Screening for Environmental Hazards at Sites with Contaminated Soil and Groundwater

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

Appendices 2-11

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DISCLAIMER

This document, *Evaluation of Environmental Hazards at Sites with Contaminated Soil and Groundwater* (Summer 2008), is a technical report prepared by staff of the Hawai'i Department of Health (HDOH), Environmental Management Division. The document updates and replaces the document *Screening for Environmental Concerns at Sites with Contaminated Soil and Groundwater* (Interim Final, May 2005 and interim updates).

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

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

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GLOSSARY OF TERMS

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

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APPENDIX 2

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

USEPA REGIONAL SCREENING LEVELS USER'S GUIDE (MAY 2008, TEXT ONLY)

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

1.0 Introduction

This appendix summarizes models and exposure assumptions used to generate risk-based action levels for soil, tapwater and indoor air that are incorporated into the HDOH Tier 1 Environmental Action Levels presented in Appendix 1. Risk-based action levels for soil and tapwater follow models and assumptions used to develop the USEPA *Regional Screening Levels* (RSLs, USEPA 2008). The RSLs represent a consolidation of *Preliminary Remedial Goals* (PRGs) previously published by individual USEPA regions. Previous editions of the HDOH guidance in particular referenced PRGs developed and published by USEPA Region IX (USEPA 2004a).

A copy of the 2008 USEPA RSL *User's Guide* is attached. This document presents a detailed discussion of the equations and assumptions used to calculate the RLSs. Risk-based soil action levels were developed for the following exposure scenarios:

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

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

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

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

The USEPA RSL guidance only presents risk-based soil action levels for residential and commercial/industrial land use scenarios. A third set of action levels is incorporated into the HDOH Tier 1 EALs for construction and trench workers. A summary of exposure assumptions for all scenarios is provided in Table1. References for the development of this exposure scenario are discussed in more detail below and in Appendix 1. The soil action levels can be used in site-specific Environmental Hazard Evaluations to evaluate in contaminants in deep or otherwise isolated soils to help target remedial efforts.

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

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

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

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

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

2.0 Construction/Trench Workers Exposure Scenario

Direct-exposure screening levels for deep soils are calculated based on a construction/trench worker exposure scenario. Exposure assumptions are summarized in Table 1. The assumed exposed skin area and soil ingestion rate are based on guidance presented in the *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites (USEPA 2002).* The inhalation rate, body weight, averaging time and target hazard quotient are set equal to assumptions used in the USEPA RSL*s* (USEPA 2008) for consistency with screening levels for occupational exposure assumptions. The soil adherence factor is taken from trench-worker exposure scenario assumptions developed by the Massachusetts Department of Environmental Protection for use in calculating screening levels for Deep soils (MADEP 1994).

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

"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 2004). 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 Action Levels

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

Equation 1: Residential Exposures to Carcinogenic Contaminants in Indoor Air

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

Equation 2: 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 3: 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 4: 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 H and E-3 of Appendix 1.

REFERENCES

MADEP, 1994, *Background Documentation for the Development of the MCP Numerical Standards:* Massachusetts Department of Environmental Protection, Bureau of Waste Site Cleanup and Office of Research and Standards, April 1994.

RWQCBCV, 2007, *A Compilation of Water Quality Goals*: California Environmental Protection Agency, Regional Water Quality Control Board, Central Valley Region (August 2007), http://www.waterboards.ca.gov/centralvalley/water_issues/water_quality_standards_limits/water_quality_goals/index.shtml

USEPA, 1974, Development of Emission Factors for Fugitive Dust Sources: U.S. Environmental Protection Agency, Publication No. EPA-450/3-74-037, (prepared by Cowherd, C., Axetell, K., Guenther, C., and Jutze, G., Midwest Research Institute).

USEPA, 1985, Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources: U.S. Environmental Protection Agency, Office of Air and Radiation, Publication No. AP-42, Fourth Edition, September 1985.

USEPA, 2002, Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites: U.S. Environmental Protection Agency, Solid Waste and Emergency Response, OSWER 9355.4-24, December 2002.

USEPA, 2004a, Preliminary Remediation Goals: U.S. Environmental Protection Agency, Region IX, October 2004.

USEPA, 2004a, *User's Guide For Subsurface Vapor Intrusion Into Buildings*: U.S. Environmental Protection Agency Office of Emergency and Remedial Response, March 2003, www.epa.gov/oerrpage/superfund/.

USEPA, 2008, *Regional Screening Levels*: U.S. Environmental Protection Agency, May 29, 2008, prepared by Oak Ridge National Laboratories, http://epa-prgs.ornl.gov/chemicals/index.shtml

TABLE 1. HUMAN EXPOSURE PARAMETER DEFINITIONS AND DEFAULT VALUES

Symbol	Definition (units)	Default	References (refer to USEPA 2008 for full references)
CSFo	Cancer slope factor oral (mg/kg-d)$^{-1}$	--	Chemical specific - Appendix 1, Table J
CSFi	Cancer slope factor inhaled (mg/kg-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 2004
*TRctw	Target cancer risk - construction/trench worker exposure scenario	10^{-5}	model assumption
THQ	Target hazard quotient	0.2	modified from USEPA 2004
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 2004
SAar	Exposed surface area, adult res. (cm^2/day)	5,700	Dermal Assessment, USEPA 2004 (EPA/540/R-99/005)
SAaw	Exposed surface area, adult occ. (cm^2/day)	3,300	Dermal Assessment, USEPA 2004 (EPA/540/R-99/005))
SAc	Exposed surface area, child (cm^2/day)	2,800	Dermal Assessment, USEPA 2004 (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 2004 (EPA/540/R-99/005)
AFaw	Adherence factor, occupational (mg/cm^2)	0.20	Dermal Assessment, USEPA 2004 (EPA/540/R-99/005)
*AFctw	Adherence factor, construction/trench worker (mg/cm^2)	0.30	Supplemental SSL Superfund Guidance (USEPA 2002)
AFc	Adherence factor, child (mg/cm^2)	0.20	Dermal Assessment, USEPA 2004 (EPA/540/R-99/005)
ABS	Skin absorption (unitless): chemical specific	--	Dermal Assessment, USEPA 2004 (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	Supplemental SSL Superfund Guidance (USEPA 2002)
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)	35	Supplemental SSL Superfund Guidance (USEPA 2002; 250 days total EF spread over modified ED of 7 years)
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	Supplemental SSL Superfund Guidance (USEPA 2002; 250 days total EF spread over modified ED of 7 years)
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 ([1-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, 2008, Regional Screening Levels: U.S. Environmental Protection Agency, May 2008.

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).

* HDOH guidance document only. Not presented in USEPA RSL guidance.

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

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

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

Attachment

USEPA Regional Screening Levels User's Guide (May 2008)

Screening Table Home | User's Guide | What's New | FAQ | Equations | Generic Tables | Calculator

Screening Levels for Chemical Contaminants

User's Guide

pdf version

Disclaimer

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

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

1. Introduction

The purpose of this website is to provide default screening tables and a calculator to assist Remedial Project Managers (RPMs), On Scene Coordinators (OSC's), risk assessors and others involved in decision-making concerning CERCLA hazardous waste sites and to determine whether levels of contamination found at the site may warrant further investigation or site cleanup, or whether no further investigation or action may be required.

Users within and outside the CERCLA program should use the tables or calculator results at their own discretion and they should take care to understand the assumptions incorporated in these results and to apply the SLs appropriately.

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

2. Understanding the Screening Tables

2.1 General Considerations

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

2.2 Exposure Assumptions

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

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

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

2.3 Toxicity Values

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

1. EPA's Integrated Risk Information System (IRIS)

2. The Provisional Peer Reviewed Toxicity Values (PPRTVs) derived by EPA's Superfund Health Risk Technical Support Center (STSC) for the EPA Superfund program. (Note that the PPRTV website is not open to users outside of EPA, but assessments can be obtained for use on Superfund sites by contacting Dave Crawford at Crawford.Dave@epa.gov).

3. The Agency for Toxic Substances and Disease Registry (ATSDR) minimal risk levels (MRLs)

4. The California Environmental Protection Agency/Office of Environmental Health Hazard Assessment's toxicity values (http://www.oehha.ca.gov/risk/ChemicalDB/index.asp)

5. The EPA Superfund program's Health Effects Assessment Summary. (Note that the HEAST website of toxicity values for chemical contaminants is not open to users outside of EPA, but values can be obtained for use on Superfund sites by contacting Dave Crawford at Crawford.Dave@epa.gov).

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

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

2.3.1 Reference Doses

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

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

2.3.2 Reference Concentrations

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

The chronic inhalation reference concentration is generally used for continuous or near continuous inhalation exposures that occur for 7 years or more. However, this is not a bright line, and ATSDR chronic MRLs are based on exposures longer than 1 year. EPA chronic inhalation reference concentrations are expressed in units of (mg/m^3). Cal EPA RELs are presented in µg/m^3 and have been converted to mg/m^3 for use in these screening tables. Some ATSDR inhalation MRLs are derived in parts per million (ppm) and some in mg/m^3. For use in this table all were converted into mg/m^3.

2.3.3 Slope Factors

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

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

2.3.4 Inhalation Unit Risk

The IUR is defined as the upper-bound excess lifetime cancer risk estimated to result from continuous exposure to an agent at a concentration of 1 µg/m^3 in air.

Inhalation unit risk toxicity values are expressed in units of $(mg/m^3)^{-1}$.

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

2.3.5 Toxicity Equivalence Factors

Some chemicals are members of the same family and exhibit similar toxicological properties; however, they differ in the degree of toxicity. Therefore, a toxicity equivalence factor (TEF) must first be applied to adjust the measured concentrations to a toxicity equivalent concentration.

