane	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.00	460.00	5,892	8.3E-07	1.0E+01	65.00		X
75014	Vinyl chloride (chloroethene)	1.86E+01	1.06E-01	1.23E-06	2.76E+03	1.11E+00	2.70E-02	25	259.25	432.00	5,250	8.9E-06	1.0E-01	62.50		
75092	Methylene chloride	1.11E+01	1.01E-01	1.17E-05	1.32E+04	8.98E-02	2.19E-03	25	313.00	510.00	6,706	4.7E-07	3.0E+00	84.93		
75274	Bromodichloromethane	5.50E+01	2.98E-02	1.06E-05	6.74E+03	6.56E-02	1.60E-03	25	363.15	585.85	7,000	1.8E-05	7.0E-02	163.83	X	+
75343	1,1-Dichloroethane	3.16E+01	7.42E-02	1.05E-05	5.06E+03	2.30E-01	5.62E-03	25	330.55	523.00	6,895	0.0E+00	5.0E-01	99.96		
75354	1,1-Dichloroethylene	5.89E+01	9.00E-02	1.04E-05	2.25E+03	1.07E+00	2.61E-02	25	304.75	576.05	6,247	5.0E-05	2.0E-01	96.94		
78875	1,2-Dichloropropane	4.37E+01	7.82E-02	8.73E-06	2.80E+03	1.15E-01	2.80E-03	25	369.52	572.00	7,590	1.9E-05	4.0E-03	112.99		
78933	Methyl Ethyl Ketone	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	353.00	535.00	34,920	0.0E+00	1.0E+00	71.00		
79005	1,1,2-Trichloroethane	5.01E+01	7.80E-02	8.80E-06	4.42E+03	3.74E-02	9.13E-04	25	386.15	602.00	8,322	1.6E-05	1.4E-02	133.41		
79016	Trichloroethylene	1.66E+02	7.90E-02	9.10E-06	1.10E+03	4.22E-01	1.03E-02	25	360.38	544.20	7,505	1.1E-04	3.5E-02	131.39		
79345	1,1,2,2-Tetrachloroethane	9.37E+01	7.10E-02	7.90E-06	2.97E+03	1.41E-02	3.45E-04	25	419.60	661.15	8,996	5.8E-05	2.1E-01	167.85		+
83329	Acenaphthene	4.90E+03	4.21E-02	7.69E-06	4.24E+00	6.36E-03	1.55E-04	25	550.54	803.15	12,155	0.0E+00	2.1E-01	154.21		X
86737	Fluorene	1.38E+04	6.08E-02	7.88E-06	1.90E+00	3.16E-03	7.70E-05	25	570.44	870.00	12,666	0.0E+00	1.4E-01	166.22		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.70	772.00	11,190	0.0E+00	1.4E-01	142.00		
91203	Naphthalene	1.19E+03	5.90E-02	7.50E-06	3.10E+01	1.98E-02	4.83E-04	25	491.14	748.40	10,373	0.0E+00	3.0E-03	128.18		
95501	1,2-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	1.56E+02	7.79E-02	1.90E-03	25	453.57	705.00	9,700	0.0E+00	2.0E-01	147.00		
95578	2-Chlorophenol	3.98E+02	5.01E-01	9.48E-06	2.20E+04	1.60E-02	3.91E-04	25	447.53	675.00	9,572	0.0E+00	1.9E-02	128.56		X
95954	2,4,5-Trichlorophenol	8.90E+01	2.91E-02	7.03E-06	1.19E+03	8.94E-03	2.18E-04	25	526.15	759.13	13,000	0.0E+00	3.5E-01	197.45		X
100414	Ethylbenzene	3.63E+02	7.50E-02	7.80E-06	1.69E+02	3.23E-01	7.88E-03	25	409.34	617.20	8,501	1.1E-06	1.0E+00	106.17		
100425	Styrene	7.76E+02	7.10E-02	8.00E-06	3.10E+02	1.13E-01	2.75E-03	25	418.31	636.00	8,737	0.0E+00	1.0E+00	104.15		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	484.13	707.60	11,329	0.0E+00	7.0E-02	122.17		X
106467	1,4-Dichlorobenzene	6.17E+02	6.90E-02	7.90E-06	7.38E+01	9.96E-02	2.43E-03	25	447.21	684.75	9,271	6.3E-06	1.1E-01	147.00		
106934	1,2-dibromoethane	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.00	582.80	9,986	2.2E-04	2.0E-04	188.00		
107062	1,2-Dichloroethane	1.74E+01	1.04E-01	9.90E-06	8.52E+03	4.01E-02	9.79E-04	25	356.65	561.00	7,643	2.6E-05	4.9E-03	99.96		
108101	Methyl Isobutyl Ketone	1.34E+02	7.60E-02	7.80E-06	1.90E+04	5.74E-03	1.40E-04	25	389.00	575.00	40,610	0.0E+00	8.1E-02	100.00		
108383	Xylene (m)	4.07E+02	7.00E-02	7.80E-06	1.61E+02	3.01E-01	7.34E-03	25	412.27	617.05	8,523	0.0E+00	1.0E-01	106.17		X
108883	Toluene	1.82E+02	8.70E-02	8.60E-06	5.26E+02	2.72E-01	6.64E-03	25	383.78	591.79	7,930	0.0E+00	4.0E-01	92.14		
108907	Chlorobenzene	2.19E+02	7.30E-02	8.70E-06	4.72E+02	1.52E-01	3.70E-03	25	404.87	632.40	8,410	0.0E+00	6.0E-02	112.56		
111444	Bis(2-chloroethyl)ether	7.60E+01	6.92E-02	7.53E-06	1.72E+04	7.38E-04	1.80E-05	25	451.15	659.79	9,000	3.3E-04	0.0E+00	143.11		
120127	Anthracene	2.35E+04	3.24E-02	7.74E-06	4.34E-02	2.67E-03	6.50E-05	25	615.18	873.00	13,121	0.0E+00	1.1E+00	178.24		X
120821	1,2,4-Trichlorobenzene	1.78E+03	3.00E-02	8.23E-06	3.00E+02	5.82E-02	1.42E-03	25	468.15	725.00	10,471	0.0E+00	2.0E-01	181.45		
124481	Dibromochloromethane	4.68E+02	9.60E-02	1.00E-05	4.40E+03	3.49E-02	8.50E-04	25	418.14	678.20	8,000	2.4E-05	7.0E-02	208.28	X	
127184	Tetrachloroethylene	1.55E+02	7.20E-02	8.20E-06	2.00E+02	7.54E-01	1.84E-02	25	394.40	620.20	8,288	6.9E-06	8.0E-01	165.83		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936.00	14,370	0.0E+00	1.1E-01	202.26		X
156592	cis-1,2-Dichloroethylene	3.55E+01	7.36E-02	1.13E-05	3.50E+03	1.67E-01	4.08E-03	25	333.65	544.00	7,192	0.0E+00	3.5E-02	96.94		X
156605	trans-1,2-Dichloroethylene	5.25E+01	7.07E-02	1.19E-05	6.30E+03	3.85E-01	9.38E-03	25	320.85	516.50	6,717	0.0E+00	7.0E-02	96.94		X
542756	1,3-Dichloropropene	4.57E+01	6.26E-02	1.00E-05	2.80E+03	7.26E-01	1.77E-02	25	381.15	587.38	7,000	4.0E-06	2.0E-02	110.97		
1634044	Methy tert Butyl Ether	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.00	497.10	6,678	1.0E-07	3.0E+00	88.00		

Notes:

"+" Additional RfC extrapolated from RfD-inhalation factor presented in USEPA Region IX Preliminary Remediation Goals document (USEPA 2002).
Default physio-Chemical constants included in spreadsheet replaced with constants from USEPA Region IX Preliminary Remediation Goals document (USEPA 2002) when available.
Additional physio-chemical constants from NIST 2001.

APPENDIX 5

DEVELOPMENT OF SOIL LEACHING SCREENING LEVELS

A. HIDOH 1995 SESOIL MODEL DISCUSSION
B. MADEP SESOIL ALGORITHM

A. HIDOH 1995 SESOIL MODEL DISCUSSION

RISK-BASED CORRECTIVE ACTION AND DECISION MAKING AT SITES WITH CONTAMINATED SOIL AND GROUNDWATER

VOLUME I

(Selected Sections Only)

December 1995
(Revised June 1996)

State of Hawai'i Department of Health
919 Ala Moana Blvd, Room 212
Honolulu, Hawai'i 96814

(808-586-4226)

Prepared by:
Roger D. Brewer, Ph.D.
Environmental Management Division

TABLE OF CONTENTS

CHAPTER 1: TIER 1 ACTION LEVELS FOR SOIL AND GROUNDWATER:

		Page
I.	INTRODUCTION	1
II.	BACKGROUND A. Existing Criteria B. DOH Tiered Approach to Site Remediation	2
III.	OBJECTIVES A. Groundwater Protection Objectives B. Direct-Exposure Protection Objectives	3
IV.	SESOIL VADOSE-ZONE CONTAMINANT-FATE-AND-TRANSPORT MODELS A. SESOIL Computer Application B. Impacted-Site Scenario	5
V.	DIRECT-EXPOSURE MODELS	5
VI.	DEVELOPMENT AND USE OF TIER 1 LOOKUP TABLE A. Development of Tier 1 Lookup Table B. General Application of Tier 1 Soil Action Levels C. Application of SALs to Soils Two Meters or Less From Groundwater D. Tier 2 Modification of SALs With Respect to Dilution of Leachate in Groundwater E. Application of Tier 1 Action Levels to Sites With Impacted Groundwater	6
VII.	SUMMARY	9

CHAPTER 2: TIER 2, SITE-SPECIFIC EVALUATION OF IMPACTED SOILS

		Page
I.	INTRODUCTION	18
II.	DOH TIERED APPROACH TO SITE EVALUATIONS AND REMEDIAL RESPONSE	19
III.	TIER 2 SOIL ACTION LEVELS - OBJECTIVES A. Groundwater Protection Objectives B. Direct-Exposure Objectives	20
IV.	GENERATION OF TIER 2 SALs FOR GROUNDWATER-PROTECTION CONCERNS - SESOIL APPLICATION A. SESOIL Computer Application B. SESOIL Model Procedures	21
V.	GENERATION OF TIER 2 SALs FOR GROUNDWATER-PROTECTION CONCERNS - QUIKSOIL SPREADSHEET	25
VI.	CALCULATION OF FINAL SALs FOR GROUNDWATER-PROTECTION CONCERNS	26
VII.	GENERATION OF TIER 2 SALs FOR DIRECT-EXPOSURE CONCERNS A. Direct-Exposure Model Equations B. Direct-Exposure Model Procedures C. Default Exposure Assumptions	27
VIII.	MAXIMUM-ALLOWABLE SOIL ACTION LEVELS	29
IX.	COMPARISON OF GROUNDWATER-PROTECTION AND DIRECT-EXPOSURE SALs	29
X.	APPLICATION TO SITES WITH IMPACTED GROUNDWATER	30
XI.	TIER 3 RISK ASSESSMENTS	31
REFERENCES		
ADDENDUM		
#1	EXTENT OF CONTAMINATION	
#2	UPDATE TO TIER 1 LOOKUP TABLES	

LIST OF FIGURES

Figure 1. Geologic profile of generic model.

LIST OF TABLES

TABLE 1-1. Tier 1 Action Levels for soil and groundwater

TABLE 1-2. Tier 1 and Tier 2 groundwater protection standards

TABLE 1-3. Site parameters and default values used in Tier 1 SESOIL models

TABLE 1-4. Exposure parameters and default values used in Tier 1 direct-exposure models

TABLE 2-1. Example generation of Tier 2 SALs.

TABLE 2-2. Tier 1 and Tier 2 groundwater protection standards

TABLE 2-3. Site parameters and default values used in Tier 1 SESOIL models

TABLE 2-4. Monthly climate data used in Tier 1 SESOIL standard-rainfall models

TABLE 2-5. Physical properties of basalt and common soil types in Hawai'i

TABLE 2-6. Default, physio-chemical constants for common contaminants

TABLE 2-7. Default biodegradation constants for use in Tier 2 SESOIL models

TABLE 2-8. Toxicity data for common contaminants

TABLE 2-9. Direct-exposure site parameters and default values

TABLE 2-10. Direct-exposure human-receptor parameters and default values

APPENDICES

APPENDIX A PREVIOUS SOIL CLEANUP CRITERIA (AUGUST, 1992, TGM)

APPENDIX B EXCERPTS FROM "THE NEW SESOIL USER'S GUIDE" AND "GROUNDWATER CONTAMINATION SUSCEPTIBILITY EVALUATION"

APPENDIX C DESCRIPTION AND JUSTIFICATION OF SESOIL DEFAULT, TIER 1 PARAMETER VALUES

APPENDIX D RUNNING, CALIBRATING, AND INTERPRETING SESOIL

APPENDIX E MODIFICATION AND USE OF USEPA REGION IX DIRECT-EXPOSURE MODELS

APPENDIX F TIER 1 SOIL ACTION LEVELS GENERATED FROM GROUNDWATER-IMPACT, CONTAMINANT SATURATION, AND DIRECT-EXPOSURE MODELS

APPENDIX G RAINFALL ISOHYET MAPS FOR THE MAJOR ISLANDS OF HAWAI'I

APPENDIX H EXAMPLE QUIKSOIL SPREADSHEET RESULTS

APPENDIX I EXAMPLE TIER 2 EVALUATION RESULTS

APPENDIX J EXAMPLE TIER 3 DIRECT-EXPOSURE SPREADSHEET RESULTS (DETIER3)

APPENDIX K SUPPORTING DATA FOR TIER 1 SOIL ACTION LEVELS GENERATED USING SESOIL (Addendum #3)

ACKNOWLEDGEMENTS

The Department of Health wishes to thank the following individuals for their helpful discussions and suggestions during the preparation of this report: Dr. Dave Hetrick of Oak Ridge National Laboratories; Dr. Stephen Lau, Dr. Schlomo Orr, Dr. Aly El-kadi, Dr. Frank Peterson, and Dr. Dick Green of the University of Hawai□i at M□noa; Dr. Paul Eyre and Chip Hunt of the U.S. Geological Survey (Honolulu office); Chester Lao of the City and County of Honolulu Board of Water Supply; Edwin Sakoda and Glenn Bauer of the State of Hawai□i Department of Land and Natural Resources; Dr. Barbara Brooks of Barrett Consulting Group; Steven Scott of Enviromental Graphics; Michael Barden of the Wisconsin Department of Natural Resources; Michael Anderson of the Oregon Department of Environmental Quality Control; and Herb Levine, Joe Williams, Andrew Lincoff, and Matt Small of the U.S. EPA. DOH also wishes to thank the numerous other environmental specialists working in Hawai'i and on the mainland U.S. who contributed to the preparation of this report.

EXECUTIVE SUMMARY

This report presents and describes a refined, risk-based corrective action (RBCA) process that has been implemented by the Hawai□i Department of Health (DOH) for assessment and remediation of sites with contaminated soil and groundwater. Chapter 1 presents a revision of Tier 1, DOH-recommended ("default") action levels for soil and groundwater in accordance with advances made in quantitative direct-exposure and contaminant fate-and-transport models. To reflect their purpose to serve as a guide to site remedial actions but not necessarily to serve as strict "cleanup numbers", DOH has chosen to refer to the revised criteria as soil and groundwater "action" levels.

Tier 1 soil and groundwater action levels appropriate for a given site are chosen from a lookup table based on the location of the site with respect to potential impact on drinking-water resources and annual rainfall at the site. Soil and groundwater action levels for contaminants not listed in the report can be obtained from the DOH.

Groundwater action levels adhere to state and federal surface water and drinking water standards. As a minimum, groundwater action levels are set to be protective against potential adverse impact to surface water ecosystems. For sites where drinking water resources may also be impacted, groundwater action levels are refined as needed to additionally meet drinking water standards.

Soil action levels are set to be protective of direct, residential exposure to impacted soils and adverse groundwater impact due to remobilization (e.g., leaching) of contaminants from the soil. Soil action levels are generated with the aid of computer-assisted, risk-based, direct-exposure models and vadose-zone leaching models. Action levels are contaminant-specific and based on both the potential mobility and toxicity of the contaminant.

The Tier 1 soil action levels presented in the lookup table may be overly conservative for small areas of impacted soil (e.g., less than one-half acre). Chapter 2 provides guidelines for use of the models on a Tier 2, site-specific basis. In Tier 2 site assessments, DOH allows a controlled use of the Tier 1 models to generate more site-specific soil action levels without the need for a full-scale, time-consuming, and generally costly "risk assessment (Tier 3)." Site-specific factors that can be taken into account in Tier 2 assessments include the actual volume of impacted soil at the site and the geology and hydrogeology of the site. User-friendly computer spreadsheets are available from DOH for use in Tier 2 site evaluations. For further guidance on Tier 2 procedures refer Chapter 2 of this document. DOH should be consulted prior to a facility undertaking a full-scale (Tier 3) risk assessment.