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

Dioxin Toxicity Equivalence Factors

	Dioxins and Furans	**TEF**
Chlorinated dibenzo-p-dioxins		
	2,3,7,8-TCDD	1
	1,2,3,7,8-PeCDD	1
	1,2,3,4,7,8-HxCDD	0.1
	1,2,3,6,7,8-HxCDD	0.1
	1,2,3,7,8,9-HxCDD	0.1
	1,2,3,4,6,7,8-HpCDD	0.01
	OCDD	0.0003
Chlorinated dibenzofurans		
	2,3,7,8-TCDF	0.1
	1,2,3,7,8-PeCDF	0.03
	2,3,4,7,8-PeCDF	0.3
	1,2,3,4,7,8-HxCDF	0.1
	1,2,3,6,7,8-HxCDF	0.1
	1,2,3,7,8,9-HxCDF	0.1
	2,3,4,6,7,8-HxCDF	0.1
	1,2,3,4,6,7,8-HpCDF	0.01
	1,2,3,4,7,8,9-HpCDF	0.01
	OCDF	0.0003

PCBs			
	IUPAC No.	**Structure**	
Non-*ortho*	77	3,3',4,4'-TetraCB	0.0001
	81	3,4,4',5-TetraCB	0.0003
	126	3,3',4,4',5-PeCB	0.1
	169	3,3',4,4',5,5'-HxCB	0.03
Mono-*ortho*	105	2,3,3',4,4'-PeCB	0.00003
	114	2,3,4,4',5-PeCB	0.00003
	118	2,3',4,4',5-PeCB	0.00003
	123	2',3,4,4',5-PeCB	0.00003
	156	2,3,3',4,4',5-HxCB	0.00003
	157	2,3,3',4,4',5'-HxCB	0.00003
	167	2,3',4,4',5,5'-HxCB	0.00003
	189	2,3,3',4,4',5,5'-HpCB	0.00003
Di-*ortho**	170	2,2',3,3',4,4',5-HpCB	0.0001
	180	2,2',3,4,4',5,5'-HpCB	0.00001

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

Carcinogenic polycyclic aromatic hydrocarbons

Provisional Guidance for Quantitative Risk Assessment of Polycyclic Aromatic Hydrocarbons (EPA/600/R-93/089, July 1993), recommends that a toxicity equivalency factor (TEF) be used to convert concentrations of carcinogenic polycyclic aromatic hydrocarbons (cPAHs) to an equivalent concentration of benzo(a) pyrene when assessing the risks posed by these substances. These TEFs are based on the potency of each compound relative to that of benzo(a)pyrene. For the toxicity value database, these TEFs have been applied to the toxicity values. Although this is not in complete agreement with the direction in the aforementioned documents, this approach was used so that toxicity values could be generated for each cPAH. Additionally, it should be noted that computationally it makes little difference whether the TEFs are applied to the concentrations of cPAHs found in environmental samples or to the toxicity values as long as the TEFs are not applied to both. However, if the adjusted toxicity values are used, the user will need to sum the risks from all cPAHs as part of the risk assessment to derive a total risk from all cPAHs. A total risk from all cPAHs is what is derived when the TEFs are applied to the environmental concentrations of cPAHs and not to the toxicity values.

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

Toxicity Equivalency Factors for Carcinogenic Polycyclic Aromatic Hydrocarbons

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

2.4 Chemical-specific Parameters

Several chemical specific parameters are needed for development of the SLs. Different hierarchies are used for organic and inorganic compounds.

2.4.1 Organic Compounds

1. Values were taken from http://www.epa.gov/opptintr/exposure/pubs/episuite.htm. These programs estimate various chemical-specific properties. The calculations for these SL tables use the experimental values for a property over the estimated values.
2. EPA Soil Screening Level (SSL) Exhibit C-1.
3. WATER8, which has been replaced with WATER9.
4. Syracuse Research Corporation (SRC). 2005. CHEMFATE Database. SRC. Syracuse, NY. Accessed July 2005.
5. Syracuse Research Corporation (SRC). 2005. PHYSPROP Database. SRC. Syracuse, NY. Accessed July 2005.

2.4.2 Inorganic Compounds

For unitless Henry's Law (ammonia, chlorine, cyanogen, cyanogen chloride, hydrogen cyanide only):

1. Syracuse Research Corporation (SRC). 2005. PHYSPROP Database. SRC. Syracuse, NY. (http://www.syrres.com/esc/physdemo.htm).
2. Yaws' Handbook of Thermodynamic and Physical Properties of Chemical Compounds. Knovel, 2003. (http://www.knovel.com).

For Kd (soil-water partition coefficient):

1. EPA Soil Screening Level (SSL) Table C.4 (http://www.epa.gov/superfund/health/conmedia/soil/index.htm).
2. Baes, C.F. 1984. Oak Ridge National Laboratory. A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture. http://homer.ornl.gov/baes/documents/ornl5786.html. Values are also found in Superfund Chemical Data Matrix (SCDM) (http://www.epa.gov/superfund/sites/npl/hrsres/tools/scdm.htm).

For molecular weights:

1. EPI (http://www.epa.gov/oppt/exposure/pubs/episuite.htm)
2. Syracuse Research Corporation (SRC). 2005. PHYSPROP Database. SRC. Syracuse, NY. (http://www.syrres.com/esc/physdemo.htm).

For Vapor Pressure:

1. NIOSH Pocket Guide to Chemical Hazards (NPG), NIOSH Publication No. 97-140, February 2004. (http://www.cdc.gov/niosh/npg/npg.html).
2. 2) Syracuse Research Corporation (SRC). 2005. CHEMFATE Database. SRC. Syracuse, NY. (http://www.syrres.com/esc/chemfate.htm).
3. Syracuse Research Corporation (SRC). 2005. PHYSPROP Database. SRC. Syracuse, NY. (http://www.syrres.com/esc/physdemo.htm).

For diffusivity in air and water, if desired at all, for the gasses and mercuric compounds:

1. WATER 9, (EPA 2001). See section 4.9.2.

3. Using the SL Tables

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

- Prioritizing multiple sites or operable units or areas of concern within a facility or exposure units
- Setting risk-based detection limits for contaminants of potential concern (COPCs)
- Focusing future site investigation and risk assessment efforts (e.g., selecting COPCs for the baseline risk assessment)
- Identifying contamination which may warrant cleanup
- Identifying sites, or portions of sites, which warrant no further action or investigation
- Initial cleanup goals when site-specific data are lacking

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

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

- Summary Table - provides a list of contaminants, toxicity vales, MCLs and the lesser (more protective) of the cancer and noncancer SLs for resident soil, industrial soil, resident air, industrial air and tapwater.
- Residential Soil Supporting Table - provides a list of contaminants, toxicity vales and the cancer and noncancer SLs for resident soil.
- Industrial Soil Supporting Table - provides a list of contaminants, toxicity vales and the cancer and noncancer SLs for industrial soil.
- Residential Air Supporting Table - provides a list of contaminants, toxicity vales and the cancer and noncancer SLs for resident air.
- Industrial Air Supporting Table - provides a list of contaminants, toxicity vales and the cancer and noncancer SLs for industrial air.
- Residential Tapwater Supporting Table - provides a list of contaminants, toxicity vales, MCLs and the cancer and noncancer SLs for tapwater.

3.1 Developing a Conceptual Site Model

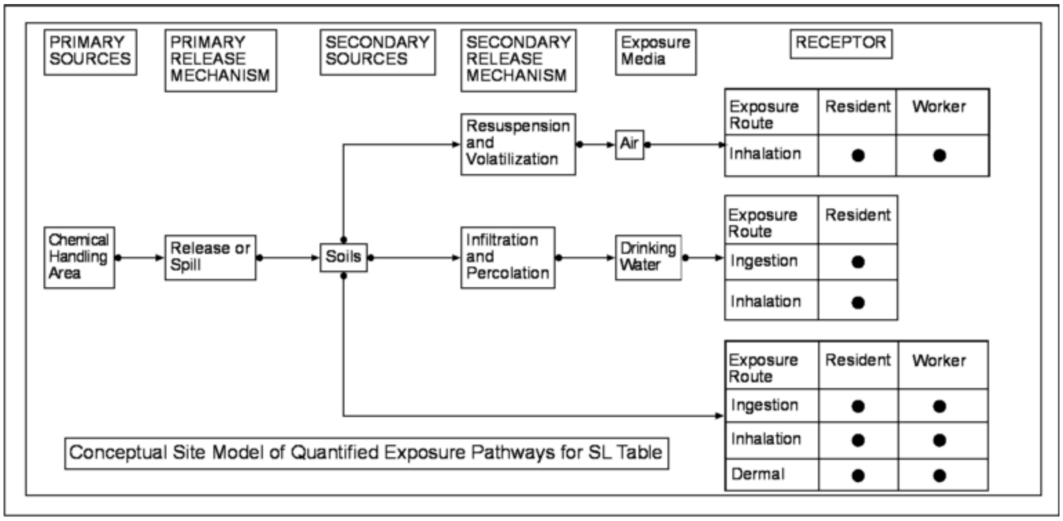
When using generic SLs at a site, the exposure pathways of concern and site conditions should match those used in developing the SLs presented here. (Note, however, that future uses may not match current uses. Future uses are potential site uses that may occur in the future. At Superfund sites, future uses should be considered as well as current uses. RAGS Part A, Chapter 6, provides guidance on selecting future-use receptors.) Thus, it is necessary to develop a conceptual site model (CSM) to identify likely contaminant source areas, exposure pathways, and potential receptors. This information can be used to determine the applicability of SLs at the site and the need for additional information. The final CSM diagram represents linkages among contaminant sources, release mechanisms, exposure pathways, and routes and receptors based on historical information. It summarizes the understanding of the contamination problem. A separate CSM for ecological receptors can be useful. Part 2 and Attachment A of the Soil Screening Guidance for Superfund: Users Guide (EPA 1996) contains the steps for developing a CSM.

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

- Are there potential ecological concerns?
- Is there potential for land use other than those used in the SL calculations (i.e., residential and commercial/industrial)?
- Are there other likely human exposure pathways that were not considered in development of the SLs?
- Are there unusual site conditions (e.g. large areas of contamination, high fugitive dust levels, potential for indoor air contamination)?

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

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



3.2 Background

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

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

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

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

3.3 Potential Problems

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

- Applying SLs to a site without adequately developing a conceptual site model that identifies relevant exposure pathways and exposure scenarios.
- Not considering the effects from the presence of multiple contaminants, where appropriate.
- Use of the SLs as cleanup levels without adequate consideration of the other NCP remedy selection criteria on CERCLA sites.
- Use of SL as cleanup levels without verifying numbers with a toxicologist or regional risk assessor.
- Use of outdated SLs when tables have been superseded by more recent values.
- Not considering the effects of additivity when screening multiple chemicals.
- Applying inappropriate target risks or changing a cancer target risk without considering its effect on noncancer, or vice versa.
- Not performing additional screening for pathways not included in these SLs (e.g,. vapor intrusion, fish consumption).
- Adjusting SLs upward by factors of 10 or 100 without consulting a toxicologist or regional risk assessor.

4. Technical Support Documentation

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

4.1 Residential Soil

4.1.1 Noncancer

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

- incidental ingestion of soil,

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

- inhalation of particulates emitted from soil,

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

- dermal contact with soil,

$$SL_{\text{res-sol-nc-der}}\left(\text{mg/kg}\right)=\frac{THQ\times AT_r\left(\frac{365\text{ days}}{\text{year}}\right)\times ED_c\left(6\text{ years}\right)\times BW_c\left(15\text{ Kg}\right)}{EF_r\left(\frac{350\text{ days}}{\text{year}}\right)\times ED_c\left(6\text{ year}\right)\times\frac{1}{\left(RfD_o\left(\frac{\text{mg}}{\text{Kg-day}}\right)\times GIABS\right)}\times SA_c\left(\frac{2800\text{ cm}^2}{\text{day}}\right)\times AF_c\left(\frac{0.2\text{ mg}}{\text{cm}^2}\right)\times ABS_d\times\frac{10^{-6}\text{Kg}}{1\text{mg}}}$$

- Total.