CHAPTER 1

IV. SESOIL VADOSE-ZONE CONTAMINANT-FATE-AND-TRANSPORT MODELS

SESOIL Computer Application

The potential for residual contamination to be leached from vadose zone soils and carried downward into groundwater was modeled using the RiskPro SESOIL computer application (General Sciences Corporation, 1993, Version 1.07). An overview of the SESOIL application is presented in "The New SESOIL User's Guide (August, 1994)" published by the Wisconsin Department of Natural Resources (Hetrick et al., 1994). Excerpts from the publication are provided in Appendix B. A sensitivity analysis of SESOIL conducted by the Wisconsin Department of Natural Resources (WDNR, 1993) is included in the appendix.

SESOIL is a relatively simple and very user-friendly vadose-zone, contaminant-fate-and-transport computer application. The application allows for a monthly resolution of contaminant flux into the groundwater. In actuality, contaminant levels in leachate as it passes into groundwater could exceed the target maximum concentration levels during some portion of the month and the monthly average still fall below these target objectives. Resolution on a monthly scale is, however, the current best-available technology and, given the numerous other uncertainties involved in determining site cleanup levels, DOH feels that evaluation of groundwater impact on a month-averaged scale is adequate.

Impacted-Site Scenario

The generic impacted-site scenario used in the Tier 1 SESOIL simulations is depicted in Figure 1 and described in Table 1-3. The rationale behind the parameter values chosen is discussed in Appendix C. A technical discussion regarding use of the SESOIL computer application to generate groundwater-protection soil action levels that address potential groundwater impact is provided in Appendix D. An example of a SESOIL output file is provided in Attachment 1 of Appendix D. Results of the SESOIL models that were used to generate the Tier 1 lookup table (Table 1-1) are given in Appendix F.

SESOIL simulations are relatively easy to set up and run. As described in Appendix D, however, proper interpretation of SESOIL output is not necessarily straight forward and there is ample room to draw misleading or erroneous conclusions. The user must thoroughly understand the relationship between the SESOIL model simulation and the desired soil leaching model scenario. Use of SESOIL to generate alternative soil action levels for Tier 2 purposes <u>must</u> follow the procedures outlined in appendices C and D unless otherwise approved or directed by DOH.

TABLE 1-1a.Tier 1 Action Levels for soil and groundwater: Rainfall ≤ 200cm/year

RAINFALL ≤200CM/YEAR				
	DRINKING WATER SOURCE THREATENED		DRINKING WATER SOURCE NOT THREATENED	
Contaminant	Groundwater (mg/l)	Soil (mg/kg):	Groundwater (mg/l)	Soil (mg/kg):
Benzene	0.005	0.05	1.7	1.7
Toluene	1.0	16	2.1	34
Ethylbenzene	(0.14)	0.50	0.14	0.50
Xylene	10	23	[10]	23
Benzo(a)pyrene	0.0002	1.0de	[0.0002]	1.0de
Acenaphthene	(0.32)	18sat	0.32	18sat
Fluoranthene	(0.013)	11sat	0.013	11sat
Naphthalene	0.24	41sat	0.77	41sat
PCE	0.005	0.29	0.145	5.0de
1,1 DCE	0.046	0.47de	3.9	0.47de
Vinyl Chloride	0.002	0.18de	[0.002]	0.18de
TCE	0.005	0.01	0.70	1.5
1,1,1 TCA	0.20	0.10	6.0	3.0
PCBs (all)	0.0005	1de	0.002	1de
Lead (total)	(0.0056)	400de	0.0056	400de
Cadmium (total)	0.005	38de	0.009	38de
TPH-residual fuels	NS	5,000	NS	5,000
TPH-middle distillates	NS	5,000	NS	5,000
TPH-gasolines	NS	2,000	NS	2,000

TABLE 1-1b.Tier 1 Action Levels for soil and groundwater: Rainfall > 200cm/year

RAINFALL >200CM/YEAR				
	DRINKING WATER SOURCE THREATENED		DRINKING WATER SOURCE NOT THREATENED	
Contaminant	Groundwater (mg/l)	Soil (mg/kg):	Groundwater (mg/l)	Soil (mg/kg):
Benzene	0.005	0.05	1.7	0.68
Toluene	1.0	2.6	2.1	5.5
Ethylbenzene	(0.14)	0.13	0.14	0.13
Xylene	10	8	[10]	8
Benzo(a)pyrene	0.0002	1.0de	[0.0002]	1.0de
Acenaphthene	(0.32)	18sat	0.32	18sat
Fluoranthene	(0.013)	11sat	0.013	11sat
Naphthalene	0.24	41sat	0.77	41sat
PCE	0.005	0.04	0.145	1.1
1,1 DCE	0.046	0.47de	3.9	0.47de
Vinyl Chloride	0.002	0.18de	[0.002]	0.18de
TCE	0.005	0.004	0.70	0.56
1,1,1 TCA	0.20	0.06	6.0	1.9
PCBs (all)	0.0005	1de	0.002	1de
Lead (total)	(0.0056)	400de	0.0056	400de
Cadmium (total)	0.005	38de	0.009	38de
TPH-residual fuels	NS	5,000	NS	5,000
TPH-middle distillates	NS	5,000	NS	5,000
TPH-gasolines	NS	2,000	NS	2,000

TABLE 1-1 (cont.). Tier 1 Action Levels for soil and groundwater: Notes

ANNOTATIONS:

unmarked criteria: groundwater-protection concerns dominate
de: direct-exposure concerns dominate
sat: saturation concentration, groundwater-protection concerns dominate
(): Same as surface water; surface water standard more stringent than drinkingwater standard.
[]: Same as drinking water; surface water standards not set.
NS: no standard, no drinking water or surface water criteria set.
PCE: tetrachloroethylene, DCE: dichloroethylene, TCE: trichloroethylene, TCA: trichloroethane, PCBs: polychlorinated biphenyls, TPH: total petroleum hydrocarbons

NOTES:

1. Determination of groundwater utility should be determined based on the DOH policy *Determination of Groundwater Utility at Leaking Underground Storage Tank Sites (September 13, 1995).* (HIDOH, 1995b)
2. TPH criteria as presented in *Reporting, Remediation, and Management of Petroleum-Contaminated Soil (December, 1995).* (HIDOH, 1995d). Gasolines: characterized by a predominance of alkyl benzenes and straight-chain, branched, and cyclo- alkanes and alkenes with carbon ranges of C6 to C12. Middles distillates (e.g., kerosene, diesel fuel, home heating fuel, jet fuel, etc.): characterized by a predominance of straight-chain alkanes and polynuclear aromatic hydrocarbons with carbon ranges of C12 to C24. Residual fuels: characterized by long chain alkanes (carbon range >C24) and less predominant aromatics that include phenathrenes, benzopyrenes, and other poly-nuclear aromatic hydrocarbons.
3. The facility should contact DOH for further guidance when laboratory practical quantification limits exceed the recommended groundwater criteria.
4. Lowermost limit on soil action levels for benzene leachate concerns set at 0.05mg/kg based on field experience rather than adhering to SESOIL results. (See Chapter 1.)
5. Soil action levels set for leachate-impact concerns (SALs not annotated with "sat" or "de") assume depth to groundwater is two meters or less and assume no dilution of leachate in groundwater (i.e., Dilution Attentuation Factor (DAF) = 1. Not applicable to TPH criteria. See Chapter 2 and Table 1 in Appendix F.).
6. Refer to Tier 2 discussion (Chapter 2) for guidance on adjustment of Tier 1 leachate-impact SALs with respect to depth to groundwater from the base of the impacted soil and site-specific DAFs.

GROUNDWATER-IMPACT MODEL (see text)

Climate data: Standard rainfall models: '□huimanu Loop station data adjusted to 200cm annual rainfall.

High rainfall models: Honom□ Mauka station data adjusted to 400cm annual rainfall.

Geologic model: Sand or very permeable saprolite/soil overlying fractured, porous basalt.

DIRECT-EXPOSURE MODEL (see text)

Assumes long-term residential exposure to impacted soil through inhalation, ingestion, and dermal absorption.

TABLE 1-2. Tier 1 and Tier 2 groundwater protection standards

Contaminant	[1,2]Current/Potential Drinking Water Resource (mg/l)	[1,3]Non-Drinking Water Resource (mg/l)
Benzene	0.005	1.7
Toluene	1.0	2.1
Ethylbenzene	(0.14)	0.14
Xylene	10	[10]
Benzo(a)pyrene	0.0002	[0.0002]
Acenaphthene	(0.32)	0.32
Fluoranthene	(0.013)	0.013
Naphthalene	[5]0.24	0.77
PCE	0.005	[4]0.145
1,1 DCE	0.046	3.9
Vinyl Chloride	0.002	[0.002]
TCE	0.005	0.70
1,1,1 TCA	0.20	6.0
Lead (total)	(0.0056)	[4]0.0056
Cadmium	0.005	[4]0.0093
PCBs	0.0005	[6]0.002

() Same as surface water; surface-water standard more stringent than drinking water standard.
[] Same as drinking water; surface-water standards not set.
1. Groundwater utility as defined by DOH (refer to HIDOH, 1995b).
2. Drinking water MCL for contaminant unless otherwise noted (HAR Chapter 11-20. 1994).
3. Surface water acute standard (or chronic standard where available and applicable) for contaminant unless otherwise noted (HAR Chapter 11-54, 1992).
4. Marine chronic surface water quality standard as established in HAR, HAR 11-54.
5. Drinking water criteria provided in USEPA Region IX Preliminary Remediation Goals document (USEPA, 1995).
6. Ecology-based, freshwater acute standard used for PCBs. (Freshwater and chronic standards are based on FDA action levels for PCBs in fish for commercial consumption rather than ecological impact and were not used in this study.).

TABLE 1-3. Site parameters and default values used in Tier 1 SESOIL models

Climate Data:

Air Temperature:	25°C (all months)
Evapotranspiration (cm/day):	40% of rainfall
Precipitation (cm/month):	200 or 400cm/year, month-specific
Storm Duration (days)	month-specific
Number of Storms:	month-specific
Days per Month:	30.4 (default, all months)

Soil Properties:

Bulk Density (g/cm^3):	1.5 (all layers)
Intrinsic Permeability (cm^2):	0 (specified in soil column input)
Disconnectedness Index:	3.5 (all layers)
Effective Porosity:	0.3 (all layers)
Organic Carbon Content (%):	0.1 (layer specific)
Cation Exchange Capacity (meq/100g):	0 (all layers)
Freundich Equation Exponent:	1.0 (all layers)

Application Data:

Number of years of input data:	25
Number of geologic column layers:	4
Application area:	1,000cm^2
Spill mode:	Instantaneous
Pollutant input mode:	Concentration (ug/g)
Washload Simulation:	not used

Soil Column Properties:

Layer #	Thickness	Permeability	[1]OC Content
1 (soil)	200cm	1E-07cm^2	same as input
2 (soil)	100cm	1E-07cm^2	1.0
3 (basalt)	400cm	1E-06cm^2	0.001
4 (basalt)	1cm	1E-06cm^2	0.001

1. Foc as a fraction of the input soil property value

Pollutant Loading Data (Layer 1 only)

1st year, 1st month	Input concentration (ug/g) calibrated to specific contaminant & model
Load for all other months	0 ug/g
Volatilization (fraction)	0.2 (all months)

CHAPTER 2

TIER 2, SITE-SPECIFIC EVALUATION OF IMPACTED SOILS

I. INTRODUCTION

The generic, Tier 1 soil action levels (SALs) presented in Chapter 1 are set to satisfy groundwater and direct-exposure objectives at sites with extensive amounts of contamination. For sites with limited contamination, however, the Tier 1 SALs may be overly stringent and lead to unnecessary cleanup actions. This chapter presents guidelines for generating more site-specific, "Tier 2" soil action levels using the same models and procedures incorporated into the development of the Tier 1 lookup tables.

The Tier 2 process allow facilities to take into account the actual volume of contaminated soil at the site, the depth to groundwater and the expected dilution of contaminant leachate as it passes into groundwater. Corresponding site-specific data that may be incorporated into the Tier 2 models include the aerial extent of contamination, the thickness of the impacted soil interval, the depth to groundwater from the base of the impacted soil, the regional groundwater gradient and the annual rainfall at the site.

In accordance with objectives set forth in development of the Tier 1 SALs, Tier 2 SALs must address the following concerns:

1. Potential adverse impact on groundwater due to leaching of residual contamination from impacted soil,

2. Potential adverse impact on groundwater due to remobilization of free-phase product in impacted soils, and

3. Potential threats to human health due to direct exposure to impacted soil.

Tier 2 SALs generated to satisfy the above groundwater-protection and direct-exposure concerns are compared and the most stringent SAL (i.e., the SAL that satisfies both concerns) are applied to the site. An example is given in Table 2-1.

[Note that the groundwater action levels presented in Chapter 1 are fixed and cannot be made more "site-specific". As discussed at the end of this chapter, however, exceeding groundwater action levels at a site does not necessarily require that immediate, engineered remedial actions are necessary.]

Tier 2 SALs can be generated by use of one or more of four DOH-approved computer models and spreadsheets:

1. SESOIL (General Sciences Corporation, version 1.07 and later updates) - used to address leachate impact on groundwater and potential mobilization of free product from

impacted soil;

2. QUIKSOIL (DOH spreadsheet) - used as a quick but simplistic and conservative alternative to SESOIL to address leachate impact on groundwater; (Not recommended for highly volatile or biodegradable contaminants or for sites where the base of the impacted soil is greater than ten meters from groundwater.);

3. DAF (DOH spreadsheet) - used to approximate a site-specific dilution attenuation factor (DAF) that reflects the dilution of leachate it mixes with groundwater. Tier 1 or Tier 2 SALs generated with SESOIL or Tier 2 SALs generated with QUIKSOIL should be multiplied by the site DAF to refine final SALs for groundwater-protection concerns.

4. DETIER2 (DOH spreadsheet) - used to evaluate potential impact on human health from direct-exposure to impacted soil.

The groundwater-protection models are especially applicable to sites impacted with relatively mobile organic contaminants. The SESOIL computer application is available from the noted distributor. The QUIKSOIL, DAF, and DETIER2 spreadsheets are available from the DOH Solid and Hazardous Waste Branch. SESOIL models normally take ten to thirty minutes to complete once the operator has collected the necessary input data and has become familiar with the application. Use of the application must adhere to procedures presented in this chapter unless otherwise approved or directed by DOH. Spreadsheet calculations take only a matter of minutes.

Site investigations should be carried out in accordance with guidelines presented in the DOH "Technical Guidance Manual for Underground Storage Tank Closure and Release Response (TGM)" and subsequent updates (HIDOH, 1992, 1995a, 1995b, 1995c, 1995d). At all contaminant release sites, the extent of soil and groundwater impact should be delineated out to Tier 1 soil and groundwater action levels unless otherwise approved or directed by DOH. In cases where groundwater has been impacted by a release but groundwater contaminant levels do not exceed Tier 1 action levels, it may, however, be appropriate to investigate and assess impacted soil with respect to direct-exposure concerns only. (Refer to section 9 and to Appendix F, Table 3.)

Facilities are encouraged to use the Tier 2 models to address site-specific remediation needs rather than rely on the Tier 1 lookup tables or before undertaking a more costly and time consuming "Tier 3" site evaluation. Facilities should be aware, however, that re-use and disposal of impacted soil left in place at a site may fall under regulation by the DOH Office of Solid Waste Management should that soil ever be excavated, regardless of whether the soil meets Tier 1, 2, or 3 criteria for groundwater-protection and direct-exposure concerns (refer to HIDOH, 1995d).

Section 2 and 3 of this chapter reviews DOH's tiered approach for setting appropriate soil and groundwater action levels at a site and discusses groundwater-protection and direct-exposure objectives. Sections 4, 5, 6, and 8 present models for generation of Tier 2 SALs for groundwater-protection concerns. Section 7 presents a model for generation of Tier 2 SALs for direct-exposure concerns. Section 9 summarizes the procedure for choosing the appropriate SAL for a site and provides results from four example sites. **Readers are encouraged to briefly review the example**

results (Appendix I) before moving on to the main text of this chapter.

Section 10 provides additional guidance for sites where groundwater has already been impacted by a vadose-zone release. The final section of the chapter briefly reviews the intent of Tier 3 risk assessments and introduces a Tier 3, direct-exposure spreadsheet (DETIER3) available from DOH for public use. Note that for use in this report, the term "soil" refers to any unlithified, subsurface, solid media.

II. DOH TIERED APPROACH TO SITE EVALUATIONS AND REMEDIAL ACTIONS

In the past, DOH has allowed the use of site-specific risk assessments ("Tier 3") as an alternative to use of default, generally conservative, soil and groundwater action levels ("Tier 1"). The high costs and general lengthy review time typical associated with formal risk assessments, however, made the use of this option prohibitive at all but the largest release sites or sites where potential remedial costs outweighed risk assessment costs.

In response to this dilemma, DOH has refined its tiered approach to site remedial actions to include a conservative but more flexible and cost-efficient method of setting site-specific soil action levels - Tier 2. The overall concept of the tiered approach to site evaluations is detailed in the ASTM document entitled "Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites (ASTM, 1994)." (Note that DOH has chosen not to use the example quantitative models presented in the ASTM document.)

In Tier 1, a facility refers to conservative, default ("generic") soil action levels provided by the DOH that can be used at any impacted site (refer to Chapter 1). The Tier 1 action levels were generated by incorporating default, conservative impacted-site and exposure assumptions into standardized, quantitative groundwater-protection and direct-exposure models used by the DOH.

In Tier 2, the subject of this chapter, a facility is permitted to substitute actual site data into the same models used to generate Tier 1 SALs as well as additional, DOH-approved models and evaluate groundwater-protection and direct-exposure concerns on a controlled, but more site-specific basis.

In Tier 3, a facility employs alternative groundwater-impact models, direct-exposure models, and/or input parameter assumptions to evaluate an impacted site and supports all input data with a thorough and rigorous risk assessment. Procedures that should be followed for the preparation of Tier 3 risk assessments are briefly outlined at the end of this chapter and more fully discussed in DOH technical guidance manuals (HIDOH,1992).

Impacted sites with contaminant concentrations in excess Tier 1 soil or groundwater action levels required to initiate followup "action," whether this be remediation to default action levels (Tier 1), limited refinement of soil action levels to reflect more site-specific data (Tier 2), or full refinement of soil action levels based on a detailed, site-specific risk assessment (Tier 3).

III. TIER 2 SOIL ACTION LEVEL - OBJECTIVES

Groundwater Protection Objectives

The importance of Hawaii's groundwater and surface water resources cannot be overemphasized. Essentially 100% Hawaii's drinking water comes from groundwater resources. The quality of the state's inland and coastal surface waters is intricately tied to the quality of the islands groundwater and likewise plays a crucial role in the ecological and, in turn, economic health of the state.

Tier 2 soil action levels for groundwater-protection concerns must be set to meet the following objectives:

1) Leachate that infiltrates through the vadose zone and recharges any groundwater system must not cause the groundwater to be impacted at greater than DOH standards for surface water (either marine or fresh water, whichever is the more stringent).

2) Leachate that infiltrates through the vadose zone and recharges a groundwater system that is a current or potential source of drinking water must not lead to a groundwater impact that exceeds either surface water or drinking water standards.

3) Due to the heightened threat of groundwater impact, residual contamination present in the vadose-zone should not exceed Tier 1, theoretical saturation levels for individual contaminants of concern.

The delineation and utility of groundwater systems on the islands should be made in accordance with the DOH policy statement "Determination of Groundwater Utility at Leaking Underground Storage Tank Sites (HIDOH, 1995b)." For the purposes of both Tier 1 and Tier 2 site evaluations, DOH assumes that all leachate that infiltrates through the vadose zone will impact a groundwater system. It is further assumed that all groundwater systems are potentially interconnected to bodies of surface water (streams, rivers, lakes, marshes, coastal waters, etc.) and that all of these surface water bodies are ecologically important.

DOH groundwater action levels for common contaminants of concern are repeated in Table 2-2. As discussed in Chapter 1, groundwater action levels for all sites are initially set to meet surface water quality criteria. This is intended to be protective of aquatic ecosystems should contaminated groundwater migrate or otherwise be discharged into a body of surface water. The criteria presented are based on state and federal acute or, when available, chronic surface water standards. For sites where the groundwater of concern is a current or potential source of drinking water ("Drinking Water Source Threatened" in Table 1-1), action levels are adjusted where needed to ensure that state drinking water standards or alternative drinking water criteria are additionally met. Note that drinking water standards are substituted for surface water standards where the latter have not been established (e.g., benzo(a)pyrene).

Direct-Exposure Objectives

In addition to addressing groundwater protection concerns, Tier 2 SALs ultimately applied to a site must be also be protective of residential exposure to impacted soils through inhalation, ingestion, and dermal absorption. With the exception of only a few compounds, most notably benzo(a)pyrene and PCBs, direct-exposure soil action levels generated are set to meet a one-in-a-million (10^{-6})

cancer risk for carcinogenic contaminants and a hazard quotient of "1" for non-carcinogenic contaminants. The use of alternative direct-exposure objectives and assumptions at a site must be justified and documented in a Tier 3 risk assessment that is submitted to DOH for review and approval.

IV. GENERATION OF TIER 2 SALs FOR GROUNDWATER-PROTECTION CONCERNS - SESOIL APPLICATION

SESOIL Computer Application

RiskPro's SESOIL vadose-zone contaminant fate and transport computer application (GSC, 1993, Version 1.07) developed by General Sciences Corporation (GSC) or updates to the application must be used for Tier 2 evaluations of potential groundwater impact unless otherwise approved or directed by DOH. An overview of the RiskPro SESOIL application is presented in "The New SESOIL User's Guide (August, 1994)" published by the Wisconsin Department of Natural Resources (Hetrick et al., 1994). Excerpts from the publication are provided in Appendix B. A sensitivity analysis of SESOIL conducted by the Wisconsin Department of Natural Resources (WDNR, 1993) is included in the appendix.

Other versions of the SESOIL application may be inappropriate for use in either Tier 2 or Tier 3 site evaluations. An example of unacceptable versions of SESOIL include the SESOIL module in the 1995 "Decision Support Software" computer application put forth by the American Petroleum Institute (API, 1994). Output from this version of SESOIL provides only a yearly resolution of groundwater impact, rather than monthly as in the original version of the application.

A table of SESOIL-generated SALs based on the default Tier 1 site scenario are presented in Appendix F for variable depths to groundwater. As an alternative to re-running SESOIL models at sites where depth to groundwater may be an important
factor in setting groundwater protection SALs, facilities can refer to SALs presented in Appendix F for use in Tier 2 assessments. The default SALs should be multiplied by the appropriate site dilution attenuation factor, as described below, in order to generate a final groundwater protection SAL for the site.

Unless otherwise approved or directed by DOH, use of SESOIL to generate soil action levels for Tier 2 (or Tier 3) purposes must follow assumptions and procedures described in this chapter. Note that for Tier 3 site evaluations, any vadose-zone application can be used provided that the application generates at least a monthly resolution for groundwater impact. If the model results are not as conservative as would have been produced using the GSC version of SESOIL, however, then the discrepancy should be discussed and justified in the Tier 3 report and use of the application approved by DOH.

SESOIL Model Procedures

Procedures regarding use of SESOIL to generate initial Tier 2 SALs are described below. Each step corresponds to an input module of the application. Fill out and submit the SESOIL worksheet provided in Appendix D (attachment D2) for each mode run. A summary of the input data parameters and default values used in the Tier 1 models is provided in Table 2-3. A complete

description and discussion of the Tier 1 default parameter values is provided in Appendix C.

Step 1: Input Model Simulation Information

Note the site name, DOH ID number, and contaminant modeled in the module heading. "Raingage station" refers to the source of climate data used in the simulation. The number of years of climate data input will normally be "1" (climate data is repeated in subsequent model simulation years). The model simulation time will vary based on the physio-chemical nature of the contaminant and the hydrogeology of the site. (Due to memory limitations, the IBM 466DX used for Tier 1 could not run SESOIL simulations greater than 25 years in length.)

Step 2: Input Climate Data

Input data from the most correlative climate station (an optional climate data set is available with the RiskPro SESOIL application). Evapotranspiration can be directly calculated from input cloud cover, humidity, and albedo data. For most climate stations, however, these data are not available. If this is the case, input a value of "0" for monthly cloud cover, humidity, and albedo data and input evapotranspiration as a fraction of total rainfall based on the island location of the site as follows (data from Atlas of Hawai'i, 1983): Ni'ihau: 72% total rainfall, Kaua'i: 24% total rainfall, O'ahu: 36% total rainfall, Moloka'i: 54% total rainfall, Maui: 27% total rainfall, L□na'i: 66% total rainfall, Kaho'olawe: 70% total rainfall, and Hawai'i: 44% total rainfall. Note that evapotranspiration data must be input as cm/day.

Where appropriate climate data are not available, determine the annual rainfall for the site based on maps provided in Appendix G. Refer to the default climate data provided in Table 2-4 and modify the default monthly precipitation (total 200cm/year) to reflect actual annual rainfall determined for the site (e.g., for sites with 100cm of annual rainfall the default precipitation data would be multiplied by a factor of 0.5). Input evapotranspiration as the appropriate, daily fraction of total rainfall based on the island that the site is located on (see above).

Step 3: Input Soil Property Data

Input site-specific soil property data where supported by information gained during the site investigation or related published reports. Otherwise, use the default, Tier 1 parameter values noted in Table 2-3. For sites where mixtures of contaminants are present (e.g., petroleum releases), assume that an organic carbon content of no more than 0.1% is available for sorption of any given contaminant.

The data input into the soil property module are applied to the uppermost layer of the geologic model and then used as default values for subsequent layers. Input a value of "0" for the default soil permeability. Layer-specific permeability will be set in the "Soil Column Properties" module (step 6).

The default soil property data presented in Table 2-3 are based on information published by the U.S. Department of Agriculture (Foote et al., 1972; USDOA, 1976; USDOA, 1992) and the University of

Hawai'i - M□noa Water Resources Research Center (Miller et al., 1988; Mink and Lau, 1990), and also on discussions with local experts of Hawaii's soils and hydrogeology (Table 2-5). Refer to the discussion in Appendix C and the DOH Tier 1 document for additional discussion regarding soil and bedrock properties in Hawai'i.

Step 4: Input Physio-Chemical Constants for Contaminant

Default physio-chemical constants and biodegradation rates for common contaminants are provided in tables 2-6 and 2-7. These constants should be used for both the SESOIL and direct-exposure models unless otherwise approved or directed by DOH. Contact the DOH Solid and Hazardous Waste Branch for information regarding contaminants not listed in the table. A value of "0" will normally be input for the hydrolysis and complexation constants noted in the module. Refer to Appendix C for a discussion on the source and justification of the default physio-chemical constants and biodegradation rates provided. Input physio-chemical constants can be supplemented with site-specific soil data where available (e.g., soil batch tests, etc.).

Step 5: Input Application Data

Input a value of "25" for the number of years of model simulation data. This should be sufficient for most model simulations. The number of soil layers input is governed by the geologic profile determined for the site. **Include a 1cm- thick layer at the base of the column and input the same soil/bedrock properties as the layer overlying it.** In the model simulation, this 1cm-thick layer directly overlies groundwater. Inclusion of a thin, basal layer is used to improve the precision of the SESOIL output data regarding the mass of contaminant moving from the vadose-zone into the groundwater (used in step 7).

The input application area reflects the areal extent of impacted soil and is used in conjunction with layer thickness to calculate contaminant mass. SESOIL automatically generates the site latitude based on the input climate station. The spill mode should be set to "Instantaneous" to reflect the one-time presence of residual contamination in the model impacted layer (i.e., no continuous source). "Pollutant Load" should be set to "Concentration" to reflect soil contaminant concentration as input in the next module. Washload simulations are not applicable for Tier 2 models.

Step 6: Input Soil Column Properties

Input thickness and permeability data for each geologic layer. Refer to the default permeability data provided in Table 2-5 where site-specific data are not available. The number of soil sublayers will normally be set to one.

For the layers underlying the uppermost unit, input a value of "1" for all soil-property, factoring parameters except organic carbon (OC). For organic carbon, input factors that reflect site-specific data where available. For sites where site-specific OC data are not available, assume an organic carbon content of 0.0001% for all lithified (rock) units and for all sediment and soil layers situated at greater than 3 meters depth (following assumptions used in Tier 1) and adjust the input OC factor values accordingly. For sites where mixtures of contaminants are present (e.g., petroleum), assume a

maximum of 0.1% OC for soils within three meters of the surface and 0.0001% OC for all lithified units and for all layers situated at greater than 3 meters depth.

Step 7: Input Pollutant Loading Data

Input a value of "0" for the first data-input year of the "mass transformed", "sink", and "ligand" columns unless otherwise approved or directed by DOH. The input factor will be repeated for all subsequent years of data. **Input a value of "0.2" for "volatilization factor" to limit contaminant loss due to volatilization to 20% of the maximum possible (required).** Note that unlike the factors noted above the volatilization factor must be repeated for <u>every</u> simulation year. (Click on the column heading and use the column math function to expedite data input.) The application erroneously assumes a volatilization factor of 1 for all months where no data is input.

Input a value of "0" for the monthly pollutant load of each year of input data (i.e., the number of data-input years noted in Step 5) except the first month of the first year. Following the procedures outlined in Appendix D, adjust the input soil concentration for the 1st year, 1st month until the model is calibrated to target groundwater-protection objective. **(Do not include assumed dilution of leachate at this point!)**

Step 8: Extract Groundwater-Impact SAL from Output Data.

Extract the SESOIL-generated SAL from the calibrated output file by following the procedures outlined in Appendix D. Change the SAL units to mg/kg. The final, site SAL for groundwater-protection concerns will be calculated by multiplying the SESOIL-generated SAL by the dilution attenuation factor determined for the site, as discussed below.

Unedited (except for format) output files for SESOIL model simulations must be included with the report documenting the derivation of each Tier 2 soil action level. The version of SESOIL used to generate the Tier 2 soil action levels must be clearly indicated in the report. Warning messages in the output file regarding input rainfall and permeability data are based on the input of extremely variable data and are intended to prompt the user to recheck the input data modules. If the input data is correct then the warnings can generally be ignored.

Table 2-1. Example generation of Tier 2 SALs. Site - Inland area over basal, unconfined, drinking water groundwater system in basalt; base of impacted soil ≥ 10m above top of groundwater; moderate rainfall (150cm/year); areal extent of soil impacted above Tier 1 SALs = 900m^2, thickness of soil impacted above Tier 1 SALs = 2m (assumed same for each contaminant)

[1]Contaminant	[2]SESOIL SAL (mg/kg)	[3]Site DAF	[4]Groundwater Protection SAL (mg/kg)	[5]Direct-Exposure SAL (mg/kg)	**[6]SAL chosen for site (mg/kg)**
Benzene	0.027	2.5	0.07	6.8	**0.07**
Toluene	124	2.5	[4]170sat	5340	**170**
PCE	2.3	2.5	5.8	5.8	**5.8**

1. Contaminants noted exceeded Tier 1 soil action levels (SALs) at the example site.

2. Default Tier 1 SESOIL SALs for groundwater protection taken from lookup table rather than re-running SESOIL to generate site-specific SALs for groundwater protection (refer to Appendix F, Table 1a).

3. Site dilution attenuation factor (DAF) as calculated using DAF spreadsheet.

4. Site SALs for groundwater-protection concerns calculated by multiplying the SESOIL SAL times the leachate dilution attenuation factor determined for the site. Maximum groundwater-protection SAL is the contaminants theoretical saturation limit ("sat", refer to Appendix F, Table 2).

5. Contaminant direct-exposure SALs as calculated using DETIER2 spreadsheet.

6. SAL chosen for site reflects the contaminant pathway of most concern.

TABLE 2-2. Tier 1 and Tier 2 groundwater protection standards

Contaminant	[1,2]Current/Potential Drinking Water Resource (mg/l)	[1,3]Non-Drinking Water Resource (mg/l)
Benzene	0.005	1.7
Toluene	1.0	2.1
Ethylbenzene	(0.14)	0.14
Xylene	10	[10]
Benzo(a)pyrene	0.0002	[0.0002]
Acenaphthene	(0.32)	0.32
Fluoranthene	(0.013)	0.013
Naphthalene	[5]0.24	0.77
PCE	0.005	[4]0.145
1,1 DCE	0.046	3.9
Vinyl Chloride	0.002	[0.002]
TCE	0.005	0.70
1,1,1 TCA	0.20	6.0
Lead (total)	(0.0056)	[4]0.0056
Cadmium	0.005	[4]0.0093
PCBs	0.0005	[6]0.002

() Same as surface water; surface-water standard more stringent than drinking water standard.
[] Same as drinking water; surface-water standards not set.
1. Groundwater utility as defined by DOH (refer to HIDOH, 1995b).
2. Drinking water MCL for contaminant unless otherwise noted (HAR Chapter 11-20. 1994).
3. Surface water acute standard (or chronic standard where available and applicable) for contaminant unless otherwise noted (HAR Chapter 11-54, 1992).
4. Marine chronic surface water quality standard as established in HAR, HAR 11-54.
5. Drinking water criteria provided in USEPA Region IX Preliminary Remediation Goals document (USEPA, 1995).
6. Ecology-based, freshwater acute standard used for PCBs. Both freshwater and chronic standards are based on FDA action levels for PCBs in fish for commercial consumption rather than ecological impact.