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

4.1.1 Carcinogenic

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

- incidental ingestion of soil,

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

where:

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

- inhalation of particulates emitted from soil,

$$SL_{\text{res-sol-ca-inh}}\left(\text{mg/kg}\right)=\frac{TR\times AT_r\left(\frac{365\text{ days}}{\text{year}}\right)\times LT\left(70\text{ years}\right)}{IUR\left(\mu\text{g}/\text{m}^3\right)^{-1}\times\left(\frac{1000\ \mu\text{g}}{\text{mg}}\right)\times EF_r\left(\frac{350\text{ days}}{\text{year}}\right)\times\left(\frac{1}{VF_s\left(\frac{\text{m}^3}{\text{Kg}}\right)}+\frac{1}{PEF_w\left(\frac{\text{m}^3}{\text{Kg}}\right)}\right)\times ED_r\left(30\text{ years}\right)\times ET_{rs}\left(\frac{24\text{ hours}}{\text{day}}\right)\times\left(\frac{1\text{ day}}{24\text{ hours}}\right)}$$

- dermal contact with soil,

$$SL_{\text{res-sol-ca-der}}\left(\text{mg/kg}\right)=\frac{TR\times AT_r\left(\frac{365\text{ days}}{\text{year}}\right)\times LT\left(70\text{ years}\right)}{\left(\frac{CSF_o\left(\frac{\text{mg}}{\text{Kg-day}}\right)^{-1}}{GIABS}\right)\times EF_r\left(\frac{350\text{ days}}{\text{year}}\right)\times DFS_{adj}\left(\frac{361\text{ mg-Year}}{\text{Kg-day}}\right)\times ABS_d\times\left(\frac{10^{-6}\text{Kg}}{\text{mg}}\right)}$$

where:

$$DFS_{adj}\left(\frac{361\text{ mg-Year}}{\text{Kg-day}}\right)=\frac{ED_c\left(6\text{ years}\right)\times SA_c\left(\frac{2800\text{ cm}^2}{\text{day}}\right)\times AF_c\left(\frac{0.2\text{ mg}}{\text{cm}^2}\right)}{BW_c\left(15\text{ Kg}\right)}+\frac{ED_r\text{-}ED_c\left(24\text{ years}\right)\times SA_a\left(\frac{5700\text{ cm}^2}{\text{day}}\right)\times AF_a\left(\frac{0.07\text{ mg}}{\text{cm}^2}\right)}{BW_a\left(70\text{ Kg}\right)}$$

- Total.

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

4.2.3 Mutagenic

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

- incidental ingestion of soil,

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

where:

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

- inhalation of particulates emitted from soil,

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

- dermal contact with soil,

$$SL_{\text{res-sol-mu-der}}\,(\text{mg/kg})=\frac{TR\times AT_r\left(\frac{365\text{ days}}{\text{year}}\times LT\,(70\text{ years})\right)}{\left(\frac{CSF_o\left(\frac{\text{mg}}{\text{Kg-day}}\right)^{-1}}{GIABS}\right)\times EF_r\left(\frac{350\text{ days}}{\text{year}}\right)\times DFSM_{adj}\left(\frac{1445\text{ mg-Year}}{\text{Kg-day}}\right)\times ABS_d\times\left(\frac{10^{-6}\text{Kg}}{\text{mg}}\right)}$$

where:

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

- Total.

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

4.1.3 Vinyl Chloride - Carcinogenic

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

- incidental ingestion of soil,

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

- inhalation of particulates emitted from soil,

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

- dermal contact with soil,

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

- Total.

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

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

4.2 Outdoor Worker Soil

4.2.1 Noncancer

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

- incidental ingestion of soil,

$$SL_{w\text{-}sol\text{-}nc\text{-}ing}\,(mg/kg)=\frac{THQ\times AT_{ow}\left(\frac{365\ days}{year}\times ED_{ow}\,(25\ years)\right)\times BW_{ow}\,(70\ Kg)}{EF_{ow}\left(250\ \frac{days}{year}\right)\times ED_{ow}\,(25\ years)\times\frac{1}{RfD_o\left(\frac{mg}{kg\text{-}day}\right)}\times IR_{ow}\left(100\ \frac{mg}{day}\right)\times\left(\frac{10^{-6}\ Kg}{1\ mg}\right)}$$

- inhalation of particulates emitted from soil,

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

- dermal exposure,

$$SL_{w\text{-}sol\text{-}nc\text{-}der}\,(mg/kg)=\frac{THQ\times AT_{ow}\left(\frac{365\ days}{year}\times ED_{ow}\,(25\ years)\right)\times BW_{ow}\,(70\ Kg)}{EF_{ow}\left(250\ \frac{days}{year}\right)\times ED_{ow}\,(25\ years)\times\left(\frac{1}{RfD_o\left(\frac{mg}{kg\text{-}day}\right)\times GIABS}\right)\times SA_{ow}\left(\frac{3300\ cm^2}{day}\right)\times AF_{ow}\left(\frac{0.2\ mg}{cm^2}\right)\times ABS_d\times\left(\frac{10^{-6}\ Kg}{1\ mg}\right)}$$

- Total.

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

4.2.2 Carcinogenic

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

- incidental ingestion of soil,

$$SL_{w\text{-}sol\text{-}ca\text{-}ing}\,(\text{mg/kg}) = \frac{TR \times AT_{ow}\left(\frac{365\ \text{days}}{\text{year}}\right) \times LT\,(70\ \text{years}) \times BW_{ow}\,(70\ \text{Kg})}{EF_{ow}\left(250\ \frac{\text{days}}{\text{year}}\right) \times ED_{ow}\,(25\ \text{years}) \times CSF_o\left(\frac{\text{mg}}{\text{kg-day}}\right)^{-1} \times IR_{ow}\left(100\ \frac{\text{mg}}{\text{day}}\right) \times \left(\frac{10^{-6}\ \text{Kg}}{1\ \text{mg}}\right)}$$

- inhalation of particulates emitted from soil,

$$SL_{w\text{-}sol\text{-}ca\text{-}inh}\,(\text{mg/kg}) = \frac{TR \times AT_{ow}\left(\frac{365\ \text{days}}{\text{year}}\right) \times LT\,(70\ \text{years})}{EF_{ow}\left(250\ \frac{\text{days}}{\text{year}}\right) \times ED_{ow}\,(25\ \text{years}) \times ET_{ws}\left(\frac{8\ \text{hours}}{\text{day}}\right) \times \left(\frac{1\ \text{day}}{24\ \text{hours}}\right) \times IUR\left(\mu\text{g}/\text{m}^3\right)^{-1} \times \left(\frac{1000\ \mu\text{g}}{\text{mg}}\right) \times \left(\frac{1}{VF_s\left(\frac{\text{m}^3}{\text{kg}}\right)} + \frac{1}{PEF_w\left(\frac{\text{m}^3}{\text{kg}}\right)}\right)}$$

- dermal exposure,

$$SL_{w\text{-}sol\text{-}ca\text{-}der}\,(\text{mg/kg}) = \frac{TR \times AT_{ow}\left(\frac{365\ \text{days}}{\text{year}}\right) \times LT\,(70\ \text{years}) \times BW_{ow}\,(70\ \text{Kg})}{EF_{ow}\left(250\ \frac{\text{days}}{\text{year}}\right) \times ED_{ow}\,(25\ \text{years}) \times \left(\frac{CSF_o\left(\frac{\text{mg}}{\text{kg-day}}\right)^{-1}}{GIABS}\right) \times SA_{ow}\left(\frac{3300\ \text{cm}^2}{\text{day}}\right) \times AF_{ow}\left(\frac{0.2\ \text{mg}}{\text{cm}^2}\right) \times ABS_d \times \left(\frac{10^{-6}\ \text{Kg}}{1\ \text{mg}}\right)}$$

- Total.

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

4.3 Indoor Worker Soil

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

4.3.1 Noncancer

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

- incidental ingestion of soil,

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

- inhalation of particulates emitted from soil,

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

- Total.

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

4.3.2 Carcinogenic

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

- incidental ingestion of soil,

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

- inhalation of particulates emitted from soil,

$$SL_{iw\text{-}ca\text{-}inh}\,(mg/kg)=\frac{TR\times AT_{iw}\left(\frac{365\ days}{year}\times LT\ (70\ years)\right)}{EF_{iw}\left(250\ \frac{days}{year}\right)\times ED_{iw}\ (25\ years)\times ET_{ws}\left(\frac{8\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times IUR\left(\mu g/_{m^3}\right)^{-1}\times\left(\frac{1000\ \mu g}{mg}\right)\times\left(\frac{1}{VF_s\left(\frac{m^3}{kg}\right)}+\frac{1}{PEF_w\left(\frac{m^3}{kg}\right)}\right)}$$

- Total.

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

4.4 Tapwater

4.4.1 Noncarcinogenic

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

- ingestion of water,

$$SL_{water\text{-}nc\text{-}ing}\,(\mu g/L)=\frac{THQ\times AT_r\left(\frac{365\ days}{year}\times ED_r\ (30\ years)\right)\times BW_a\ (70\ Kg)\times\left(\frac{1000\ \mu g}{mg}\right)}{EF_r\left(350\ \frac{days}{year}\right)\times ED_r\ (30\ years)\times\frac{1}{RfD_o\left(\frac{mg}{kg\text{-}d}\right)}\times IRW_a\left(\frac{2\ L}{day}\right)}$$

- inhalation of volatiles,

$$SL_{water\text{-}nc\text{-}inh}\,(\mu g/L)=\frac{THQ\times AT_r\left(\frac{365\ days}{year}\times ED_r\ (30\ years)\right)\times\left(\frac{1000\ \mu g}{mg}\right)}{EF_r\left(350\ \frac{days}{year}\right)\times ED_r\ (30\ years)\times ET_{rw}\left(\frac{24\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times\frac{1}{RfC\left(mg/_{m^3}\right)}\times K\left(\frac{0.5\ L}{m^3}\right)}$$

- Total.

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

4.4.2 Carcinogenic

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

- ingestion of water,

$$SL_{water\text{-}ca\text{-}ing}\,(\mu g/L)=\frac{TR\times AT_r\left(\frac{365\ days}{year}\times LT\ (70\ years)\right)\times\left(\frac{1000\ \mu g}{mg}\right)}{EF_r\left(\frac{350\ days}{year}\right)\times CSF_o\left(\frac{mg}{kg\text{-}day}\right)^{-1}\times\left(IFW_{adj}\left(\frac{1.086\ L\text{-}Year}{Kg\text{-}day}\right)\right)}$$

where:

$$IFW_{adj}\left(\frac{1.086\ L\text{-}Year}{Kg\text{-}day}\right)=\frac{ED_c\ (6\ years)\times IRW_c\left(\frac{1\ L}{day}\right)}{BW_c\ (15\ Kg)}+\frac{ED_r\text{-}ED_c\ (24\ years)\times IRW_a\left(\frac{2\ L}{day}\right)}{BW_a\ (70\ Kg)}$$

- inhalation of volatiles,

$$SL_{water\text{-}ca\text{-}inh}\,(\mu g/L)=\frac{TR\times AT_r\left(\frac{365\ days}{year}\times LT\ (70\ years)\right)}{EF_r\left(\frac{350\ days}{year}\right)\times ED_r\ (30\ years)\times ET_{rw}\left(\frac{24\ hours}{day}\right)\times\left(\frac{1\ day}{24\ hours}\right)\times IUR\left(\mu g/_{m^3}\right)^{-1}\times K\left(\frac{0.5\ L}{m^3}\right)}$$

- Total.