Table 2-3. Site parameters and default values used in Tier 1 SESOIL models

Climate Data:	[1]Default Values
Air Temperature:	month-specific
Evapotranspiration (cm/day):	36% of rainfall, month specific
Precipitation (cm/month):	200cm/year, month-specific
Storm Duration (days)	month-specific
Number of Storms:	month-specific
Days per Month:	30.4 (default, all months)
Soil Properties:	
Bulk Density (g/cm^3):	1.3
Intrinsic Permeability (cm^2):	specified in soil column input
Disconnectedness Index:	3.5
Effective Porosity:	0.3
Organic Carbon Content (%):	0.1
Cation Exchange Capacity (meq/100g):	0
Freundich Equation Exponent:	1.0

Soil Column Properties:

Layers	[2]Thickness	[3]Permeability	[4]Organic Carbon
soil	site specific	1E-07cm^2	0.1%
basalt/bedrock	site specific	1E-06cm^2	0.0001%

1. Refer to default values presented in Table 2-4 for month-specific data.
2. Total thickness reflects assumed depth to groundwater.
3. Values used in Tier 1 models. Refer to Table 2-5 for default permeability values.
4. Foc as a fraction of input soil property value.

TABLE 2-4. Monthly climate data used in Tier 1 SESOIL standard-rainfall models. (Modified Ahuimanu Loop climate station data)

Month	[1]Air Temperature (□C)	[2]Evapotrans-piration (cm/day)	[3]Precipitation (cm/month)	Duration (days)	Number of Storms	Month Length (days)
Oct.	25	0.21	12.02	0.31	12.2	30.4
Nov.	24	0.24	14.06	0.36	12.2	30.4
Dec.	23	0.28	15.90	0.43	11.1	30.4
Jan.	22	0.39	22.54	0.50	10.0	30.4
Feb.	22	0.22	12.88	0.35	10.1	30.4
Mar.	22	0.28	16.37	0.33	12.6	30.4
Apr.	23	0.27	15.32	0.36	13.6	30.4
May	24	0.18	10.68	0.27	13.0	30.4
June	25	0.14	7.87	0.26	11.5	30.4
July	25	0.14	8.10	0.29	12.5	30.4
Aug.	25	0.16	9.19	0.26	12.8	30.4
Sept.	25	0.14	7.92	0.23	11.8	30.4

Annual Totals: Precipitation: 200cm, Evapotranspiration: 80cm, Surface Runoff: 48cm (Groundwater Recharge = 72cm)

1. Air temperature data from K□ne'ohe Mauka climate station (Owenby and Ezell, 1992). All other data modified from '□huimanu Loop climate station.

2. Evapotranspiration calculated as 40% of daily rainfall.

3. '□huimanu Loop monthly precipitation adjusted to produce 200cm annual rainfall versus actual 223cm/yr. Input precipitation reduced by 24% to account for surface runoff.

TABLE 2-5. Physical properties of basalt and common soil types in Hawai'i

Properties	Basalt	Saprolite (a)/ silty sediment	Saprolite (b)	Clay (c)	Sand
Range Hydraulic Conductivity (in/hr)	-	2 to 6	0.6 to 2.0	0.06 to 0.2	6 to 20
Range Hydraulic Conductivity (m/d)	up to 300+	1 to 4	0.1 to 0.4	0.04 to 0.12	4 to 12
Range Permeability (cm^2)	1E-8 to 4E-6	1E-8 to 5E-8	5E-9 to 1E-8	5E-10 to 5E-9	5E-8 to 1E-7
Model Hydraulic Conductivity (m/d)	100	4	0.4	0.2	12
Model Permeability (cm^2)	1E-06	5E-08	5E-09	2E-9	1E-07
Organic Carbon at >50cm depth (%)	no data (0%)	0 to 1.0%	0 to 1.0%	highly variable	0 to 0.1%
Bulk Density (g/cm^3)	1.6	1.3	1.3	1.3	1.7

Saprolite (a): Silty clay - Wahiaw□, Helemano, Waik□ne, Loleka'a soil series.
Saprolite (b): Silty clay - 'Ewa, Waialua soil series.
Clay (c): Lualualei, Ka'ena series.

Sources of published data:

1. Soil Survey of the Islands of Kaua'i, O'ahu, Maui, Moloka'i, and Lana'i, State of Hawai'i (Foote et al., 1972);
2. Soil Survey Laboratory Data and Descriptions for Some Soils of Hawai'i (USDOA, 1976);
3. Hydrogeologic Characteristics of Subsoil and Saprolite and Their Relation to Contaminant Transport, Central O'ahu, Hawai'i (Miller et al., 1988);
4. Aquifer Identification and Classification for O'ahu (Mink and Lau, 1990);
5. Hawai'i Field Office Technical Guide (Section II, Engineering Index Properties, USDOA, 1992).

TABLE 2-6. Default, physio-chemical constants for common contaminants

[1]Constituent	Water Solubility (mg/l)	Diffusion Coefficient-air (cm^2/s)	Henry's Constant (m^3-atm/mole)	KOC (ml/g)	Molecular Weight
Benzene	1800	0.088	0.0055	65	78
Toluene	520	0.078	0.0066	260	92
Ethylbenzene	680	0.075	0.0079	220	110
Xylene (mixed)	200	0.087	0.0053	240	110
[2]Benzo(a)pyrene	0.0039	0.045	0.0000024	881000	252
Acenaphthene	4	0.064	0.0012	4600	150
[2]Fluoranthene	0.26	0.051	0.0000087	41700	202
Naphthalene.	31	0.069	0.0013	1300	130
PCE	150	0.072	0.023	660	170
1,1 DCE	400	0.079	0.15	65	97
Vinyl Chloride	1100	0.110	0.70	57	63
TCE	1000	0.081	0.0089	130	130
1,1,1 TCA	950	0.080	0.0028	150	130

1. Source of data USEPA (1995) unless otherwise noted.
2. Data after Montgomery and Welkom (1991) and Neff et al. (1994).

TABLE 2-7. Default biodegradation constants for use in Tier 2 SESOIL models

Constituent	Range Aerobic Half-life (days)	Range Anaerobic Half-life (days)	Model Liquid-Phase Half-life (days)	Model Liquid-Phase Biodegradation Rate (1/days)	Model Solid-Phase Biodegradation Rate (1/days)
Benzene	5 to 16	112 to 730	112	0.0062	0.0031
Toluene	4 to 22	56 to 210	56	0.0124	0.0062
Ethylbenzene	3 to 10	176 to 228	176	0.0039	0.0020
Xylene (mixed)	7 to 28	180 to 365	180	0.0039	0.0019
Benzo(a)pyrene	56 to 529	228 to 2117	529	0.0013	0.0007
Acenaphthene	12.3 to 102	49.2 to 408	102	0.0068	0.0034
Fluoranthene	140 to 440	558 to 1774	558	0.0012	0.0006
Naphthalene	0.5 to 20	25 to 258	25	0.0277	0.0139
PCE	180 to 365	98 to 1643	365	0.0019	0.0009
1,1 DCE	28 to 180	81 to 173	180	0.0039	0.0019
Vinyl Chloride	28 to 180	112 to 730	180	0.0039	0.0019
TCE	180 to 365	98 to 1642	365	0.0019	0.0009
1,1,1 TCA	140 to 273	560 to 1092	560	0.0012	0.0006

Half-life data after Howard et al. (1991).

REFERENCES

Anderson, M. R., 1992, Development of Soil Cleanup Levels Based on Analysis of the Leachate Pathway: Environmental Cleanup Division, Oregon Department of Environmental Quality Control.

Foote, D. E., Hill, E. L., Nakamura, S., and Stephens, F., 1972, Soil Survey of the Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawai'i: United States Department of Agriculture, Soil Conservation Service, 232p.

GSC. 1993. *RISKPRO's SESOIL for Windows (Version 1.07, December 1993)*: General Sciences Corporation, Laurel, Maryland.

Hetrick, D. M., Scott, S. J., and Barden, M. J., 1994, *The New SESOIL User's Guide, August 1, 1994*: Wisconsin Department of Natural Resources, Emergency & Remedial Response Section.

HIDOH. 1995b. Determination of Groundwater Utility at Leaking Underground Storage Tank Sites (September 19, 1995): State of Hawai'i Department of Health, Environmental Management Division, Solid and Hazardous Waste Branch, Underground Storage Tank Section.

Howard, P. H., Boethling, R. S., Jarvis, W. F., Meylan, W. M., and Michalenko, E. M., 1991, *Handbook of Environmental Degradation Rates*: Lewis Publishers; Chelsea, Michigan, (ISBN# 0-87371-358-3), 725p.

Miller, M., Green, R., Peterson, F., Jones, R., and Loague, K., 1988, Hydrogeologic Characteristics of Subsoil and Saprolite and Their Relationship to Contaminant Transport, Central O'ahu, Hawai□i: Water Resources Research Center, University of Hawai'i at Manoa, Technical Report No. 178.

Mink, J. F. and Lau, S. L., 1990, Aquifer Identification and Classification for O'ahu: Groundwater Protection Strategy for Hawai'i: Water Resources Research Center, University of Hawai'i at M□noa, Technical Report No. 179.

Montgomery, J. H. and Welkom, 1991, *Groundwater Chemicals Desk Reference*: Lewis Publishers, Chelsea; Michigan, ISBN# 0-87371-286-2, 640p.

Neff, J. M., Langseth, D. E., Graham, E. M., Sauer, T. C. Jr., Gnewuch, S. C., 1994, Transport and Fate of Non-BTEX Petroleum Chemicals in Soil and Groundwater: American Petroleum Institute, Health and Environmental Sciences Department, Publication No. 4593.

Owenby, J. R. and Ezell, D. S., 1992, Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days, 1961-1990, Hawai'i (January, 1992), U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Climatology of the United States Bulletin No. 81.

USDOA. *Soil Survey Laboratory Data and Descriptions for Some Soils of Hawai'i (1976):* United States Department of Agriculture, Natural Resource Conservation Service, Honolulu, Soil Survey Investigations Report No. 29.

USDOA 1992. *Hawai'i Field Office Technical Guide (Section II, Engineering Index Properties,1992):* United States Department of Agriculture, Natural Resource Conservation Service, Honolulu.

USDOC. 1985-1993. *Local Climatological Data - Honolulu, Hawai'i (1985 through 1993 reports):* United States Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), ISSN 0198-1706.

WDNR. 1993. *Groundwater Contamination Susceptibility Evaluation - SESOIL Modeling (May 3, 1993):* Wisconsin Department of Natural Resources, Bureau of Solid and Hazardous Waste, Emergency and Remedial Response Section.

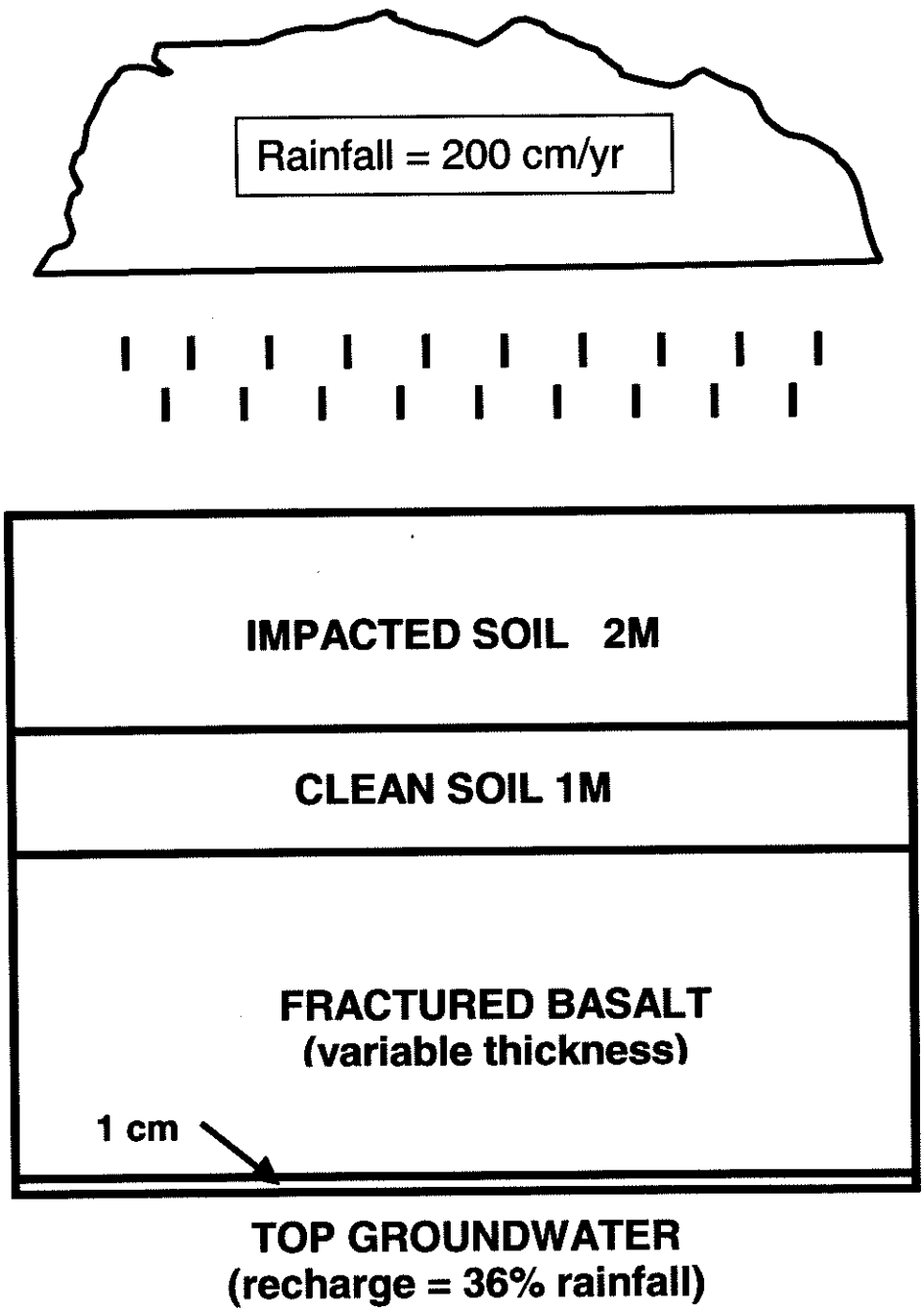


Figure 1. Geologic profile of generic model.

B. MADEP SESOIL ALGORITHM

The method used by the Ontario Ministry of Environment and Energy (MOEE 1996) to develop soil screening levels for leaching concerns was adopted from guidance published by the Massachusetts Department of Environment Protection (MADEP). This appendix provides relevant sections and appendices from the 1994 MADEP publication entitled "Background Documentation for the Development of the Massachusetts Contingency Plan Numerical Standards".

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

MCP APPENDIX F

DEVELOPMENT OF

DILUTION/ATTENUATION FACTORS (DAFs)

FOR THE LEACHING-BASED

SOIL STANDARDS

DEVELOPMENT OF DILUTION/ATTENUATION FACTORS (DAFs) FOR THE LEACHING-BASED SOIL STANDARDS

INTRODUCTION

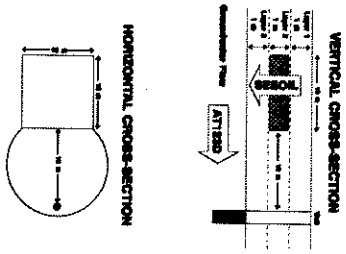
The Massachusetts Department of Environmental Protection has developed dilution attenuation factors (DAFs) in order to establish soil cleanup criteria for the protection of groundwater from leaching of residual contaminants in soil. DEP has adopted the modeling approach utilized by the State of Oregon in a similar process. This report describes the model and its application toward the development of DAFs for Massachusetts for a limited number of compounds of concern, and the subsequent development of one regression algorithm that relates DAFs developed by Oregon to those applicable in Massachusetts; and another algorithm that relates DAFs to chemical specific parameters. The pathway to groundwater is only one consideration in the final determination of an acceptable soil cleanup level.

THE OREGON MODEL

The Oregon model (Anderson, 1992) assumes a generic setting for a release of contaminant in the unsaturated zone and then applies the combination of SESOIL and AT123D models to estimate impact of the initial soil loading on a receptor assumed directly downgradient of the site via the groundwater pathway. The SESOIL and AT123D models, while previously individually developed (see References, Bonazountas, 1984 and Yeh, 1981), are a part of the risk assessment Graphical Exposure Modeling System (GEMS) developed by USEPA. A pc-based version of this (PCGEMS) was developed for USEPA by General Sciences Corporation (1989). The two models can now be linked so that SESOIL can pass leachate loadings to the saturated zone AT123D model.

The Oregon model's site setting (see Figure 1) assumes a 3-meter thick unsaturated zone, divided into three 1-meter layers. Contamination is initially released in the middle layer, as might occur for a leaking tank or for a residual contaminant remaining after some remedial excavation with clean cover backfill, and is uniformly distributed in this layer over a 10 meter by 10 meter area. The unsaturated zone and aquifer are assumed to be the same sandy soil with uniform properties. The upper and lower unsaturated zone layers are initially clean, as is the aquifer.

FIGURE 1
CONCEPTUAL SETTING



Source: Anderson (1991)

SESOIL inputs include the soil type parameters, chemical properties, application rates, and the climatic conditions of the area. The model is run as a transient monthly estimator of leachate volumes and concentrations. Initially, no other transport mechanisms other than leaching, partitioning, and volatilization were considered. Oregon used default values in SESOIL for Portland Oregon climatic conditions, but distributed total precipitation uniformly over the year.

SESOIL was initially found to overestimate losses via volatilization. A parameter, the volatilization fraction (VOLF), was introduced to allow adjustment of losses through this pathway and allow a site-specific calibration. This factor may be varied in time and space. The Oregon study used a uniform VOLF factor of 0.2, based on consultation with a panel of experts. One other soil-related parameter is the disconnectedness index. This parameter varies for and within soil types. Two values are given as SESOIL defaults, and the larger, 7.5, has been used in the simulations. An increase in this parameter appears to result in a higher soil moisture, lower leachate rates, and somewhat lower DAFs (i.e., is more conservative) for the compounds run.

AT123D inputs include general aquifer properties, source configuration, loadings to groundwater, soil partition coefficients, and dispersivity values. The aquifer is assumed to be infinitely wide and thick. The pc-based version of AT123D accepts monthly transient loading rates calculated by SESOIL, and also provides a preprocessor for input file preparation and editing. In utilizing the model, the center of the 10 by 10 meter source area is assumed to be at coordinates 0,0,0. The positive x-axis is in the direction of flow. Calculated concentrations are maximum along the x-axis (y=0) and at the water table surface (z=0). Since the receptor is assumed to be 10 meters from the downgradient edge of the source area, the concentration at x=15, y=0, and z=0 represents the receptor location. Oregon used longitudinal, transverse, and vertical dispersivities of 20m, 2m, and 2m, respectively. These values seem high for a sandy aquifer, but the values have been retained to be consistent with the Oregon base values and to be protective of the Commonwealth's sensitive aquifers on Cape Cod. DAFs are proportional to the dispersivities, particularly sensitive to the vertical dispersivity.

Oregon ran the model for 10 indicator compounds and then developed a multiple linear regression model relating the DAF to the organic partition coefficient (K_{oc}) and the Henry's Law constant (H) to provide preliminary DAFs for sixty other organic compounds. Soil cleanup levels were generated based on the regression algorithm and a safe drinking water level for each compound. In some cases, risk based levels determined by other pathways were lower than the levels required to protect groundwater. In these instances, the lower value was selected as the soil target level. A similar approach was taken to develop the MCP Method 1 Standards, as described in Section 5.3.

SIMULATIONS FOR MASSACHUSETTS

The approach taken to develop DAFs for Massachusetts was to determine the effect that varying the location (changing the climatic conditions from Portland, Oregon to Boston, Massachusetts in SESOIL) would have on the Oregon calculated DAFs. If the model system was essentially linear with respect to loading, then DAFs already calculated for Oregon would be directly related to DAFs appropriate for Massachusetts, and the general algorithm developed by Oregon (with coefficients adjusted) could also be used to estimated DAFs for other compounds. To this end, model runs were made using the Oregon input values for SESOIL and AT123D with the exception of climate parameter values. Eight indicator compounds were selected: benzene, toluene, ethylbenzene, o-xylene, trichloroethene, tetrachloroethene, 1,1,1-trichloroethane, and naphthalene.

The input values for SESOIL are shown in Tables F-1 through F-4, and those for AT123D are shown on Table F-5. Depending on the mobility of the compound through the transport pathway, model runs varied from 2 years to 6 years as necessary to determine the maximum concentration attained at the receptor location for a specific compound. A point to consider in the adoption of the Oregon values, or adjustments to them, is the need to agree with the physio-chemical parameters that were used to generate the DAFs. Even in the eight indicator compounds selected, various accepted databases provide some widely varying values for S, H and K_{oc}. For example, for PCE, H is reported with an order of magnitude difference, and values of K_{oc} and solubility differing by a factor of 2 are reported for ethylbenzene in the literature.

Output concentrations at the selected receptor location demonstrated a cyclical nature due to seasonal variations in precipitation and net recharge. Maximum concentrations were not always attained in the first cycle due to seasonal variability. However, the model output appeared to be linear with respect to the initial loading, allowing soil cleanup levels to be estimated based on the linear DAF approach. Table F-6 shows the model-based DAFs for Oregon and Massachusetts, and also, based on listed safe drinking water levels and the estimated DAFs for Massachusetts, what soil target levels would be for the eight indicator compounds run.

TABLE F-1
CLIMATE PARAMETER VALUES
FOR THE SESOIL MODEL

Default climate values for Boston as contained in the SESOIL model. Latitude = 42 degrees.

TABLE F-2
SOIL PARAMETER VALUES
FOR THE SESOIL MODEL

Intrinsic permeability $=1x10^{-7}$ cm^2
Source area=1,000,000 cm^2
Porosity =0.3
Disconnectedness index = 7.5
Soil bulk density = 1.5 gm/cm^3
Soil organic carbon = 0.1%

Layer 1 thickness = 100 cm
Layer 2 thickness = 100 cm
Layer 3 thickness = 100 cm
No further sublayering specified

Clay content = 0%

All other parameters set to zero except those to indicate uniform parameters in all layers.

TABLE F-3
APPLICATIONS DATA
FOR SESOIL MODEL

Application month = October only
layer = 2
rate = 1500 microgm/cm^2
year = 1 only

Based on the area, thickness and bulk density, this produces an initial concentration of 10 ppm. No other sources are added.

Volatile fraction (VOLF) = 0.2

Uniform in time and space.

All other parameter values set to zero.

TABLE F-4
CHEMICAL DATA FOR SESOIL MODEL

Compound	MW	K_{oc} ml/g	S mg/L	H atm-m^3/mol	DA cm^2/sec
benzene	78	83	1780	0.0055	0.109
ethylbenzene	106	575	161	0.00343	0.093
toluene	92	270	535	0.00668	0.100
o-xylene	106	302	171	0.00527	0.093
TCE	131	124	1100	0.00912	0.083
PCE	166	468	200	0.00204	0.075
1,1,1-TCA	133	157	730	0.0231	0.080
naphthalene	128	1288	31	0.00118	0.085

MW = molecular weight
K_{oc} = organic carbon partition coefficient
S = solubility in water
H = Henry's Law constant
DA = diffusion coefficient in air

TABLE F-5
AT123D MODEL INPUT PARAMETER VALUES

Soil bulk density	= 1.5 g/cc
Porosity	= 0.3
Hydraulic conductivity	= 0.5 m/hr
Hydraulic gradient	= 0.005
Longitudinal dispersivity	= 20.0 m
Transverse dispersivity	= 2.0 m
Vertical dispersivity	= 2.0 m

Loading (kg/hr) passed by SESOIL link program
Distribution coefficient = K_{oc} * fraction organic carbon
Source area = 10 m by 10 m, centered at 0,0
initial z penetration = 0

Degradation rates initially zero

TABLE F-6
MODEL OUTPUT DRAFT DAFS
COMPARISON AND SOIL LEVELS

Oregon Compound	Mass DAF	DAF	DRINKING WATER LEVEL mg/L	SOIL TARGET LEVEL ppm
benzene	44.4	56.5	0.005	0.28
ethylbenzene	103.5	121.1	0.700	84.8
toluene	64.5	80.6	1.000	80.6
o-xylene	65.4	83.3	10.000	833.3
TCE	65.4	76.3	0.005	0.38
PCE	73.0	86.2	0.005	0.43
1,1,1-TCA	133.2	169.2	0.200	33.8
naphthalene	207.0	222.2	0.280	62.2

STATISTICAL RELATIONSHIPS

A linear regression was run on the eight DAF data pairs with DAFs for Oregon as the independent variable. The model was :

$$DAF_{Mass} = A + B*DAF_{Oregon}$$

That is, the regression was not forced through the origin. For the eight data pairs, the equation was

$$DAF_{Mass} = 12.39 + 1.053*DAF_{Oregon}$$

with an r of 0.9913. Thus, over the range of data spanned by these eight compounds, the correlation appears good. Table F-7 shows a comparison of the DAFs calculated by the model and those by the linear regression equation above for the eight indicator compounds. Differences between the two methods are less than 10 percent.

A multiple linear regression algorithm for DAF(Mass) as a function of K_{oc} and H was also developed along the same lines as that developed by Oregon. This allows the calculation of DAFs for compounds for which Oregon did not consider, and which also may be used exclusively from the linear regression cited above. Two models were considered:

(a) $DAF = A + B*H + C*K_{oc}$, and
(b) $DAF = B*H + C*K_{oc}$.

where A, B, and C are regression coefficients. As with the Oregon analysis, it proved that the constant term was not statistically different from zero, and the simpler second model was adopted. Regression analysis yielded:

$$DAF = 6207 * H + 0.166 * K_{oc}$$

The fit here is somewhat better than the r-squared value of .956 for the Oregon model in that one compound with a large residual (carbon tetrachloride with a residual of 30) was not used here, and the average difference is much smaller with the eight compounds than for Oregon's ten. Table F-8 shows the relationship between the model DAFs and the regression expression predicted values. Only one compound varies more than 10 percent while six of the eight have percent differences less than five.

TABLE F-7
COMPARISON BETWEEN MODEL DAFS AND LINEAR REGRESSION DAFS BASED ON OREGON DAFS

Compound	Model DAF	Regr. DAF	%Diff.
benzene	56.5	59.1	4.60
ethylbenzene	121.1	121.4	0.25
toluene	80.6	80.3	-0.37
o-xylene	83.3	81.3	-2.40
TCE	76.3	81.3	6.55
PCE	86.2	89.3	3.60
1,1,1-TCA	169.2	152.6	-9.81
naphthalene	222.2	230.4	3.69

TABLE F-8
RESULTS OF THE MULTIPLE LINEAR REGRESSION EQUATION FOR H AND KOC

Compound	Model DAF	Predicted	% Diff.
benzene	56.5	47.9	-15.2
ethylbenzene	121.1	116.7	- 3.6
toluene	80.6	86.3	7.1
o-xylene	83.3	82.8	- 0.5
TCE	76.3	77.2	1.2
PCE	86.2	90.4	4.9
1,1,1-TCA	169.2	169.4	0.1
naphthalene	222.2	221.1	- 0.5

BIODEGRADATION

It is intuitive that biodegradation may play an important role in attenuating the potential impact of residual contaminants in soils on groundwater. However, there are a great many site-specific conditions that will determine actual biodegradation rates. Further, literature values cover a wide range and the exact conditions under which they were estimated are rarely known. Literature values should be applied only with great caution

to any estimation of contaminant fate and transport. In order to evaluate the potential effect of biodegradation, rate constants cited by Howard et al (1991) were input to the model for the five compounds of the eight indicator compounds known to degrade aerobically. This eliminated the chlorinated compounds TCE, PCE, and 1,1,1-TCA. In addition, one additional rate for benzene (0.002/day from the California LUFT guidance) was also run. Four runs were made for benzene as the most critical compound, at the California rate, at the high and low rates cited by Howard and at the geometric mean of the Howard high and low rates. Only one rate, the low Howard value, was used for each of the other four compounds. The reason for this will be seen shortly.

The degradation rates in Howard appear to be high, with half lives for the BTEX compounds on the order of days. This implies that within a year, residual concentrations in soil would be reduced by biodegradation several (three to six) orders of magnitude. Table F-9 presents the results of the model runs.

For all situations except for the two lowest rates for benzene, the DAFs become huge. In essence, this indicates that only trace amounts of the contaminants ever reach the groundwater table. Soil target level estimation using large DAFs and the linear approach should be done only with extreme caution. A contaminant in the subsurface will attempt to reach equilibrium concentrations in the air, moisture and sorbed to soil. At some total concentration, equilibrium solubility in moisture would be exceeded, indicating the probable presence of free product. In this case, the linearity and basic assumptions in the model may be violated. Of further consideration are the potential toxic effects on the biological population as concentrations of the compounds increase. For these circumstances, estimation of soil target levels considering biodegradation is very difficult.

TABLE F-9
RESULTS OF THE BIODEGRADATION RUNS

Compound	Rate in Soil 1/day	Rate in Water 1/day	DAF
benzene	0.002	0.001 *	84.7
benzene	0.0433	0.000963	2178.
benzene	0.0775	0.00817	1.5×10^{4}
benzene	0.1386	0.0693	5.7×10^{7}
toluene	0.0315	0.02475	8.7×10^{6}
ethylbenzene	0.0693	0.00304	1.8×10^{13}
o-xylene	0.02475	0.001899	2.8×10^{5}
naphthalene	0.01444	0.00269	8.6×10^{10}

* Note: Odencrantz's article on the California LUFT parameter values did not cite a rate for water. This was assumed here to be half that in soil. Note that not much more degradation occurs in the aquifer due to the rapid travel time to the receptor of about 11 to 12 days (large longitudinal dispersivity and low retardation).

SENSITIVITY

A detailed sensitivity analysis was not done at this point in time. However, Oregon did perform some sensitivity analyses, and sensitivity of these models as applied in California's LUFT program is discussed in another article (Odencrantz, et al, 1992)

REFERENCES

Anderson, M. 1992. Development of Generic Soil Cleanup Levels Based on Analysis of the Leachate Pathway. Environmental Cleanup Division, Department of Environmental Quality, State of Oregon, May 12, 1992.

Bonazountas, M. and J. Wagner. 1984. SESOIL. A Seasonal Soil Compartment Model. A.D. Little for USEPA.

General Sciences Corporation. 1989. PCGEMS User's Guide. Release 1.0. Prepared for U.S. Environmental Protection Agency Office of Pesticides and Toxic Substances Exposure Evaluation Division

Howard, P. et al. 1991. Handbook of Environmental Degradation Rates Lewis Publishers, Chelsea, Michigan.

Odencrantz, J., et al. 1992. Transport Model Parameter Sensitivity for Soil Cleanup Level Determinations Using SESOIL and AT123D in the Context of the California Leaking Underground Fuel Tank Field Manual. Journal of Soil Contamination 1(2):159-182.

Yeh, G. 1981. AT123D: Analytical Transient One-, Two-, and Three- Dimensional Simulation of Waste Transport in the Aquifer System. Oak Ridge National Laboratory. ORNL-5602.

APPENDIX 6

RATIONAL FOR MOEE ECOTOXICITY-BASED SOIL CRITERIA

ISNB: 0-7778-2818-9

RATIONALE FOR THE DEVELOPMENT AND APPLICATION OF GENERIC SOIL, GROUNDWATER AND SEDIMENT CRITERIA FOR USE AT CONTAMINATED SITES IN ONTARIO

Report prepared by:

Standards Development Branch
Ontario Ministry of Environment and Energy

December 1996

Report prepared for:

Ontario Ministry of Environment and Energy

Version 1.1

Acknowledgements

This document was prepared by the Criteria Development Subgroup (A. L. Kuja, Chair) under the direction of the Criteria Development, Site Assessment and Site Specific Risk Assessment Work Group (R.G. Pearson, Chair). Following consultation, all modifications were made by the document editors: A. L. Kuja and R. G. Pearson, Phytotoxicology Section, Standards Development Branch.

The efforts of the following individuals are greatfully acknowledged:

Standards Development Branch:	Richard Aucoin Tim Fletcher Bill Gizyn Lee Hofmann Goff Jenkins Randy Jones	Bryan Leece Angela Li-Muller Marius Marsh Pavel Muller Doug Spry Franca Ursitti
Central Regional Office:	Ron Lall	
Ottawa District Office:	Andy Lewis	
Cambridge District Office:	Bill Bardswick	
Security Account Office:	Patrick Leung	
Environmental Monitoring and Reporting Branch:	Mike Scafe Sam Singer	
Science and Technology Branch:	Ulo Sibul	
Waterfront Regeneration Trust:	Beth Benson	

The Criteria Development Subgroup would also like to recognize and thank the Massachusetts Department of Environmental Protection, Bureau of Waste Site Clean-up and the Office of Research and Standards for their co-operation in providing the committee with the MCP Standards Approach background document and databases.