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

4.4.3 Mutagenic

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

- ingestion of water,

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

where:

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

- inhalation of volatiles,

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

- Total.

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

4.4.4 Vinyl Chloride - Carcinogenic

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

- ingestion of water,

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

- inhalation of volatiles,

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

- Total.

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

4.5 Resident Ambient Air

4.5.1 Noncarcinogenic

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

- inhalation of volatiles

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

4.5.2 Carcinogenic

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

- inhalation of volatiles

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

4.5.3 Vinyl Chloride - Carcinogenic

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

- inhalation of volatiles

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

4.5.4 Mutagenic

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

- inhalation of volatiles

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

4.6 Worker Ambient Air

4.6.1 Noncarcinogenic

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

- Inhalation of volatiles

$$SL_{\text{w-air-nc}}\left(\mu g/m^3\right)=\frac{THQ\times AT_w\left(\frac{365\text{ days}}{\text{year}}\times ED_r\,(25\text{ years})\right)\times\left(\frac{1000\,\mu g}{mg}\right)}{EF_w\left(\frac{250\text{ days}}{\text{year}}\right)\times ED_w\,(25\text{ years})\times ET_w\left(\frac{8\text{ hr}}{24\text{ hr}}\right)\times\frac{1}{RfC\left(mg/m^3\right)}}$$

4.6.2 Noncarcinogenic

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

- Inhalation of volatiles

$$SL_{\text{w-air-ca}}\left(\mu g/m^3\right)=\frac{TR\times AT_w\left(\frac{365\text{ days}}{\text{year}}\times LT\,(70\text{ years})\right)}{EF_w\left(\frac{250\text{ days}}{\text{year}}\right)\times ED_w\,(25\text{ years})\times ET_w\left(\frac{8\text{ hr}}{24\text{ hr}}\right)\times IUR\left(\mu g/m^3\right)^{-1}}$$

4.7 Ingestion of Fish

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

4.7.1 Noncarcinogenic

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

- consumption of fish.

$$SL_{res\text{-}fsh\text{-}nc\text{-}ing}\,(mg/kg)=\frac{THQ\times AT_r\left(\frac{365\text{ days}}{\text{year}}\times ED_c\,(30\text{ years})\right)\times BW_a\,(70\text{ Kg})}{EF_r\left(\frac{350\text{ days}}{\text{year}}\right)\times ED_c\,(30\text{ year})\times\frac{1}{RfD_o\left(\frac{mg}{Kg\text{-}day}\right)}\times IRF_a\left(\frac{5.4\times10^4\text{ mg}}{\text{day}}\right)\times\frac{10^{-6}Kg}{1mg}}$$

4.7.2 Carcinogenic

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

- consumption of fish.

$$SL_{res\text{-}fsh\text{-}ca\text{-}ing}\,(mg/kg)=\frac{TR\times AT_r\left(\frac{365\text{ days}}{\text{year}}\times LT\,(70\text{ years})\right)\times BW_a\,(70\text{ Kg})}{EF_r\left(\frac{350\text{ days}}{\text{year}}\right)\times ED_c\,(30\text{ year})\times CSF_o\left(\frac{mg}{Kg\text{-}day}\right)^{-1}\times IRF_a\left(\frac{5.4\times10^4\text{ mg}}{\text{day}}\right)\times\frac{10^{-6}Kg}{1\text{ mg}}}$$

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

4.8 Soil to Groundwater

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

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

4.8.1 Noncarcinogenic Tapwater Equations for SSLs

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

4.8.2 Carcinogenic Tapwater Equations for SSLs

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

4.8.3 Method 1 for SSL Determination

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

- method 1.

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

where:

$$\theta_a\left(\frac{L_{air}}{L_{soil}}\right)=n\left(\frac{L_{water}}{L_{soil}}\right)-\theta_w\left(\frac{0.3\,L_{water}}{L_{soil}}\right);$$

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

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

4.8.4 Method 2 for SSL Determination

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

- method 2.

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

4.8.5 Determination of the Dilution Factor

The SSL values in the download tables are based on a dilution factor of 1. The dilution factor default for the calculator is 20 for 0.5 acre source. If all of the parameters needed to calculate a site-specific dilution factor are known, they may be entered.

- dilution factor.

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

where:

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

4.9 Supporting Equations and Parameter Discussion

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

4.9.1 Particulate Emission Factor (PEF)

Inhalation of contaminants adsorbed to respirable particles (PM10) was assessed using a default PEF equal to 1.36 x 10^9 m^3/kg. This equation relates the contaminant concentration in soil with the concentration of respirable particles in the air due to fugitive dust emissions from contaminated soils. The generic PEF was derived using default values that correspond to a receptor point concentration of approximately 0.76 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. Definitions of the input variables are in Table 1.

With the exception of specific heavy metals, the PEF does not appear to significantly affect most soil screening levels. The equation forms the basis for deriving a generic PEF for the inhalation pathway. For more details regarding specific parameters used in the PEF model, refer to Soil Screening Guidance: Technical Background Document. The use of alternate values on a specific site should be justified and presented in an Administrative Record if considered in CERCLA remedy selection.

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

where

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

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

4.9.2 Volatilization Factor (VF)

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

VF is only calculated for volatile organic compounds (VOCs). VOCs, for the purpose of this guidance, are chemicals with a Henry's Law constant of 1 x 10^{-5} atm-m^3/mole or greater and with a molecular weight of less than 200 g/mole.

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

where

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

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

Diffusivity in Water (cm^2/s)

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

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

where

T typically = 25 ^oC

If density is not available,

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

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

Diffusivity in Air (cm^2/s).

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

$$D_{ia}\left(\frac{cm^2}{s}\right)=\frac{0.00229\times\left(T\,^{o}C+273.16\right)^{1.5}\times\sqrt{0.034+\left(\frac{1}{MW\left(\frac{g}{mol}\right)}\right)}\times MW_{cor}}{\left(\left(\frac{MW\left(\frac{g}{mol}\right)}{2.5\times\rho\left(\frac{g}{cm^3}\right)}\right)^{0.333}+1.8\right)^{2}}$$

where

T typically = 25 ^{o}C

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

If density is not available,

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

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

5. Special Considerations

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

5.1 Cadmium

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

5.2 Lead

Residential SLs for Lead are derived based on pharmacokinetic models. EPA’s Integrated Exposure Uptake Biokinetic (IEUBK) model is 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 SLs that are considered "protective" or "acceptable" by EPA.

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

For more information on EPA’s lead models and other lead-related topics, please go to:
http://www.epa.gov/oerrpage/superfund/health/contaminants/lead/index.htm

5.3 Manganese

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

5.4 Vanadium and Thallium Compounds

The oral RfD for Thallium, used in this website, is derived from the IRIS oral RfD for Thallium Sulfate by factoring out the molecular weight (MW) of the sulfate ion. Thallium Sulfate (Tl_2S0_4) has a molecular weight of 504.82. The two atoms of Thallium contribute 81% of the MW. Thallium Sulfate's oral RfD of 8E-05 multiplied by 81% gives a Thallium oral RfD of 6.48E-05.

The oral RfD toxicity value for Vanadium, used in this website, is derived from the IRIS oral RfD for Vanadium Pentoxide by factoring out the molecular weight

(MW) of the oxide ion. Vanadium Pentoxide (V_20_5) has a molecular weight of 181.88. The two atoms of Vanadium contribute 56% of the MW. Vanadium Pentoxide's oral RfD of 9E-03 multiplied by 56% gives a Vanadium oral RfD of 5.04E-03.

5.5 Uranium

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

5.6 Aminodinitrotoluenes

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

5.7 PCBs

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

5.8 Soil Saturation Limit (C_{sat})

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

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

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

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

where

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

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

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

5.9 SL Theoretical Ceiling Limit

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

5.10 Target Risk

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

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

Some users of this SL Table may plan to multiply the cancer SL concentrations by 10 or 100 to set 'action levels' for triggering remediation or to set less stringent cleanup levels for a specific site after considering non-risk-based factors such as ambient levels, detection limits, or technological feasibility. This risk management practice recognizes that there may be a range of values that may be 'acceptable' for carcinogenic risk (EPA's risk management range is one-in-a-million [10^{-6}] to one-in-ten thousand [10^{-4}]). However, this practice could lead one to overlook serious noncancer health threats and it is strongly recommended that the user consult with a toxicologist or regional risk assessor before doing this. Carcinogens are indicated by an asterisk ('*') in the SL Table where the noncancer SLs would be exceeded if the cancer value that is displayed is multiplied by 100. ('**') indicate that the noncancer values would be exceeded if the cancer SL were multiplied by 10. There is no range of 'acceptable' noncarcinogenic 'risk' for CERCLA sites. Therefore, the noncancer SLs should not be multiplied by 10 or 100 when setting final cleanup criteria. In the rare case where noncancer SLs are more stringent than cancer SLs set at one-in-one-million risk, a similar approach has been applied (e.g. 'max').

SL concentrations in the printed Table are risk-based, but for soil there are two important exceptions: (1) for several volatile chemicals, SLs may exceed the soil saturation level ('sat') and (2) SLs may exceed a non-risk based 'ceiling limit' concentration of 10^{+5} mg/kg ('max') for relatively less toxic inorganic and semivolatile contaminants. For more information on the 'sat' value in the SL Table, please see the discussion in Section 5.8. For more information on the 'max' value in the SL Table, please see the discussion in Section 5.9.

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

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

- Risk-based SLs for some chemicals in soil exceed unity (>1,000,000 mg/kg), which is not possible.
- The ceiling limit of 10^{+5} mg/kg is equivalent to a chemical representing 10% by weight of the soil sample. At this contaminant concentration (and higher), the assumptions for soil contact may be violated (for example, soil adherence and wind-borne dispersion assumptions) due to the presence of the foreign substance itself.
- SLs currently do not address short-term exposures (e.g., pica children and construction workers). Although extremely high soil SLs are likely to represent relatively non-toxic chemicals, such high values may not be justified if in fact more toxicological data were available for evaluating short-term and/or acute exposures.

5.11 Screening Sites with Multiple Contaminants

Since the screening levels in the tables are contaminant specific, users needing to screen sites with multiple contaminants, especially sites with multiple contaminants affecting the same target organ, may wish to use this website's calculator. User's are encouraged to consult with risk assessors in that EPA Regional Office when evaluating or screening contamination at a site with multiple contaminants.

5.12 Deriving Soil Gas SLs

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

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

Table 1. Standard Default Factors

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

$SL_{water-mu-inh}$	Resident Tapwater Groundwater Mutagenic Inhalation (ug/L)	Mutagen-specific	Determined in this calculator
$SL_{water-mu-tot}$	Resident Tapwater Groundwater Mutagenic Total (ug/L)	Contaminant-specific	Determined in this calculator
$SL_{water-nc-ing}$	Resident Tapwater Groundwater Noncarcinogenic Ingestion (ug/L)	Contaminant-specific	Determined in this calculator
$SL_{water-nc-inh}$	Resident Tapwater Groundwater Noncarcinogenic Inhalation (ug/L)	Mutagen-specific	Determined in this calculator
$SL_{water-nc-tot}$	Resident Tapwater Groundwater Noncarcinogenic Total (ug/L)	Contaminant-specific	Determined in this calculator
$SL_{res-sol-ca-ing}$	Resident Soil Carcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{res-sol-ca-der}$	Resident Soil Carcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{res-sol-ca-inh}$	Resident Soil Carcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{res-sol-ca-tot}$	Resident Soil Carcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{res-soil-ca-vc-ing}$	Resident Soil Carcinogenic Vinyl Chloride Ingestion (mg/kg)	Vinyl Chloride -specific	Determined in this calculator
$SL_{res-soil-ca-vc-der}$	Resident Soil Carcinogenic Vinyl Chloride Dermal (mg/kg)	Vinyl Chloride-specific	Determined in this calculator
$SL_{res-soil-ca-vc-inh}$	Resident Soil Carcinogenic Vinyl Chloride Inhalation (mg/kg)	Vinyl Chloride-specific	Determined in this calculator
$SL_{res-soil-ca-vc-tot}$	Resident Soil Carcinogenic Vinyl Chloride Total (mg/kg)	Vinyl Chloride-specific	Determined in this calculator
$SL_{res-sol-mu-ing}$	Resident Soil Mutagenic Ingestion (mg/kg)	Mutagen-specific	Determined in this calculator
$SL_{res-sol-mu-der}$	Resident Soil Mutagenic Dermal (mg/kg)	Mutagen-specific	Determined in this calculator
$SL_{res-sol-mu-inh}$	Resident Soil Mutagenic Inhalation (mg/kg)	Mutagen-specific	Determined in this calculator
$SL_{res-sol-mu-tot}$	Resident Soil Mutagenic Total (mg/kg)	Mutagen-specific	Determined in this calculator
$SL_{res-sol-nc-ing}$	Resident Soil Noncarcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{res-sol-nc-der}$	Resident Soil Noncarcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{res-sol-nc-inh}$	Resident Soil Noncarcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{res-sol-nc-tot}$	Resident Soil Noncarcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-ca-ing}$	Worker Soil Carcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-ca-der}$	Worker Soil Carcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-ca-inh}$	Worker Soil Carcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-ca-tot}$	Worker Soil Carcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-nc-ing}$	Worker Soil Noncarcinogenic Ingestion (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-nc-der}$	Worker Soil Noncarcinogenic Dermal (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-nc-inh}$	Worker Soil Noncarcinogenic Inhalation (mg/kg)	Contaminant-specific	Determined in this calculator
$SL_{w-sol-nc-tot}$	Worker Soil Noncarcinogenic Total (mg/kg)	Contaminant-specific	Determined in this calculator
Toxicity Values			
RfD_o	Chronic Oral Reference Dose (mg/kg-day)	Contaminant-specific	EPA Superfund hierarchy
RfC	Chronic Inhalation Reference Concentration (mg/m^3)	Contaminant-specific	EPA Superfund hierarchy
CSF_o	Chronic oral Slope Factor (mg/kg-day)$^{-1}$	Contaminant-specific	EPA Superfund hierarchy
IUR	Chronic Inhalation Unit Risk (ug/m^3)$^{-1}$	Contaminant-specific	EPA Superfund hierarchy
Miscellaneous Variables			
TR	target risk	1×10^{-6}	Determined in this calculator
THQ	target hazard quotient	1	Determined in this calculator
K	Andelman Volatilization Factor (L/m^3)	0.5	U.S. EPA 1991b (pg. 20)
AT_r	Averaging time - resident (days/year)	365	U.S. EPA 1989 (pg. 6-23)
AT_{ow}	Averaging time - worker (days/year)	365	U.S. EPA 1989 (pg. 6-23)
LT	Lifetime (years)	70	U.S. EPA 1989 (pg. 6-22)
Ingestion, and Dermal Contact Rates			
IRW_c	Drinking Water Ingestion Rate - Child (L/day)	1	
IRW_a	Drinking Water Ingestion Rate - Adult (L/day)	2	U.S. EPA 1989 (Exhibit 6-11)
IFW_{adj}	Drinking Water Ingestion Rate - Age-adjusted (L-year/kg-day)	2	Calculated using the aged adjusted intake factors equation
	Mutagenic Drinking Water Ingestion Rate - Age-		Calculated using the aged adjusted

$IFWM_{adj}$	adjusted (L-year/kg-day)	3.39	intake factors equation
IRS_c	Resident Soil Ingestion Rate - Child (mg/day)	200	U.S. EPA 1991a (pg. 15)
IRS_a	Resident Soil Ingestion Rate - Adult (mg/day)	100	U.S. EPA 1991a (pg. 15)
IFS_{adj}	Resident Soil Ingestion Rate - Age-adjusted (mg-year/kg-day)	114	Calculated using the aged adjusted intake factors equation
$IFSM_{adj}$	Mutagenic Resident Soil Ingestion Rate - Age-adjusted (mg-year/kg-day)	489.5	Calculated using the aged adjusted intake factors equation
IRF_a	Fish Ingestion Rate (mg/day)	5.4×10^4	U.S. EPA 1991a (pg. 15)
SA_c	Resident soil surface area - child (cm^2)	2800	U.S. EPA 2002 (Exhibit 1-2)
SA_a	Resident soil surface area - adult (cm^2)	5700	U.S. EPA 2002 (Exhibit 1-2)
AF_c	Resident soil adherence factor-child (mg/cm^2)	0.2	U.S. EPA 2002 (Exhibit 1-2)
AF_a	Resident soil adherence factor-adult (mg/cm^2)	0.07	U.S. EPA 2002 (Exhibit 1-2)
DFS_{adj}	Resident soil dermal contact factor- age-adjusted (mg-year/kg-day)	361	Calculated using the aged adjusted intake factors equation
$DFSM_{adj}$	Mutagenic Resident soil dermal contact factor- age-adjusted (mg-year/kg-day)	1445	Calculated using the aged adjusted intake factors equation
SA_{ow}	Worker soil surface area - adult (cm^2)	3300	U.S. EPA 2002 (Exhibit 1-2)
AF_{ow}	Worker soil adherence factor-child (mg/cm^2)	0.2	U.S. EPA 2002 (Exhibit 1-2)
ABS	Fraction of contaminant absorbed dermally from soil (unitless)	Contaminant-specific	U.S. EPA 2004 (Exhibit 3-4)
GIABS	Fraction of contaminant absorbed in gastrointestinal tract (unitless) Note: if the GIABS is >50% then it is set to 100% for the calculation of dermal toxicity values.	Contaminant-specific	U.S. EPA 2004 (Exhibit 4-1)
Exposure Frequency, Exposure Duration, and Exposure Time Variables			
EF_r	Exposure Frequency - residential (days/yr)	350	U.S. EPA 1991a (pg. 15)
EF_{ow}	Exposure Frequency - worker (days/yr)	250	U.S. EPA 1991a (pg. 15)
ED_r	Exposure Duration - resident (yr)	30	U.S. EPA 1991a (pg. 15)
ED_c	Exposure Duration -child resident (yr)	6	U.S. EPA 1991a (pg. 15)
ED_{ow}	Exposure Duration - worker (yr)	25	U.S. EPA 1991a (pg. 15)
ET ra	Exposure Time - resident air (hr/hr)	1	24 hrs per 24 hr Day
Soil to Groundwater SSL Factor Variables			
I	Infiltration Rate (m/year)	0.18	U.S. EPA. 1996a (pg. 31)
L	source length parallel to ground water flow (m)	400	U.S. EPA. 1996a (pg. 31
i	hydraulic gradient (m/m)	1.2	U.S. EPA. 1996a (pg. 31
K	aquifer hydraulic conductivity (m/year)	40	U.S. EPA. 1996a (pg. 31
θ_w	water-filled soil porosity (L_{water}/L_{soil})	0.3	U.S. EPA. 1996a (pg. 31
θ_a	air-filled soil porosity (L_{air}/L_{soil})	$= n- \theta_w$	U.S. EPA. 1996a (pg. 31
n	total soil porosity(L_{pore}/L_{soil})	$= 1-(\rho_b/\rho_s)$	U.S. EPA. 1996a (pg. 31
ρ_s	soil particle density (Kg/L)	2.65	U.S. EPA. 1996a (pg. 31
ρ_b	dry soil bulk density (kg/L)	1.5	U.S. EPA. 1996a (pg. 31
H'	Dimensionless Henry Law Constant (unitless)	analyte-specific	U.S. EPA. 1996a (pg. 31
K_d	soil-water partition coefficient (L/kg)	$= K_{oc}*f_{oc}$ for organics	U.S. EPA. 1996a (pg. 31
K_{oc}	soil organic carbon/water partition coefficient (L/kg)	analyte-specific	U.S. EPA. 1996a (pg. 31
f_{oc}	fraction organic carbon in soil (g/g)	0.002	U.S. EPA. 1996a (pg. 31
d_a	aquifer thickness (m)	12	U.S. EPA. 1996a (pg. 31
d_s	depth of source (m)	2	U.S. EPA. 1996a (pg. 31
d	mixing zone depth (m)	calculated	U.S. EPA. 1996a (pg. 31
Particulate Emission Factor Variables			
PEF	Particulate Emission Factor - Minneapolis (m^3/kg)	1.36×10^9(region-specific)	Determined in this calculator
Q/C	Inverse of the Mean Concentration at the Center of a 0.5-Acre-Square Source (g/m^2-s per kg/m^3)	93.77 (region-specific)	Determined in this calculator
V	Fraction of Vegetative Cover (unitless)	0.5	U.S. EPA 1996a (pg. 23)
U_m	Mean Annual Wind Speed (m/s)	4.69	U.S. EPA 1996a (pg. 23)
U_t	Equivalent Threshold Value of Wind Speed at 7m	11.32	U.S. EPA 1996a (pg. 23)