1 INTRODUCTION 94

2 OVERVIEW OF THE APPROACH, GUIDING PRINCIPLES AND MAJOR 94
2.1 General Approach 94
3.2.3 Additional Soil Criteria Components Incorporated by MOEE 96
3.2.3.1 Terrestrial Ecological Soil Criteria Component 96
3.2.3.1.1 Exposure Pathways and Protection of Ecological Receptors at Various Land Uses 96
3.2.3.1.2 Existing MOEE Soil Clean-up/Decommissioning Guidelines (SCUGs) 98
3.2.3.1.3 The Netherlands "C Level" Ecotoxicity Criteria 101

1 BACKGROUND 105

2 RATIONALES FOR ECOTOXCITY-BASED SOIL CRITERIA 105

APPENDIX A: Criteria Tables A to F..... A(1)
Appendix A.1: Ontario Soil, Groundwater and Sediment Quality Criteria Tables..... A(2)
Appendix A.1.1: Table A - Surface Soil/Full Depth and Groundwater Remediation Criteria for Three Land Uses (Agricultural, Residential/Parkland and Industrial/Commercial) in a Potable Groundwater Situation..... A(3)
Appendix A.1.2: Table B - Surface Soil/Full Depth and Groundwater Remediation Criteria for Two Land Uses (Residential/Parkland and Industrial/Commercial) in a Non-Potable Groundwater Situation. ..... A(8)
Appendix A.1.3: Table C - Sub-Surface Soil Remediation Criteria for Two Land Uses (Residential/Parkland and Industrial/Commercial) in a Potable Groundwater Situation..... A(13)

Appendix A.1.4: Table D - Sub-Surface Soil Remediation Criteria for Two Land Uses (Residential/Parkland and Industrial/Commercial) in a Non-Potable Groundwater Situation..... A(18)
Appendix A.1.5: Table E - Sediment Quality Criteria..... A(23)
Appendix A.1.6: Table F - Ontario Background Soil Concentrations..... A(28)
Appendix A.2: Summary Tables of Criteria Components for Soil and Groundwater. ..... A(33)
Appendix A.2.1: Table A Criteria Components - Coarse Textured Soil (Surface/Full Depth) - Potable Groundwater Situation..... A(38)
Appendix A.2.2: Table B Criteria Components- Coarse Textured Soil

(Surface/Full Depth) - Non-Potable Groundwater Situation. ..... A(55)
Appendix A.2.3: Table C Criteria Components - Coarse Textured Soil (Sub-surface) - Potable Groundwater Situation. ..... A(68)
Appendix A.2.4: Table D Criteria Components - Coarse Textured Soil (Sub-Surface) - Non-Potable Groundwater Situation. ..... A(77)
Appendix A.2.5: Table A Criteria Components - Medium/Fine Textured Soil (Surface/Full Depth) - Potable Groundwater Situation. ..... A(86)
Appendix A.2.6: Table B Criteria Components- Medium/Fine Textured Soil (Surface/Full Depth) - Non-Potable Groundwater Situation..... A(103)
Appendix A.2.7: Table C Criteria Components - Medium/Fine Textured Soil (Sub-surface) - Potable Groundwater Situation..... A(116)
Appendix A.2.8: Table D Criteria Components - Medium/Fine Textured Soil (Sub-Surface) - Non-Potable Groundwater Situation..... A(125)

APPENDIX B: Detailed Rationale Support Documentation. ..... B(1)
Appendix B.1: Criteria Development Spreadsheets Containing Toxicological and Contaminant Transport Input Parameters Utilized in the Derivation of Soil and Groundwater Criteria..... B(2)
Appendix B.1.1: Derivation of Direct Contact S-1 Soil Concentrations ..... B(3)
Appendix B.1.2: Derivation of Direct Contact S-2 Soil Concentrations..... B(8)
Appendix B.1.3: Derivation of Direct Contact S-3 Soil Concentrations..... B(13)
Appendix B.1.4: Derivation of Leaching-Based Soil Concentrations (Coarse Textured Soils). ..... B(20)
Appendix B.1.5: Derivation of Leaching-Based Soil Concentrations (Medium/Fine Textured Soils)..... B(23)
Appendix B.1.6: Derivation of GW-1 and GW-3 Groundwater Concentrations ..... B(26)
Appendix B.1.7: Derivation of GW-2 Groundwater Concentrations (for Coarse Textured Soil Situations). ..... B(33)
Appendix B.1.8: Derivation of GW-2 Groundwater Concentrations (for Medium/Fine Textured Soil Situations)..... B(36)
Appendix B.1.9: Derivation of Soil-to-Indoor Air Concentrations (Coarse Textured Soils)..... B(39)

Appendix B.1.10: Derivation of Soil-to-Indoor Air Concentrations (Medium/Fine Textured Soils)..... B(42)
Appendix B.1.11: Unit Conversions for Soil to Indoor Air Vapour Transport Model (S/IA Eq.7)..... B(45)
Appendix B.2: Soil:Air Degassing Modelling for VOCs. ..... B(48)
Appendix B.3: Rationale for MOEE Ecotoxicity-Based Soil Criteria..... B(94)
Appendix B.4: U.S. EPA Ambient Water Quality Criteria (AWQC) for Fresh Water And Lowest Observable Effects Levels (LOELs) for Fresh Water Organisms from the Aquatic Information and Retrieval System (AQUIRE) Database..... B(140)

Appendix B.5: Relevant Portions of Massachusetts Background Documentation for the Development of the MPC Numerical Standards. ..... B(150)

LIST OF FIGURES

Error! No table of contents entries found.

Figure 5: Selection of Generic Soil and Ground Water Criteria 64

LIST OF TABLES

Table 1:	Summary of Soil Ingestion and Dermal Contact Rates	12
Table 2:	S-1, S-2 and S-3 Ceiling Values for Soils	20
Table 3:	Cancer Potency of PAHs Relative to Benzo(a)pyrene	25
Table 4:	Jury Model - Infinite Contamination Thickness	40
Table 5:	Generic Soil Remediation Criteria Development Process - 1996	48
Table 6:	Generic Groundwater Remediation Criteria Development Process - 1996	49

1 INTRODUCTION

This document describes the rationale behind the development of effects-based generic soil, groundwater and sediment quality criteria, to be used in place of the 1989 soil clean-up levels in the remediation of contaminated sites in Ontario. This rationale document replaces the document entitled "Soil Clean-up Guidelines for Decommissioning of Industrial Lands: Background and Rationale for Development". The use and application of these criteria are described in the "Guideline for Use at Contaminated Sites in Ontario" (1996) which replaces the MOE 1989 "Guideline for the Decommissioning and Clean-up of Sites in Ontario" and the 1993 "Interim Guidelines for the Assessment and Management of Petroleum Contaminated Sites in Ontario".

This introduction is the first of four sections comprising the rationale document. Section 2 provides an overview of the environmental approach, guiding principles, and remediation options and their linkage with the criteria development process. Section 3 describes in detail, the process and assumptions used in the development of the soil and groundwater criteria. This includes a full description of the Massachusetts methodology that was adopted for use in Ontario, as well as the modifications and additional components that were utilized. All references utilized in this document are listed in Section 4. The criteria tables, on which decisions relating to site remediation will be based, are found in Appendix A. Also provided in Appendix A are summary tables of all criteria components. Additional scientific documents and supporting information for the development of the criteria are found in Appendix B.

2 OVERVIEW OF THE APPROACH, GUIDING PRINCIPLES AND MAJOR ASPECTS OF THE CRITERIA DEVELOPMENT PROCESS.

2.1 General Approach

The revision of the Ministry's 1989 guideline for the decommissioning and clean-up of contaminated sites is predicated on providing a more flexible, environmentally protective approach which will be applicable to a greater number of environmental contaminants and provide an increased level of guidance and remediation options to proponents. From an environmental aspect, this flexibility was achieved by more closely matching receptors and exposure pathways to land and groundwater use categories, and to the extent possible, to site conditions which affect contaminant transport and exposure.

The MOEE has participated in the development of a protocol for setting effects-based soil quality criteria under the National Contaminated Sites Remediation Program of the Canadian Council of Ministers of Environment (CCME). These protocols are summarized in the CCME document entitled "A Protocol for the Derivation of Ecological Effects Based and Human Health Based Soil Quality Criteria for Contaminated Sites." (1994). However, as the development of soil clean-up criteria based on CCME criteria documents will take several years, the MOEE explored other options to provide effects-based criteria.

The Department of Environmental Protection, Bureau of Waste Site Cleanup and the Office of Research and Standards for the Commonwealth of Massachusetts, have jointly produced chemical-specific standards for use under their revised Massachusetts Contingency Plan (MCP) which was promulgated in October 1993. Generic criteria for 106 inorganic/organic contaminants were developed using a risk characterization approach to provide protection to human and environmental health.

After a review of the general assumptions and multi-media components of the MCP approach, a decision was made to adopt and modify this approach for generic soil and groundwater "risk-based" site remediation criteria in Ontario. The MCP approach was selected as it appeared to best meet Ontario's needs for a large number of effects-based soil and groundwater criteria which address most potential human health and aquatic exposure pathways. It was also chosen because both the toxicological assessments and exposure scenarios carried out by the Massachusetts Department of Environmental Protection (DEP) had been subjected to extensive public consultation and had been promulgated as standards.

All assumptions for risk characterization, dose-response and toxicity information, methods, calculations and data inputs to the MCP standards development process are detailed in the Massachusetts document entitled "Background Documentation for the Development of the MCP Numerical Standards" (1994). The relevant portions of this document have been included in Appendix B.5. Modifications were made to various inputs into the MCP spreadsheets so that the criteria for the 106 chemicals would better represent the Ontario situation.

3.2.3 Additional Soil Criteria Components Incorporated by MOEE

3.2.3.1 Terrestrial Ecological Soil Criteria Component

The MCP approach addresses primarily human-health effects with some consideration of indirect ecological effects (aquatic) through the soil/groundwater leaching-based concentrations (GW-3). However, there is no consideration for direct soil contact exposure for terrestrial ecological receptors. As MOEE is also committed to providing ecological protection, ecotoxicity criteria were included in the development process for soil criteria. Ontario ecological effects-based criteria for inorganics were incorporated into the process to develop surface restoration criteria for soils. The decision was made that terrestrial ecological protection for direct contact below the 1.5 meter depth, was not appropriate. Therefore, only human health and indirect ecological effects through leaching (via groundwater to surface water) were considered for sub-surface soil criteria (>1.5m depth).

The Netherlands have also developed ecosystem toxicity-based soil criteria for several inorganic and organic contaminants. These concentrations were utilized in the process when Ontario ecological criteria did not already exist. The Massachusetts DEP developed soil and groundwater criteria (based on human health) for 106 inorganic and organic chemicals. The integration of additional criteria for metals and inorganic parameters, based on ecological data, increased the soil chemical list to 115.

The following inorganic parameters were added to the soil criteria development process: barium, boron, chromium (total), cobalt, copper, molybdenum, electrical conductivity (mS/cm), nitrogen (total), and sodium absorption ratio (SAR).

The Massachusetts DEP chose to develop a human health risk-based criterion for chromium III and VI but not for total chromium. MOEE has ecological effects-based criteria for total chromium. Therefore, the committee decided to include total chromium on the chemical list. The Phytotoxicology Section of the MOEE Standards Development Branch has recently developed soil quality criteria for boron based on phytotoxicity effects data. Boron has been included in the chemical list; however, the boron criteria, which address the 'available' boron in soil are based on a 'hot water extract' rather than bulk soil analysis. The development of the boron criteria is described in detail in Appendix B.3.

3.2.3.1.1 Exposure Pathways and Protection of Ecological Receptors at Various Land Uses

In determining numerical criteria for soil based on potential ecological effects, it was necessary to make judgements as to what receptors should be protected and what level of protection was required for each land use category. A full range of philosophies exist, from protection against the earliest detectable effects to any species that could potentially occur on a site, or be affected by contamination at a site, to protection against the most severe of effects to very common

species which normally occur on sites of a particular land use category. The philosophy that is adopted can, therefore, strongly influence the final generic criteria derived. This section outlines the level of ecological protection which forms the basis for the development of the ecological criteria for each of the three land use categories: agricultural, residential/parkland and industrial/commercial.

To the extent permitted by available scientific evidence, these types of protection were incorporated into the criteria development process for each land use category. However, it must be stressed that in many cases, the lack of scientific evidence prohibited the development of an ecological component.

Agricultural Land Use Category

Soils that are to be used for agricultural purposes should be able to support the growth of a wide range of commercial crops as well as the raising of livestock. Contamination due to anthropogenic activities should not result in noticeable yield reductions of commercial crops that cannot be remedied through normal farming practices. Soil concentrations of chemical parameters also should be sufficiently low that there are no known or suspected adverse impacts on domestic grazing animals, including migratory and transitory wildlife, through both direct soil ingestion or through ingestion of plants grown on the soil. Since soil invertebrates and microorganisms provide important functions for the overall health of a soil, and the plants supported by the soil, these populations should not be adversely affected to the point where functions such as nutrient cycling, soil:root symbiotic relationships and decomposition are significantly reduced or impaired.

A consideration of all of the above factors also must recognize that in certain situations, agricultural chemicals are utilized because they are capable of selective toxicological action against undesirable plants and soil organisms. In these situations, a case specific approach will be necessary in the soil remediation process.

Residential/Parkland Land Use Category

The need for protection of commercial crops in the residential/parkland land use category is not as apparent as for agriculture; nevertheless, the common practice of growing backyard vegetable gardens and allotment gardens results in there being little practical difference between the plant species to be protected at residential sites and those at agricultural sites. Since parkland is included with residential land use in this category, it is also necessary to protect migratory and transitory species that may utilize such sites. The major difference from agricultural sites is that, for residential/parkland sites, the protection of domestic grazing animals such as sheep and cattle is not an important consideration.

Industrial/Commercial Land Use Category

It is not necessary to require as high a degree of protection for on-site ecological receptors at an industrial or commercial site as it is for agricultural or residential/parkland sites. The soil at industrial sites should be capable of supporting the growth of some native and ornamental trees, shrubs and grasses, but, it is not as important to protect against yield or growth reductions to the same extent as for residential and agricultural properties, nor to protect as wide a range of species. Since it would be highly undesirable to have transitory or migratory species being affected by utilizing any specific industrial or commercial property, criteria should be sufficiently protective to prevent such adverse effects on these species.

3.2.3.1.2 Existing MOEE Soil Clean-up/Decommissioning Guidelines (SCUGs)

The rationale on which the 1989 guidelines was based was described in the MOE publication "Soil Clean-up Guidelines for Decommissioning of Industrial Lands: Background and Rationale for Development" (MOE, 1991). This publication has been replaced and relevant information applicable to those parameters that were utilized in the 1995 criteria development process can be found in Appendix B.3.

Soil clean-up criteria were developed for the following parameters: As, Cd, Cr (total), CrVI, Co, Cu, Pb, Hg, Mo, Ni, Se, Ag, Zn, soil pH range, Electrical Conductivity and Sodium Absorption Ratio. However, in the case of Cd, Pb, and Hg, the 1989 criteria were influenced more by human health considerations rather than ecological effects, and accordingly these criteria were discarded (with the exception of Cd for the agricultural land use category).

Re-examination of the rationale for the 1989 ecological criteria indicated that although the process was much less rigorous than the most recent CCME protocol for the development of ecological criteria, it did offer several important features:

- the criteria have been utilized in Ontario for 15 years without any evidence to indicate that protection was not provided

- the criteria have been widely adopted for use in other jurisdictions including the CCME without any evidence of problems

- early evidence from the new CCME process which has been applied to a limited number of parameters indicates that the 1989 ecological criteria are in reasonable agreement with the results from this process

- a thorough review of the available literature combined with an experimental program by the Phytotoxicology Section has confirmed that in the case of copper, the 1989 values are

fully in line with values that emerge from this type of analysis

Based on this assessment, a decision was made to incorporate the 1989 ecological criteria. The following additional considerations were utilized.

A strong argument can be made that the 1989 SCUGs for Cd (i.e. 3 ppm for coarse-textured soils and 4 ppm for medium/fine textured soils) are still valid for the agricultural use category. Cd is an element that is not readily eliminated in mammals, and it is known to bio-accumulate in tissue. Grazing animals that are ingesting Cd accumulated in plants growing on contaminated soils and from the soils themselves may be more at risk from Cd accumulation than is accounted for by any criterion higher than the current MOEE SCUG of 3 ppm (e.g. the Netherlands ecotoxicity criterion for Cd is 12 ug/g). It is known that wild ungulates grazing on lands with natural background Cd concentrations can accumulate Cd in the kidneys to the point where the kidneys are unfit for consumption. Some species of food plants (i.e. spinach and lettuce) have been observed to accumulate Cd in the edible portions of the plant to levels that would be of concern, even at relatively low soil Cd concentrations. Although the change of the Cd guideline from 3 μg/g to 12 ug may be suitable for residential purposes, there is little evidence that it takes the above factors into consideration for agricultural land uses.