	(m/s)		
F(x)	Function Dependent on U_m/U_t (unitless)	0.194	U.S. EPA 1996a (pg. 23)
A	Dispersion constant unitless	PEF and region-specific	U.S. EPA 2002 (pg. D-6 to D-8)
A_s	Areal extent of the site or contamination (acres)	0.5 (range 0.5 to 500)	U.S. EPA 2002 (pg. D-2)
B	Dispersion constant unitless	PEF and region-specific	U.S. EPA 2002 (pg. D-6 to D-8)
C	Dispersion constant unitless	PEF and region-specific	U.S. EPA 2002 (pg. D-6 to D-8)
Volatilization Factor and Soil Saturation Limit Variables			
VF	Volatilization Factor - Los Angeles (m^3/kg)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
Q/C_w	Inverse of the Mean Concentration at the Center of a 0.5-Acre-Square Source (g/m^2-s per kg/m^3)	68.81	U.S. EPA. 1996b (pg. 24)
D_A	Apparent Diffusivity (cm^2/s)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
T	Exposure interval (s)	9.5×10^8	U.S. EPA. 1996b (pg. 24)
ρ_b	Dry soil bulk density (g/cm^3)	1.5	U.S. EPA. 1996b (pg. 24)
θ_a	Air-filled soil porosity (L_{air}/L_{soil}) ($n-\theta_w$)	0.28	U.S. EPA. 1996b (pg. 24)
n	Total soil porosity (L_{pore}/L_{soil}) $(1-(\rho_b/\rho_s)$	0.43	U.S. EPA. 1996b (pg. 24)
θ_w	Water-filled soil porosity (L_{water}/L_{soil})	0.15	U.S. EPA. 1996b (pg. 24)
ρ_s	Soil particle density (g/cm^3)	2.65	U.S. EPA. 1996b (pg. 24)
S	Water Solubility Limit (mg/L)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
D_{ia}	Diffusivity in air (cm^2/s)	Contaminant-specific	U.S. EPA. 2001
H'	Dimensionless Henry's Law Constant	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
D_{iw}	Diffusivity in water (cm^2/s)	Contaminant-specific	U.S. EPA. 2001
K_d	Soil-water partition coefficient (L/Kg) ($K_{oc} \times f_{oc}$)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
K_{oc}	Soil organic carbon-water partition coefficient (L/Kg)	Contaminant-specific	U.S. EPA. 1996b (pg. 24)
f_{oc}	Organic carbon content of soil (g/g)	0.006	U.S. EPA. 1996b (pg. 24)

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APPENDIX 3

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

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

USER'S GUIDE FOR
EVALUATING SUBSURFACE VAPOR INTRUSION
INTO BUILDINGS

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DISCLAIMER

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

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ACKNOWLEDGMENT

Environmental Quality Management, Inc. (EQ) via Industrial Economics Incorporated (IEC) Subcontract No. 3073-002 prepared this document and the accompanying spreadsheets for the U.S. Environmental Protection Agency (EPA). Mr. Tom Robertson (EQ Project Manager) and Mr. Henry Roman (IEC Project Manager) managed the project. The work was completed on behalf of the U.S. EPA Office of Solid Waste. Ms. Janine Dinan was the government's Project Manager.

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WHAT'S NEW IN THIS VERSION!

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

1. Table 1 lists the chemicals that are commonly found at contaminated sites. This list has been expanded from the list of chemicals included in Version 2 of the model. We have also applied certain criteria to determine whether it is appropriate to run the model for these contaminants. Only those contaminants for which all of the toxicological or physical chemical properties needed to make an assessment of the indoor inhalation risk are included in the spreadsheets. A chemical is considered to be sufficiently toxic if the vapor concentration of the pure component poses an incremental life time cancer risk greater than 1 x 10^{-6} or the noncancer hazard index is greater than 1. A chemical is considered to be sufficiently volatile if its Henry's law constant is 1 x 10^{-5} atm-m^3/mole or greater. The final chemical list for Version 3 includes 108 chemicals.

2. **Chemical Property Data** - The source of chemical data used in the calculation is primarily EPA's Superfund Chemical Data Matrix (SCDM) database. EPA's WATER9 database is used for chemicals not included in the SCDM database. Appendix B contains other data sources. Henry's Law value for cumene is incorrect in the above listed reference. The correct value was determined by using EPA's system performs automated reasoning in chemistry algorithms found in "Prediction of Chemical Reactivity Parameters and Physical Properties of Organic Compounds from Molecular Structure Using SPARE." EPA-2003.

3. **Toxicity Values –** EPA's Integrated Risk Information System (IRIS) is the generally preferred source of carcinogenic unit risks and non-carcinogenic reference concentrations (RfCs) for inhalation exposure.[1] The following two sources were consulted, in order of preference, when IRIS values were not available: provisional toxicity values recommended by EPA's National Center for Environmental Assessment (NCEA) and EPA's Health Effects Assessment Summary Tables (HEAST). If no inhalation toxicity data could be obtained from IRIS, NCEA, or HEAST, extrapolated unit risks and/or RfCs using toxicity data for oral exposure (cancer slope factors and/or reference doses, respectively) from these same sources

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

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

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

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

4. Assumption and Limitations

The Johnson and Ettinger (J&E) Model was developed for use as a screening level model and, consequently, is based on a number of simplifying assumptions regarding contaminant distribution and occurrence, subsurface characteristics, transport mechanisms, and building construction. The assumptions of the J&E Model as implemented in EPA's spreadsheet version are listed in Section 2.11, Section 5, and

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[2] The oral-to-inhalation extrapolations assume an adult inhalation rate (IR) of 20 m^3/day and an adult body weight (BW) of 70 kg. Unit risks (URs) were extrapolated from cancer slope factors (CSFs) using the following equation:

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

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

$$\text{RfC } (mg/m^3) = \text{RfD } (mg/kg/d) * (1/IR)\ (m3/d)^{-1}\ (\ BW\ (kg)$$

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

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

5. Soil Parameters

A list of generally reasonable, yet conservative, model input parameters for selected soil and sampling related parameters are provided in Tables 7 and 8. These tables also provide the practical range, typical or mean value (if applicable), and most conservative value for these parameters. For building parameters with low uncertainty and sensitivity, only a single “fixed” value corresponding to the mean or typical value is provided in Table 9. Soil-dependent properties are provided in Table 10 for soils classified according to the US Soil Conservation Soil (SCS) system. If site soils are not classified according to the US SCS, Table 11 can be used to assist in selecting an appropriate SCS soil type corresponding to the available site lithologic information. Note that the selection of the soil texture class should be biased towards the coarsest soil type of significance, as determined by the site characterization program. These input parameters were developed considering soil-physics science, available studies of building characteristics, and expert opinion. Consequently, the input parameters listed in Tables 7 and 8 are considered default parameters for a first-tier assessment, which should in most cases provide a reasonably (but not overly) conservative estimate of the vapor intrusion attenuation factor for a site. The soil water filled porosity (θ_w) is dependent on the soil type and the default value was removed from the model set up. Users must define soil type or input a value for the porosity.

6. Building Parameters

Building Air Exchange Rate (Default Value = 0.25 hr^{-1})

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

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

A Michigan study indicates that a 111.5 m^2 area approximately corresponds to the 10th percentile floor space area for residential single family dwellings, based on statistics compiled by the U.S. Department of Commerce (DOC) and U.S. Housing and Urban Development (HUD). The previous median value was 9.61 m x 9.61 m.

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

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

There are little data available that provide for direct inference of mixing height. There are few sites, with a small number of houses where indoor air concentrations were above background, and where both measurements at ground level and the second floor were made (CDOT, Redfields, Eau Claire). Persons familiar with the data sets for these sites indicate that in most cases a fairly significant reduction in concentrations (factor of two or greater) was observed, although at one site (Eau Claire, "S” residence), the indoor TCE concentrations were similar in both the basement and second floor of the house. For the CDOT site apartments, there was an approximate five-fold reduction between the concentrations measured for the first floor and second floor units. Less mixing would be expected for an apartment because there are less cross-floor connections than for a house. The default value chosen for a basement house scenario (3.66 m) would be representative of a two-fold reduction or attenuation in vapor concentrations between floors.

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

The crack width and crack ratio are related. Assuming a square house and that the only crack is a continuous edge crack between the foundation slab and wall (“perimeter crack”), the crack ratio and crack width are related as follows:

$$Crack\,Ratio = \frac{4(CrackWidth / \sqrt{Subsurface\,Foundation\,Area}}{Subsurface\,Foundation\,Area}$$

There is little information available on crack width or crack ratio. One approach used by radon researchers is to back calculate crack ratios using a model for soil gas flow through cracks and the results of measured soil gas flow rates into a building. For example, the back-calculated values for a slab/wall edge crack based on soil gas-entry rates reported in Nazaroff (1992), Revzan et al. (1991), and Nazaroff et al. (1985) range from approximately 0.0001 to 0.001. Another possible approach is to measure crack openings although this, in practice, is difficult to do. Figley and Snodgrass (1992) present data from ten houses where edge crack measurements were made. At the eight houses where cracks were observed, the cracks' widths ranged from hairline cracks up to 5 mm wide, while the total crack length per house ranged from 2.5 m to 17.3 m. Most crack widths were less than 1 mm. The suggested defaults for crack ratio is regulatory guidance, literature and models also vary. In ASTM E1739-95, a default crack ratio of 0.01 is used. The crack ratios suggested in the VOLASOIL model (developed by the Dutch Ministry of Environment) range from 0.0001 to 0.0000001. The VOLASOIL model values correspond to values for a "good" and "bad" foundation, respectively. The crack ratio used by J&E (1991) for illustrative purposes ranged from 0.001 to 0.01. The selected default values fall within the ranges observed.

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

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

An alternate empirical approach was selected to determine the Q_{soil} value. This new approach is based on trace tests (i.e., mass balance approach). When soil gas advection is the primary mechanism for tracer intrusion into a building, the Q_{soil} value is estimated by measuring the concentrations of a chemical tracer in indoor air, outdoor air, and in soil vapor below a building, and measuring the building ventilation rate (Hers et al. 2000a; Fischer et al. 1996; Garbesi et al. 1993; Rezvan et al. 1991; Barbesi and Sectro 1989). The Q_{soil} values measured using this technique were compared to predicted rates using the Perimeter Crack model, for sites with coarse-grained soils. The Perimeter Crack model predictions are both higher and lower than the measured values, but overall are within one order of magnitude of the measured values. Although the Q_{soil} predicted by the models and measured using field tracer tests are uncertain, the results suggest that a "typical" range for houses on coarse-grained soils is on the order of 1 to 10 L/min. A disadvantage with the tracer test approach is that there are only limited data, and there do not appear to be any tracer studies for field sites with fine-grained soils.

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

7. Convenience Changes

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

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

SECTION 1

INTRODUCTION TO THE VAPOR INTRUSION MODEL THEORY AND APPLICATION

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

Johnson and Ettinger (J&E) (1991) introduced a screening-level model that incorporates both convective and diffusive mechanisms for estimating the transport of contaminant vapors emanating from either subsurface soils or groundwater into indoor spaces located directly above the source of contamination. In their article, J&E reported that the results of the model were in qualitative agreement with published experimental case histories and in good qualitative and quantitative agreement with detailed three-dimensional numerical modeling of radon transport into houses.

The J&E Model is a one-dimensional analytical solution to convective and diffusive vapor transport into indoor spaces and provides an estimated attenuation coefficient that relates the vapor concentration in the indoor space to the vapor concentration at the source of contamination. The model is constructed as both a steady-state solution to vapor transport (infinite or non-diminishing source) and as a quasi-steady-state solution (finite or diminishing source). Inputs to the model include chemical properties of the contaminant, saturated and unsaturated zone soil properties, and structural properties of the building.

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

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

The infinite source models for soil contamination and groundwater contamination should be used as first-tier screening tools. In these models, all but the most sensitive model parameters have been set equal to central tendency or upper bound values. Values for the most sensitive parameters may be user-defined.

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

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

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

SECTION 2

MODEL THEORY

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

2.1 MODEL SETTING

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

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

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

The suggested minimum site characterization information for a first-tier evaluation of the vapor intrusion pathway includes: site conceptual model, nature and extent of contamination distribution, soil lithologic descriptions, groundwater concentrations, and/or possibly near source soil vapor concentrations. The number of samples and measurements needed to establish this information varies by site, and it is not possible to provide a hard and fast rule.

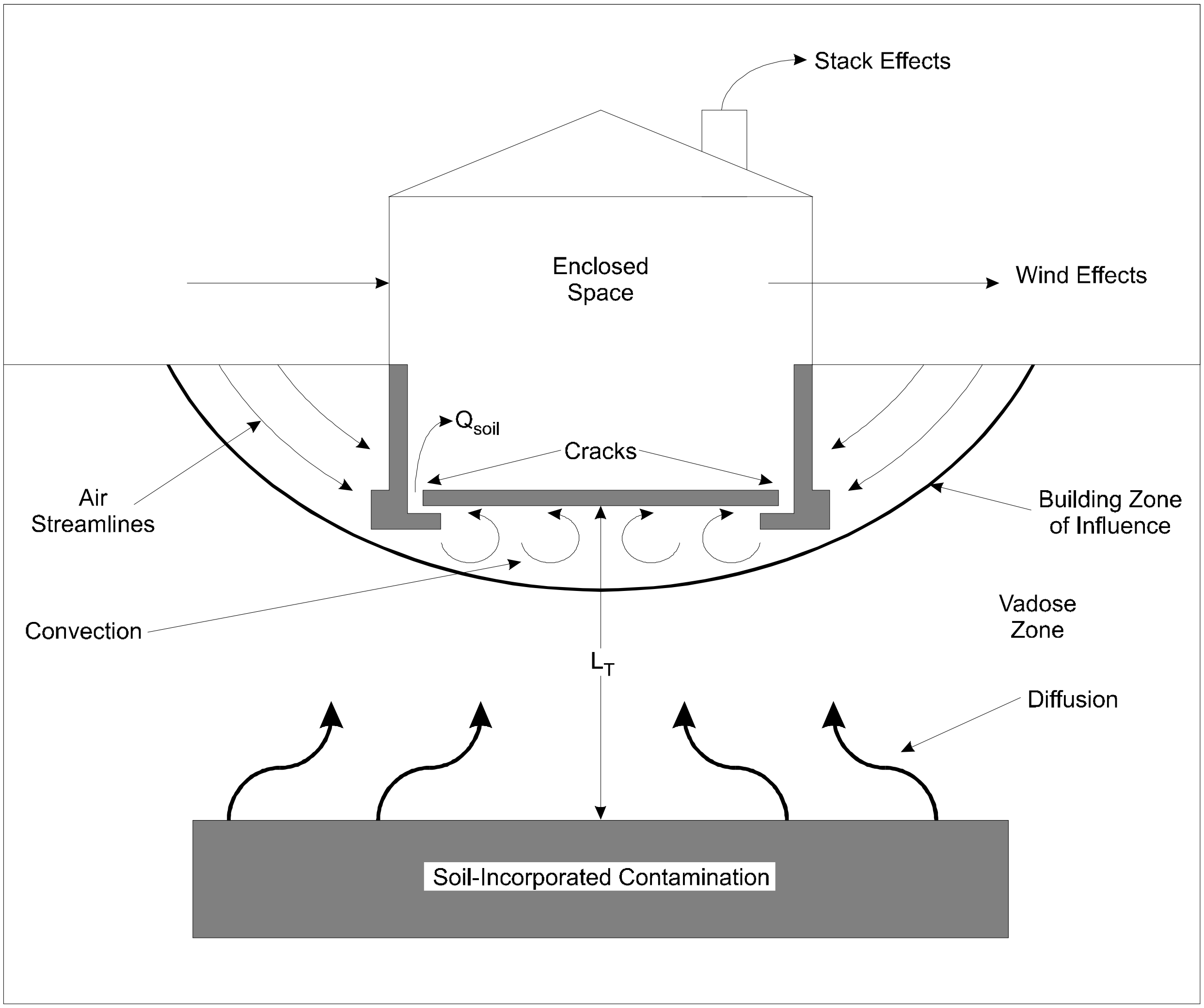


Figure 1. Pathway for Subsurface Vapor Intrusion into Indoor Air

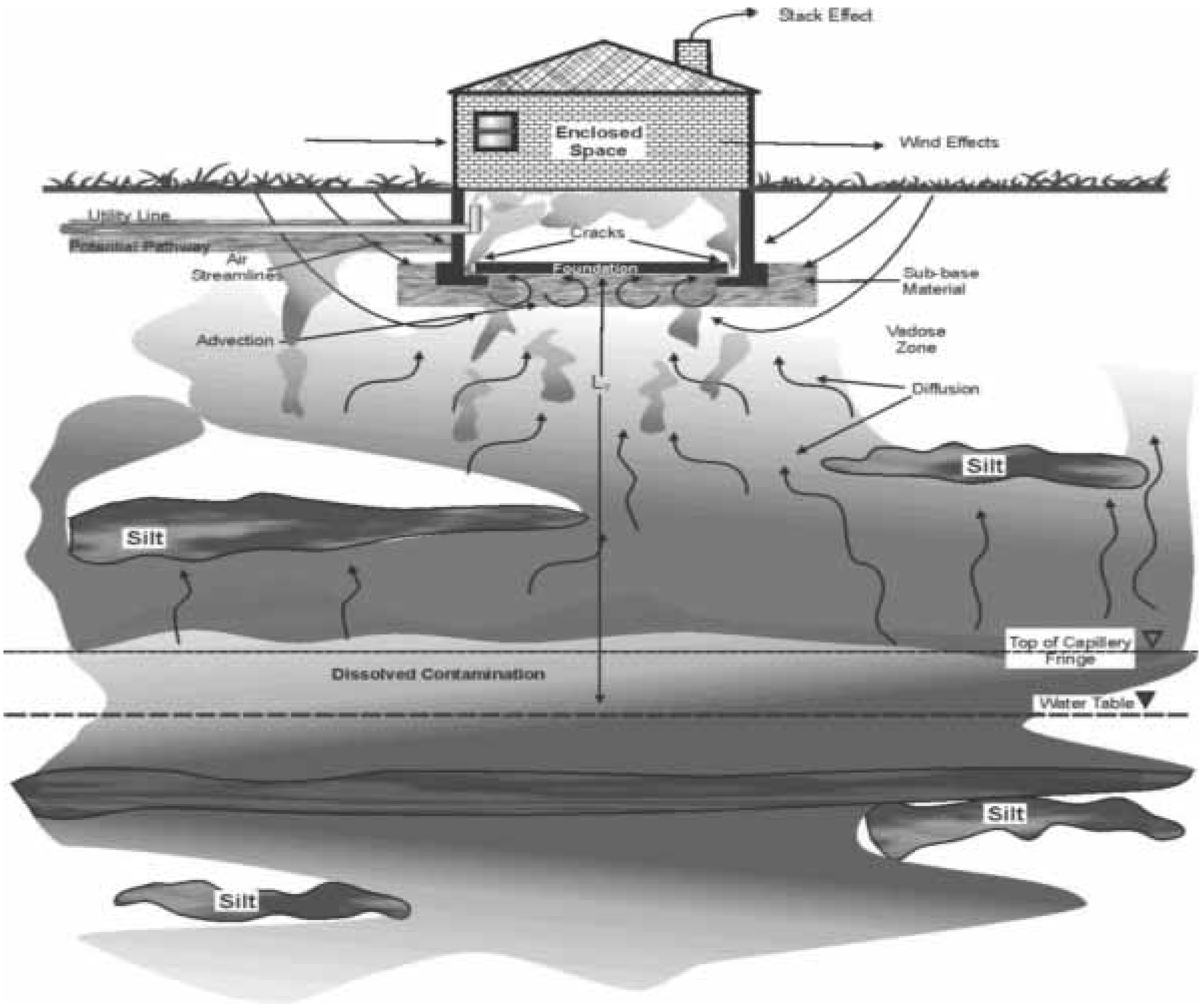


Figure 2. Vapor Pathway into Buildings

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

Table 1 lists 114 chemicals that may be found at hazardous waste sites and it indicates whether the chemical is sufficiently toxic and volatile to result in a potentially unacceptable indoor inhalation risk. It also provides a column for checking off the chemicals found or reasonably suspected to be present in the subsurface at a site. Under this approach, a chemical is considered sufficiently toxic if the vapor concentration of the pure component poses an incremental lifetime cancer risk greater than 10^{-6} or results in a non-cancer hazard index greater than one. A chemical is considered sufficiently volatile if its Henry's Law Constant is 1×10^{-5} atm-m^3/mol or greater (EPA, 1991). It is assumed that if a chemical does not meet both of these criteria, it need not be further considered as part of the evaluation. Table 1 also identifies six chemicals that meet the toxicity and volatility criteria but are not included in the vapor intrusion models because one or more of the needed physical or chemical properties has not been found in the literature.

The rate of soil gas entry (Q_{soil}) or average vapor flow rate into the building is a function solely of convection; however, the vapor concentration entering the structure may be limited by either convection or diffusion depending upon the magnitude of the source-building separation (L_T).

2.2 VAPOR CONCENTRATION AT THE SOURCE OF CONTAMAINATION

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

TABLE 1. SCREENING LIST OF CHEMICALS

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

(continued)

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

(continued)

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

(continued)

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

(continued)

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

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

[2] A chemical is considered sufficiently volatile if its Henry's law constant is 1×10^{-5} atm-m^3/mol or greater.

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

C_R = Initial soil concentration, g/g

ρ_b = Soil dry bulk density, g/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.

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

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

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

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:

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

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 (= 8.205 E-05 atm-m^3/mol-°K).

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

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

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

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

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

2.3 DIFFUSION THROUGH THE CAPILLARY ZONE

Directly above the water table, a saturated capillary zone exists whereby groundwater is held within the soil pores at less than atmospheric pressure (Freeze and Cherry, 1979). Between drainage and wetting conditions, the saturated water content varies but is always less than the fully saturated water content which is equal to the soil total porosity. This is the result of air entrapment in the pores during the wetting process (Gillham, 1984). Upon rewetting, the air content of the capillary zone will be higher than after main drainage. Therefore, the air content will vary as a function of groundwater recharge and discharge. At the saturated water content, Freijer (1994) found that the relative vapor-phase diffusion coefficient was almost zero. This implies that all remaining air-filled soil pores are disconnected and thus blocked for gas diffusion. As the air-filled porosity increased, however, the relative diffusion coefficient indicated the presence of connected air-filled pores that corresponded to the air-entry pressure head. The air-entry pressure head corresponds with the top of the saturated capillary zone. Therefore, to allow for the calculation of the effective diffusion coefficient by lumping the gas-phase and aqueous-phase together, the water-filled soil porosity in the capillary zone ($\theta_{w,cz}$) is calculated at the air-entry pressure head (h) according to the procedures of Waitz et al. (1996) and the van Genuchten equation (van Genuchten, 1980) for the water retention curve:

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

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_1 = Point of inflection in the water retention curve where d θ_w/dh is maximal, cm^{-1}

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

N = van Genuchten curve shape parameter, dimensionless

M = 1 - (1/N).