The CCME draft document "A Protocol for the Derivation of Ecological Effects Based and Human-Health Based Soil Quality Criteria" (1994) contains some equations that are useful for estimating guidelines based on food ingestion and soil ingestion by animals utilizing the land. Using these equations and data presented in the draft CCME assessment document on Cadmium (Canadian Soil Quality Criteria for Contaminated Sites: Cadmium), a guideline of 3 μg Cd/g is indicated to be appropriate for agricultural use. These equations are presented below. For these reasons, it was decided to continue using the 3 μg/g guideline for cadmium for agricultural use unless and until there is substantial justification to indicate that it too should be changed. The following is a CCME calculation of soil quality criteria based on food ingestion by animals (e.g. cattle):

EDFI = DTED x BW/FIR
= 0.0028 mg Cd kg-1BW x day-1 x 100kg / 3kg day-1
= 0.093 mg/kg dw food

SQCfi = EDFI x AFfi/BCF
= 0.093 mg/kg x 0.85/0.025
= 3.16 mg/kg

CCME calculation of soil quality criteria based on soil ingestion by animals

EDFI = DTED x BW/SIR

= 0.0028 mg Cd kg-1BW x day-1 x 100kg / 0.54kg day-1
= 0.519 mg/kg dw soil

SQCsi = EDSI x AFsi/ BF
= 0.519 mg/kg x 0.18/ 0.025
= 3.74 mg/kg

Where:

SQCfi =	Soil Quality Criteria for Food Ingestion
SQCsi =	Soil Quality Criteria for Soil Ingestion
EDFI =	Estimated dose for Food Ingestion
DTED =	Daily Threshold Effects Dose
BW =	Body Weight
FIR =	Food Ingestion Rate
SIR =	Soil Ingestion Rate
AFfi =	Apportionment factor for Food ingestion
AFsi =	Apportionment Factor for Soil Ingestion
BCF =	Bioconcentration Factor
BF =	Bioavailability Factor

The 1989 Cu, Mo, and Se SCUG criteria for agricultural/residential/parkland land uses were developed to protect grazing livestock. The industrial/commercial SCUG criteria for these three parameters provided protection to vegetation only. For this reason, the industrial/commercial SCUG criteria (for coarse-textured and medium-fine textured soils) were selected for both the residential/parkland and industrial/commercial land use categories where grazing animals are not likely to occur. The Cu, Mo and Se SCUG values that were based on protection of grazing livestock will apply to the agricultural land use category only.

The electrical conductivity of soil is essentially a measurement of the total concentration of soluble salts in the soil solution and can have a large osmotic influence on plant growth, as well as on soil organisms. The existing MOEE SCUGs for electrical conductivity (E.C.) of a soil required the use of a saturated extract. This procedure is time consuming and results are subjective; i.e. the end point of saturation is determined by the technician's expert opinion.

A fixed 2:1 water:soil procedure eliminates this uncertainty and provides a more rapid and reliable test. Both MOEE (Phytotoxicology Section) and Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) now use the 2:1 procedure for most routine samples. The water:soil ratio used for the extract affects the resultant electrical conductivity; hence, the existing SCUG of 2.0 mS/cm (agricultural/residential/parkland) and 4.0 mS/cm (commercial/industrial) were adjusted to account for the change in water:soil ratio for this criterion.

Data in Extension Bulletin E-1736 (Michigan State University, 1983) made available to the committee by the Department of Land Resource Science, University of Guelph, show that for a given E.C., in saturation extract, the expected E.C. in a 2:1 water:soil ratio would be one third of the former. The appropriate E.C. for both agricultural and residential/parkland land use categories is 0.667 mS/cm. When rounded to 0.7 mS/cm, this value corresponds with the boundary between what McKeague (1978) states "may result in a slightly stunted condition in most plants" and "slight to severe burning of most plants". This is a reasonable concentration at which to establish the E.C. SCUG and confirmed the use of the divisor of 3 as a conversion factor. Using this conversion factor, the industrial/commercial SCUG for E.C. becomes 1.4 mS/cm.

Provisional soil clean-up guidelines were also produced in 1989 for Sb, Ba, Be and V for which the knowledge of their potential adverse phytotoxic effects was more limited than for the other inorganic parameters. These provisional criteria were also incorporated into the current modified criteria development process.

In all cases, MOE SCUG criteria values for coarse-textured soils, as well as medium and fine textured soils have been adopted from the 1989 guidelines for use in the current criteria development process. Coarse-textured soils are defined here as greater than 70% sand. The medium and fine textured soil SCUGs are 20-25% higher than the corresponding values for coarse-textured soils.

3.2.3.1.3 The Netherlands "C Level" Ecotoxicity Criteria

The Dutch government published soil and groundwater clean up guidelines, "ABC values", in 1983. These guidelines have undergone revision over the last 7 years to include both human health and ecological effects-based data. A new set of C-values has been proposed (Vegter, 1993). The final integrated C-value includes a human health component, as well as the ecological component, and includes risk management adjustments. The ecological component of the C-value is derived by taking the geometric mean or the average value of the logarithm of the No Observable Adverse Effect Concentration (NOEC) (Denneman and van Gestel, 1990). This means that the C-value represents the chemical concentration at which the NOEC for 50% of the ecological species has been exceeded.

For the purposes of this guideline, the ecotoxicity component of the C-value was incorporated into the soil criteria development process in all cases where a 1989 MOE SCUG value was not available. In addition to the references listed above, more information on the Dutch guidelines can be found in the following references: van den Berg and Roels (1993); van den Berg et al. (1993); and Denneman and Robberse (1990).

Appendix B.3: Rationale for MOEE Ecotoxicity-Based Soil Criteria.

(IN: *Rational For The Development And Application Of Generic Soil Groundwater, And Sediment Criteria For Use At Contaminated Sites In Ontario,* Standards Development Branch, Ontario Ministry of Environment and Energy, December 1996 (ISNB: 0-7778-2818-9)

Appendix B.3

This appendix replaces the rationale which was the basis for the 1989 ecotoxicity-based soil remediation criteria. The original rationale is described in the 1991 MOE publication entitled "Soil Clean-up Guidelines for Decommissioning of Industrial Lands: Background and Rationale for Development". Those parameters in the original rationale, which were based on human health effects, have been removed. A rationale for a boron soil criterion (hot water extract), based on protection of vegetation and grazing animals, has been added.

All relevant information applicable to MOEE ecotoxicity-based soil values utilized in the 1995 soil remediation criteria development process are contained in the following sections. As more information on these and other soil parameters becomes available, the information will be included in this appendix as part of the rationale for deriving ecotoxicity criteria for soil remediation.

APPENDIX B.3 TABLE OF CONTENTS

1 BACKGROUND ..... (97)

2 RATIONALES FOR ECOTOXCITY-BASED SOIL CRITERIA ..... (97)
2.1 Arsenic (As) ..... (98)
2.2 Boron (B) ..... (100)
2.3 Chromium (Cr) ..... (123)
2.4 Cobalt (Co) ..... (124)
2.5 Copper (Cu) ..... (125)
2.6 Molybdenum (Mo) ..... (126)
2.7 Nickel (Ni) ..... (127)
2.8 Selenium (Se) ..... (128)
2.9 Silver (Ag) ..... (129)
2.10 Zinc (Zn) ..... (130)
2.11 Sodium Adsorption Ratio (SAR) ..... (131)

3 RATIONALES FOR PROVISIONAL ECOTOXICITY-BASED SOIL CRITERIA ..... (131)
3.1 Antimony (Sb) ..... (131)
3.2 Barium (Ba) ..... (132)
3.3 Beryllium (Be) ..... (133)
3.4 Vanadium (V) ..... (134)

4 REFERENCES ..... (135)

5 ECOTOXICITY-BASED SOIL CRITERIA TABLES ..... (139)

1 BACKGROUND

In February, 1984, the Phytotoxicology Section was requested by the Halton-Peel District Office of the MOE to provide input into the development of soil criteria for the decommissioning of certain oil refinery lands. Proposed land uses made it desirable to have separate criteria for residential and industrial redevelopment. Monenco Consultants, on behalf of one of the oil companies, undertook a large-scale literature survey in an attempt to relate contaminant concentrations in soil to toxic effects on vegetation and animals. As a result of this effort, Monenco recommended site-specific ecotoxicity-based soil criteria for a number of contaminants (Monenco Ontario Ltd., 1984a & 1984b).

Subsequent to the above-described exercise, the Phytotoxicology Section was asked to recommend soil clean-up criteria for additional contaminants. Provisional criteria for these additional elements were developed, based on literature reviews. The Phytotoxicology Section was requested by the MOE Waste Management Branch to develop clean-up levels for agricultural land use. This request was brought to the attention of the Sludge and Waste Utilization Committee. It was the opinion of this Committee that the residential/parkland clean-up levels previously developed were, with minor modifications/qualifications, also suitable for application to agricultural situations.

2 RATIONALES FOR ECOTOXCITY-BASED SOIL CRITERIA

The recommended ecotoxicity-based soil remediation criteria are shown in Section 5.1 (Table 5.1). The rationales for their development include considerations of phytotoxicity and animal health. In general, the most conservative of these considerations was used to established agricultural and residential soil criteria. Redevelopment as parkland also was felt to warrant this conservative approach, because parkland often is used by children at play, and occasionally is used for allotment gardening.

Different industrial/commercial remediation levels (normally set at twice the residential levels) were recommended where the residential and industrial criteria were both set on the same basis but where phytotoxic concerns were judged to be considerably less significant in the industrial/commercial environment. For two elements (molybdenum and selenium), residential soil remediation levels were established to prevent toxicity to grazing animals, whereas a higher industrial level was established to prevent toxicity to vegetation.

Provisional ecotoxicity-based soil remediation criteria recommended for four additional contaminants are shown in Section 5.2 (Table 5.2). Because knowledge of potential adverse effects of these elements in soil is generally more limited than for the Table 1 criteria, the provisional criteria were purposefully established in an even more conservative vein.

Since the mobility and availability of metals in soils may be highly dependent on form of

the metal, soil texture, pH and organic matter content, site-specific considerations of these parameters may reveal the suitability of different criteria. For example, where metals are known to be present in specific forms of very limited availability, higher levels may be considered. Furthermore, in researching the clean-up criteria, Monenco Consultants utilized data from studies on medium to fine textured soils (i.e. sandy soils excluded), in which mobility (availability) of metals would be lower than in coarse-textured sand (hence, metals are less likely to accumulate in sand than in clay). Therefore, it is recommended that the remediation levels for the metals and metalloids be reduced in the case of coarse-textured (greater than 70% sand) mineral soils (less than 17% organic matter). This recommendation is reflected in the remediation levels shown in Tables 5.1 and 5.2.

The rationales for individual parameters are summarized in the following sections (RATIONAL FOR As, B, Cr, co, Cu, Mo, Ni, Ag, Zin, SAR, Sb, Ba, Be, V; NOT INCLUDED IN THIS APPENDIX).

APPENDIX 7

SUMMARY OF MADEP CARBON RANGE AND TOTAL PETROLEUM HYDROCARBON RISK-BASED SCREENING LEVELS

SUMMARY OF MADEP CARBON RANGE AND TOTAL PETROLEUM HYDROCARBON TOXICITY AND PHYSIO-CHEMICAL SURROGATES

CARBON RANGE	Human Toxicity Surrogate	Aquatic Life Protection Surrogate	Organic Carbon Coefficient (Koc) (cm^3/g)	Henry's Law Constant (H) ($atm\text{-}m^3/mol$)
Aliphatics				
C5 to C8	n-hexane	n-hexane	2.27E+03	1.29E+00
C9 to C12	10 x n-hexane	decane	1.50E+05	1.56E+00
C9 to C18	10 x n-hexane	decane	6.80E+05	1.66E+00
C19 to C36	100 x n-hexane	cyclododecane	-	-
Aromatics				
C9 to C10	xylenes	ethylbenzene	1.78E+03	7.92E-03
C11 to C22	naphthalene /pyrene	PAHs	5.00E+03	7.20E-04
**Total Petroleum Hydrocarbon (TPH)	naphthalene/ pyrene	PAHs	5.00E+03	7.20E-04

* MADEP referred to both naphthalene & pyrene for the C11 to C22 range RfD in their original documents. Both have an Oral RfD of 0.03 mg/kg-d and inhalation RFC of 0.071 mg/m^3 (0.02 mg/kg-d) in MADEP guidance.

**TPH conservatively assumed to be 100% C11 to C22 aromatic compounds (major component of diesel#2, #3-#6 fuel oil, JP-4).

Reference:

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Public Hearing Draft: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, January 17, 1997.

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Redline/Strikeout Version: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, October 31, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000, Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, November 7, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1999, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Spreadsheet Detailing VPH/EPH Standards Derivation: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, May 25, 1999, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

Summary of Massachusetts DEP Carbon Range/TPH Risk-Based Screening Levels (RBSLs) (mg/kg)

*RESIDENTIAL SURFACE SOIL (S-1) - Drinking Water Resource Threatened (GW-1)

Carbon Range		Final S-1/GW-1 RBSL	Direct Exposure	Leaching	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	100	730	3400	**100**	5000
	C9 to C12	1000	15000	140000	**1000**	20000
	C9 to C18	1000	15000	490000	**1000**	20000
	C19 to C36	2500	230000	-	**2500**	20000
Aromatics	C9 to C10	100	810	**69**	100	5000
	C11 to C22	200	810	**170**	1000	10000
TPH-general	-	200	800	**200**	1000	10000

*See Massachusetts DEP MCP for full description S-1, S-2 and S-3 soils.

RESIDENTIAL SURFACE SOIL (S-1) - Groundwater Discharge to Surface Water (GW-3)

Carbon Range		Final S-1/GW-3 RBSL	Direct Exposure	Leaching	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	100	730	34000	**100**	5000
	C9 to C12	1000	15000	690000	**1000**	20000
	C9 to C18	1000	15000	2500000	**1000**	20000
	C19 to C36	2500	230000	-	**2500**	20000
Aromatics	C9 to C10	100	810	1400	**100**	5000
	C11 to C22	800	**810**	25000	1000	10000
TPH-general	-	800	**800**	25000	1000	10000

References:

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Public Hearing Draft: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, January 17, 1997.

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Redline/Strikeout Version: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, October 31, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000, Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, November 7, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1999, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Spreadsheet Detailing VPH/EPH Standards Derivation: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, May 25, 1999, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

Summary of Massachusetts DEP Carbon Range/TPH Risk-Based Screening Levels (RBSLs) (mg/kg)

*OCCUPATIONAL SURFACE SOIL (S-2) - Drinking Water Resource Threatened (GW-1)

Carbon Range		Final S-1/GW-1 RBSL	Direct Exposure	Leaching	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	500	1500	3400	**500**	5000
	C9 to C12	2500	36000	140000	**2500**	20000
	C9 to C18	2500	36000	490000	**2500**	20000
	C19 to C36	5000	670000	-	**5000**	20000
Aromatics	C9 to C10	100	2000	**69**	500	5000
	C11 to C22	200	2000	**170**	2500	10000
TPH-general	-	200	2000	**200**	2500	10000

*See Massachusetts DEP MCP for full description S-1, S-2 and S-3 soils.

OCCUPATIONAL SURFACE SOIL (S-2) - Groundwater Discharge to Surface Water (GW-3)

Carbon Range		Final S-1/GW-3 RBSL	Direct Exposure	Leaching	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	500	1500	34000	**500**	5000
	C9 to C12	2500	36000	690000	**2500**	20000
	C9 to C18	2500	36000	2500000	**2500**	20000
	C19 to C36	5000	670000	-	**5000**	20000
Aromatics	C9 to C10	500	2000	1400	**500**	5000
	C11 to C22	2000	**2000**	25000	2500	10000
TPH-general	-	2000	**2000**	25000	2500	10000

References:

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Public Hearing Draft: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, January 17, 1997.

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Redline/Strikeout Version: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, October 31, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000, Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, November 7, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1999, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Spreadsheet Detailing VPH/EPH Standards Derivation: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, May 25, 1999, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

Summary of Massachusetts DEP Carbon Range/TPH Risk-Based Screening Levels (RBSLs) (mg/kg)

*ISOLATED SUBSURFACE SOIL (S-3) - Drinking Water Resource Threatened (GW-1)

Carbon Range		Final S-1/GW-1 RBSL	Direct Exposure	Leaching	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	500	7100	3400	**500**	5000
	C9 to C12	5000	170000	140000	**5000**	20000
	C9 to C18	5000	170000	490000	**5000**	20000
	C19 to C36	5000	3100000	-	**5000**	20000
Aromatics	C9 to C10	100	9300	**69**	500	5000
	C11 to C22	200	9300	**170**	5000	10000
TPH-general	-	200	9300	**200**	5000	10000

*See Massachusetts DEP MCP for full description S-1, S-2 and S-3 soils.

ISOLATED SUBSURFACE SOIL (S-3) - Groundwater Discharge to Surface Water (GW-3)

Carbon Range		Final S-1/GW-3 RBSL	Direct Exposure	Leaching	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	500	7100	34000	**500**	5000
	C9 to C12	5000	170000	690000	**5000**	20000
	C9 to C18	5000	170000	2500000	**5000**	20000
	C19 to C36	5000	3100000	-	**5000**	20000
Aromatics	C9 to C10	500	9300	1400	**500**	5000
	C11 to C22	5000	9300	25000	**5000**	10000
TPH-general	-	5000	9300	25000	**5000**	10000

References:

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Public Hearing Draft: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, January 17, 1997.

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Redline/Strikeout Version: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, October 31, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000, Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, November 7, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1999, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Spreadsheet Detailing VPH/EPH Standards Derivation: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, May 25, 1999, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

Summary of Massachusetts DEP Carbon Range/TPH Risk-Based Screening Levels (RBSLs) (ug/L)

*GROUNDWATER - Drinking Water (GW-1)

Carbon Range		Final GW-1 RBSL	Human Consumption	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	400	**420**	5000	100000
	C9 to C12	4000	**4200**	5000	100000
	C9 to C18	4000	**4200**	5000	100000
	C19 to C36	5000	42000	**5000**	100000
Aromatics	C9 to C10	200	**230**	5000	100000
	C11 to C22	200	**230**	5000	100000
TPH-general	-	200	**230**	5000	100000

*See Massachusetts DEP MCP for full description GW-1, GW-2 and GW-3 groundwater.

*GROUNDWATER - Discharge to Surface Water (GW-3)

Carbon Range		Final GW-3 RBSL	*Aquatic Life Protection	Nuisance Ceiling	Upper Concentration Level
Aliphatics	C5 to C8	4000	**3900**	50000	100000
	C9 to C12	20000	**18000**	50000	100000
	C9 to C18	20000	**18000**	50000	100000
	C19 to C36	20000	**21000**	50000	100000
Aromatics	C9 to C10	4000	**4300**	50000	100000
	C11 to C22	30000	**30000**	50000	100000
TPH-general	-	20000	**20000**	50000	100000

*** Aquatic Life Protection = aquatic life criteria x assumed ten-fold diuition factor.**

References:

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Public Hearing Draft: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, January 17, 1997.

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Redline/Strikeout Version: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, October 31, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1997, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000, Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, November 7, 1997, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

MADEP, 1999, Revisions to the Massachusetts Contingency Plan, 310 CMR 40.000 - Spreadsheet Detailing VPH/EPH Standards Derivation: Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, May 25, 1999, www.magnet.state.ma.us/dep/bwsc/vph_eph.html

APPENDIX 8

DETERMINATION OF GROUNDWATER UTILITY (SEPTEMBER 19, 1995)

BENJAMIN J. CAYETANO
[redacted]
GOVERNOR OF HAWAII

LAWRENCE MIIKE
[redacted]
DIRECTOR OF HEALTH

STATE OF HAWAII
DEPARTMENT OF HEALTH
ENVIRONMENTAL MANAGEMENT DIVISION
SOLID AND HAZARDOUS WASTE BRANCH
919 ALA MOANA BLVD., #212
HONOLULU, HAWAII 96814

in reply, please refer to:
EMD / SHW

September 19, 1995

POLICY UPDATE
Technical Guidance Manual
for Underground Storage Tank Closure and Release Response

Determination of Groundwater Utility
at Leaking Underground Storage Tank Sites

TO ALL INTERESTED PARTIES:

The Hawai'i Department of Health's Solid and Hazardous Waste Branch, Underground Storage Tank Section, is issuing a policy update to its *Technical Guidance Manual for Underground Storage Tank Closure and Release Response* (August 1992). **This policy update is effective September 13, 1995.**

Recommended cleanup criteria at leaking underground storage tank (LUST) sites depend on, among other things, whether the ground water underlying the site is used or intended for use as a drinking water source. This policy directs owners and operators of USTs to use the aquifer system classification reports developed by the University of Hawai'i at Mānoa's Water Resources Research Center in determining the use of the ground water underlying the site.

This new policy allows for more efficient allocation of limited cleanup resources by ensuring that cleanup requirements applied to a site are appropriate for the use of the site and the surrounding area, while at the same time maintaining effective protection of human health and the environment.

Please bring this policy update to the attention of anyone you know who may have an interest in this matter. Should you have any questions regarding this policy update, please contact the Underground Storage Tank Section at (808) 586-4226.

Sincerely,

STEVEN Y.K. CHANG, P.E., MANAGER
Solid and Hazardous Waste Branch

Attachment

DETERMINATION OF GROUNDWATER UTILITY AT LEAKING UNDERGROUND STORAGE TANK SITES

Background

Soil and groundwater cleanup criteria for remedial activities pursuant to 40 CFR Part 280 Subpart F (RCRA I) and Hawai'i Revised Statutes, Chapters 342L and 128D, are based in part on the utility of the groundwater impacted or potentially impacted by the release. Cleanup criteria for release that threaten sources of drinking water are based primarily on human health concerns. Cleanup criteria for releases that threaten non-drinking water sources are based primarily on ecological/aquatic-life concerns. In general, cleanup criteria for releases that threaten drinking water are much more stringent than for those that do not.

As a useful first approximation, and in order to help maintain consistency in groundwater protection policies within the Department of Health (DOH), the SHWB informally adopted the Underground Injection Control (UIC) line as an initial demarcation between aquifer systems that serve or could potentially serve as sources of drinking water (generally beneath the inland areas of the islands) and those that could not (generally beneath the coastal areas of the islands). The UIC line was established by the DOH Safe Drinking Water Branch (working in cooperation with the Honolulu City & County Board of Water Supply, the U.S. Geological Survey, and the Water Resources Research Center of the University of Hawai'i - Mānoa, among others) for purposes of regulating the location of underground injection wells. Reference to the use of the UIC line for SHWB purposes is made in the document "Technical Guidance Manual for Underground Storage Tank (UST) Closure and Release Response (TGM, August, 1992)," prepared by the UST Section of the SHWB.

In accordance with UIC guidelines, aquifer systems mauka (inland) of the UIC line are by default considered to be current or potential sources of drinking water. Aquifer systems makai (oceanward) of the UIC line are considered by default to not be current or potential sources of drinking water. Correspondingly, cleanup criteria for release sites located mauka of the UIC line are initially set to be protective to drinking water standards. Cleanup criteria for release sites located makai of the UIC line are initially set to be protective to generally less stringent non-drinking water (surface water) standards.

Statement of Problem

The UST section of the SHWB deals with hundreds of facilities with leaking underground storage tank (LUST) sites that are required by federal and state law to report UST-related releases to DOH. Most, if not all, LUST sites are too small to technically or economically warrant a full-scale investigation of the utility of the groundwater that has been or could potentially be impacted by the release. This necessitates the use of approximated, regional groundwater-utility "zones", defined by use of such tools as the UIC line.

Numerous LUST facilities located mauka of the UIC line, however, have requested variance from use of the UIC line to approximate groundwater utility beneath their sites. The requests have been based on the known geology of the site and a position that the release does not threaten an aquifer system that currently or could potentially serve as a source of drinking water. Indeed, many of the subject sites overlie clay-rich, "caprock" coastal plain sediments that are not suitable as sources of drinking water. An extensive, subsurface investigation of the local groundwater system would likely support this at many of the sites if such an investigation was technically and economically feasible. Fortunately, recent research on aquifer systems throughout the islands addresses the bulk of these problem areas.

Aquifer Identification and Classification Technical Report Series

Since establishment of the UIC line, DOH has sponsored additional research regarding the identification, classification, and protection of groundwater resources in Hawai'i. The most important outcome of this research to date has been the "Aquifer Identification and Classification" technical report series published for each island by the Water Resources Research Center (WRRC) at the University of Hawai' i- Mānoa (see references). The reports have been incorporated into the draft Water Resources Protection Plan (March, 1992), prepared by the Department of Land and Natural Resources as part of the Hawai'i Water Plan under provisions set in Chapter 174C of the Hawai'i Revised Statutes. The DOH Office of Hazard Evaluation and Emergency Response currently uses the WRRC aquifer identification and classification reports to screen sites for prioritization.

The WRRC reports systematically review aquifer systems throughout each island and, as one element, indicate whether the aquifer system as a whole can or cannot be utilized as a source of drinking water (aquifer system "utility," second digit in aquifer system status code). Because division of the aquifer systems is based largely on geology, the WRRC aquifer classification system reports address many of the problem areas brought about by reliance on only the UIC line to approximate groundwater utility.

One of the shortcomings of the aquifer system classification reports, recognized by the authors (Mink, personal communication - Attachment A), is a lack of sufficient data to subdivide geologically-defined aquifer "types" into more narrowly-defined "units" based on the variability of groundwater quality within the aquifer system. This can be especially important in coastal areas where groundwater quality within an otherwise "drinking water" aquifer system degrades to below drinking water standards as the freshwater lens pinches out and mixes with saline water within the same geological formation. Examples include much of the basaltic coastal areas of the islands of Kaua'i, Maui, Moloka'i, and Hawai'i.

In these areas, the groundwater specialists consulted generally agreed that the UIC line can serve as a useful and valid tool for approximating the inland boundary of coastal-zone, aquifer system "units" that are not current or potential sources of drinking water (see Attachment A). Over time, continued investigation of Hawai'i's groundwater resources will naturally lead to a refinement of the boundaries between regional aquifer systems and a better breakdown of distinctive units within individual systems.

Policy Statement

Facilities with releases from USTs regulated by the UST Section of the DOH Solid and Hazardous Waste Branch must determine the utility of groundwater (generally drinking water or non-drinking water) that has been or may potentially be impacted by the release. In support of the determination of groundwater utility, the following information should be submitted to the DOH:

1. a review of the known surface and subsurface geology and hydrogeology of the site, including information gained during investigation of the release and information provided in published or unpublished reports that include the subject area (refer to TGM, August 1992 edition for information required in site investigations)

2. a description of all aquifer systems (classification, status, etc.) that have been impacted and/or could potentially be impacted by the release in accordance with the referenced aquifer system classification reports published by the WRRC, and

3. a map showing the location of the release site with respect to the boundaries of impacted or potentially impacted aquifer systems.

In addition, if the UIC line is used to approximate the inland boundaries of coastal-zone, non-drinking water aquifer system units, then the location of the UIC line with respect to the corresponding aquifer system(s) should be included on the map and discussed in the text of the report.

DOH may request additional site-specific geologic, hydrogeologic, and other pertinent information as necessary on a site-by-site basis to make final groundwater utility determinations. In particular, facilities situated near aquifer system boundaries should evaluate the geological accuracy and applicability of the aquifer system maps to their site.

DOH reserves the right to make final decisions of groundwater utility on a site-specific basis, regardless of the location of the site with respect to regional characterizations of aquifer systems. This may become especially important in areas of extensive soil and groundwater contamination, at sites located near important aquifer system boundaries where detailed subsurface data is not available, or in ecologically sensitive areas (e.g., near bodies of surface water).

The review of an aquifer systems status as a source or potential source of drinking water will be for UST section purposes only and the results of the review should not be construed as an official confirmation or refinement of the UIC line in the area of the release site. Injection well applications, if any, will be processed according to UIC regulations, Chapter 23, by the UIC program of the Safe Drinking Water Branch (SDWB) and such applications will not be excluded from UIC restrictions due to designations of what is or is not a source of drinking water that have not been approved by the SDWB.

APPROVED/~~DISAPPROVED~~

Bruce Anderson, Ph.D., Deputy Director, Environmental Health, Department of Health

9/13/95
Date

References:

Environmental Response Law, Hawai'i Revised Statutes, Chapter 128D.

Mink, J. F. and Lau, S. L., 1990, Aquifer Identification and Classification for the Island of Maui: Groundwater Protection Strategy for Hawai'i (February 1990): Water Resources Research Center, University of Hawai'i at Mānoa, Technical Report No. 185.

Mink, J. F. and Lau, S. L., 1990, Aquifer Identification and Classification for the Island of O'ahu: Groundwater Protection Strategy for Hawai'i (February 1990): Water Resources Research Center, University of Hawai'i at Mānoa, Technical Report No. 179.

Mink, J. F. and Lau, S. L., 1992, Aquifer Identification and Classification for the Island of Kaua'i: Groundwater Protection Strategy for Hawai'i (September 1992): Water Resources Research Center, University of Hawai'i at Mānoa, Technical Report No. 186.

Mink, J. F. and Lau, S. L., 1992, Aquifer Identification and Classification for the Island of Moloka'i: Groundwater Protection Strategy for Hawai'i (October 1992): Water Resources Research Center, University of Hawai'i at Mānoa, Technical Report No. 187.

Mink, J. F. and Lau, S. L., 1993, Aquifer Identification and Classification for the Island of Lanā'i: Groundwater Protection Strategy for Hawai'i (April 1993): Water Resources Research Center, University of Hawai'i at Mānoa, Technical Report No. 190.

Mink, J. F. and Lau, S. L., 1993, Aquifer Identification and Classification for the Island of Hawai'i: Groundwater Protection Strategy for Hawai'i (May 1993): Water Resources Research Center, University of Hawai'i at Mānoa, Technical Report No. 191.

State Water Code, Hawai'i Revised Statutes, Chapter 174C.

Technical Guidance Manual for Underground Storage Tank Closure and Release Response (August, 1992): Hawai'i Department of Health, Solid and Hazardous Waste Branch.

Underground Injection Control, Hawai'i Administrative Rules, Title 11, Chapter 23.

Underground Storage Tanks, Hawai'i Revised Statutes, Chapter 342L.

BENJAMIN J. CAYETANO
GOVERNOR OF HAWAII

LAWRENCE MIIKE
DIRECTOR OF HEALTH

STATE OF HAWAII
DEPARTMENT OF HEALTH
ENVIRONMENTAL MANAGEMENT DIVISION
SOLID AND HAZARDOUS WASTE BRANCH
919 ALA MOANA BLVD., #212
HONOLULU, HAWAII 96814

In reply, please refer to:
EMD/SHW

January 5, 1996

POLICY UPDATE
Addendum to: *Determination of Groundwater Utility at Leaking Underground Storage Tank Sites (September 19, 1995)*

Example Re-assessment of Groundwater Utility and Applicable Soil and Groundwater Action Levels

TO ALL INTERESTED PARTIES:

The Hawai'i Department of Health's (DOH) Solid and Hazardous Waste Branch, Underground Storage Tank Section, recently issued a policy statement entitled *Determination of Groundwater Utility at Leaking Underground Storage Tank Sites* (September 19, 1995). Attached is example language regarding the expected content of documents that are submitted to DOH for conformance with this policy.

Please bring this policy addendum to the attention of anyone you know who may have an interest in this matter. Should you have any questions regarding this addendum, please contact the Underground Storage Tank Section at (808) 586-4226.

Sincerely,

STEVEN Y. K. CHANG, P.E., MANAGER
Solid and Hazardous Waste Branch

Attachment

POLICY UPDATE
Addendum to: *Determination of Groundwater Utility at Leaking Underground Storage Tank Sites (September 19, 1995)*

Example Re-assessment of Groundwater Utility and Applicable Soil and Groundwater Action Levels

Responsible parties wishing to use the policy noted above to more precisely define groundwater utility at a leaking underground storage tank site should submit information to the Department of Health (DOH) in a format similar to that provided below. The re-assessment of groundwater utility may be included as part of a site investigation/remedial action report for the facility or as a separate letter report.

Groundwater Utility at Site

The subject site is located mauka of the DOH Underground Injection Control (UIC) line. Based on guidance presented in the DOH *Technical Guidance Manual for Underground Storage Tank Closure and Release Response* (August, 1992), the site is by default assumed to immediately overlie groundwater that is a source or potential source of drinking water. As described below, however, the utility of the groundwater immediately beneath the subject site has been re-evaluated in accordance with revised guidelines presented in the DOH policy statement entitled *Determination of Groundwater Utility at Leaking Underground Storage Tank Sites (September 19, 1995).*

In accordance with the revised guidelines, the University of Hawai'i Water Resources Research Center (WRRC) report for O'ahu (Mink and Lau, 1990) was used to determine the utility of the groundwater at the site (see attached map). The report indicates that the groundwater located immediately beneath the subject site is part of the Honolulu-Nu'uanu aquifer system of O'ahu (aquifer sector/system 30101) and is held within caprock sediments that flank the Ko'olau basalt (aquifer type 116). This is confirmed by the presence of clayey and silty sediments directly underlying the site as described in the site investigation report entitled XXXX (dated XXXX) and prepared by XXXX. The utility of this groundwater is classified in the WRRC report as unsuitable for drinking water purposes (utility status "3"). In light of this information, soil and groundwater action levels (i.e., "cleanup criteria") applied to the subject site will be based on DOH guidance put forth for sites that do not threaten sources of drinking water.