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

Hers (2002) computed the SCS class average values of the water filled porosity and the height of the capillary zone SCS soil textural classifications. Table 3 provides the class average values for each of the SCS soil types. These data replace the mean values developed by Schaap and

Leij (1998) included in the previous U.S. Environmental Protection Agency (EPA) version of the J&E Models. With the class average values presented in Table 3, a general estimate can be made of the values of $\theta_{w,cz}$ and $\theta_{a,cz}$ for each soil textural classification.

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

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

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:

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

where E = Rate of mass transfer, g/s

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

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

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

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

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

TABLE 3. CLASS AVERAGE VALUES OF THE VAN GENUCHTEN SOIL WATER RETENTION PARAMETERS FOR THE 12 SCS SOIL TEXTURAL CLASSIFICATIONS

Soil texture (USDA)	Saturated water content, θ_s	Residual water Content, θ_r	van Genuchten parameters		
			α_1 (1/cm)	N	M
Clay	0.459	0.098	0.01496	1.253	0.2019
Clay loam	0.442	0.079	0.01581	1.416	0.2938
Loam	0.399	0.061	0.01112	1.472	0.3207
Loamy sand	0.390	0.049	0.03475	1.746	0.4273
Silt	0.489	0.050	0.00658	1.679	0.4044
Silty loam	0.439	0.065	0.00506	1.663	0.3987
Silty clay	0.481	0.111	0.01622	1.321	0.2430
Silty clay loam	0.482	0.090	0.00839	1.521	0.3425
Sand	0.375	0.053	0.03524	3.177	0.6852
Sandy clay	0.385	0.117	0.03342	1.208	0.1722
Sandy clay loam	0.384	0.063	0.02109	1.330	0.2481
Sandy loam	0.387	0.039	0.02667	1.449	0.3099

The value of C_{source} is calculated using Equation 2; the value of A is assumed to be 1 cm^2; and the value of D_{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 capillary such that water molecules are subject to an upward attractive force due to surface tension at the air-water interface and the molecular attraction of the liquid and solid phases. The rise of the capillary zone can thus be estimated using the equation for the height of capillary rise in a bundle of tubes of various diameters equivalent to the diameters between varying soil grain sizes. Fetter (1994) estimated the mean rise of the capillary zone as:

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

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

α_2 = Surface tension of water, g/s (= 73)

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

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

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

R = Mean interparticle pore radius, cm

and;

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

where R = Mean interparticle pore radius, cm

D = Mean particle diameter, cm.

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

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

Nielson and Rogers (1990) estimated the arithmetic mean particle diameter for each of the 12 SCS soil textural classifications at the mathematical centroid calculated from its classification area (Figure 3). Table 4 shows the centroid compositions and mean particle sizes of the 12 SCS soil textural classes.

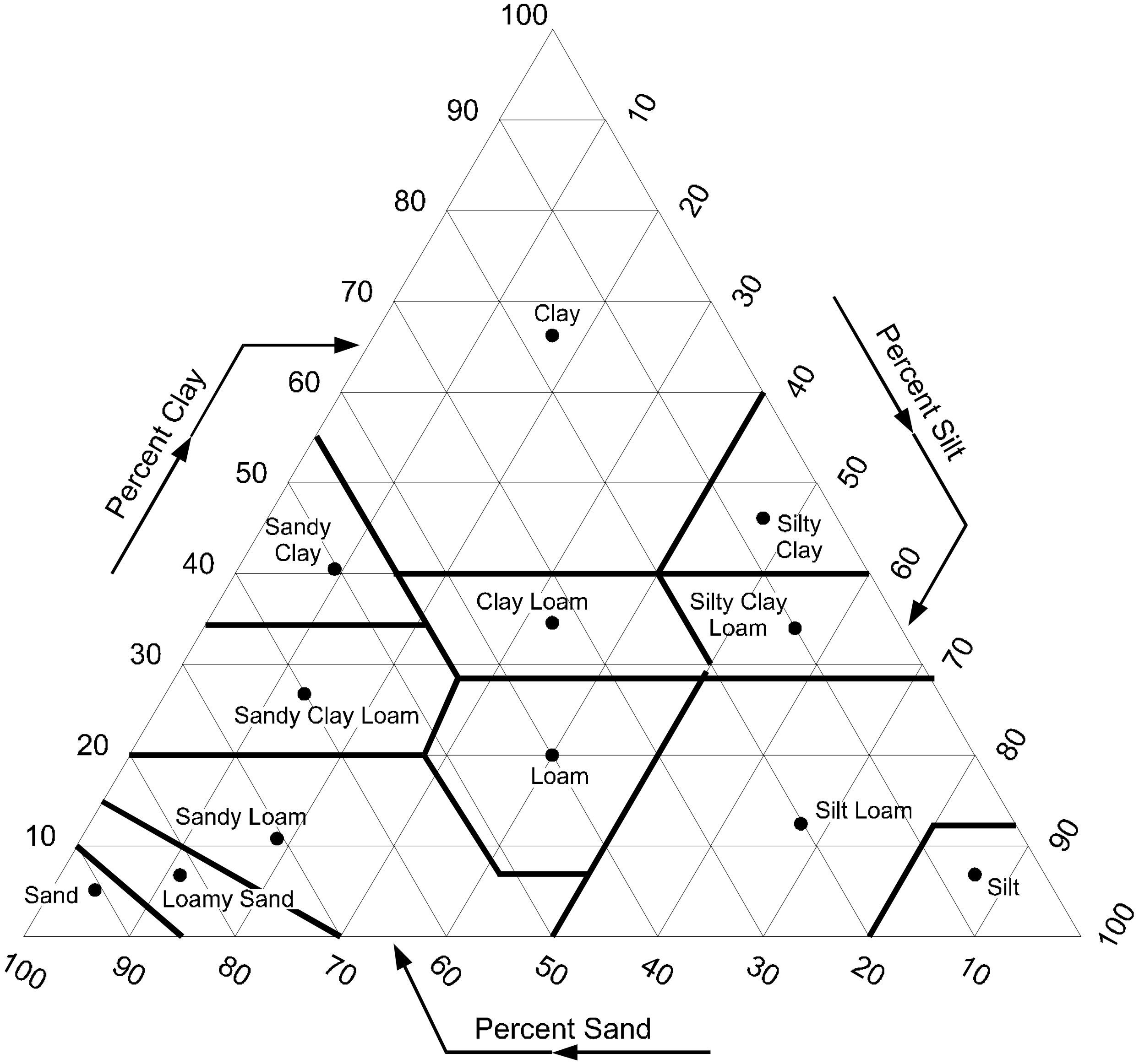


Figure 3. U.S. Soil Conservation Service Classification Chart Showing Centroid Compositions (Solid Circles)

TABLE 4. CENTROID COMPOSITIONS, MEAN PARTICLE DIAMETERS AND DRY BULK DENSITY OF THE 12 SCS SOIL TEXTURAL CLASSIFICATIONS

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

Given the mean particle diameter data in Table 4, the mean thickness of the capillary zone may then be estimated using Equations 9 and 10.

2.4 DIFFUSION THROUGH THE UNSATURATED ZONE

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

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

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

D_a = Diffusivity in air, cm^2/s

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

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

D_w = Diffusivity in water, cm^2/s

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

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

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

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

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

L_i = Thickness of soil layer i, cm

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

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

Note that in the case of cracks in the floor of the enclosed space, the value of L_T does not include the thickness of the floor, nor does the denominator of Equation 12 include the thickness of the floor and the associated effective diffusion coefficient across the crack(s). An unlimited number of soil layers, including the capillary zone, may be included in Equation 12, but all layers must be located between the source of contamination and the enclosed space floor.

2.5 THE INFINITE SOURCE SOLUTION TO CONVECTIVE AND DIFFUSIVE TRANSPORT

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

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

where α = Steady-state attenuation coefficient, unitless

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

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

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

L_T = Source-building separation, cm

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

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

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

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

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

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

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:

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

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

π = 3.14159

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

k_v = Soil vapor permeability, cm^2

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

μ = Viscosity of air, g/cm-s

Z_{crack} = Crack depth below grade, cm

r_{crack} = Equivalent crack radius, cm.

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

$$r_{crack} = \eta \left(A_B / X_{crack}\right) \qquad (16)$$

where r_{crack} = Equivalent crack radius, cm

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

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

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

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

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

Equation 13 contains the exponent of the following dimensionless group:

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

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:

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

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:

$$C_{building} = \alpha C_{source} \quad . \qquad (19)$$

2.6 THE FINITE SOURCE SOLUTION TO CONVECTIVE AND DIFFUSIVE TRANSPORT

If the thickness of soil contamination is known, the finite source solution of J&E (1991) can be employed such that the time-averaged attenuation coefficient (<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 $<\alpha>$ = 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^0 = 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;

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

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

With a calculated value for $<\alpha>$, 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 THE SOIL GAS MODELS

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

The soil gas models (SG-SCREEN and SG-ADV) are designed to allow the user to input measured soil gas concentration and sampling depth information directly into the spreadsheets. In the new models, the value of the user-defined soil gas concentration is assigned as the value of C_{source} in Equation 19. The steady-state (infinite source) attenuation coefficient (α) in Equation 19 is calculated using Equation 13. The steady-state solution for the attenuation coefficient is used because no evaluation has been made regarding the size and total mass of the source of emissions. The source of emissions, therefore, cannot be depleted over time. The soil gas models estimate the steady-state indoor air concentration over the exposure duration. For a detailed discussion of using the soil gas models as well as soil gas sampling, see Section 4 of this document.

2.8 SOIL VAPOR PERMEABILITY

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

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

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

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^oC)

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

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

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

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

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

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

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

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

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

S_{te} = Effective total fluid saturation, unitless

M = van Genuchten shape parameter, unitless.

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

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

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

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

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

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

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

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

2.9 CALCULATION OF A RISK-BASED SOIL OR GROUNDWATER CONCENTRATION

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

$$C_C = \frac{TR \; x \; AT_C \; x \; 365 \; days/yr}{URF \; x \; EF \; x \; ED \; x \; C_{building}} \qquad (29)$$

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, μg/m^3 per μg/kg-soil, or μg/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 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.

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

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

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

2.10 CALCULATION OF INCREMENTAL RISKS

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

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

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

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

2.11 MAJOR MODEL ASSUMPTIONS/LIMITATIONS

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

1. Contaminant vapors enter the structure primarily through cracks and openings in the walls and foundation.

2. Convective transport occurs primarily within the building zone of influence and vapor velocities decrease rapidly with increasing distance from the structure.

3. Diffusion dominates vapor transport between the source of contamination and the building zone of influence.

4. All vapors originating from below the building will enter the building unless the floors and walls are perfect vapor barriers.

5. All soil properties in any horizontal plane are homogeneous.

6. The contaminant is homogeneously distributed within the zone of contamination.

7. The areal extent of contamination is greater than that of the building floor in contact with the soil.

8. Vapor transport occurs in the absence of convective water movement within the soil column (i.e., evaporation or infiltration), and in the absence of mechanical dispersion.

9. The model does not account for transformation processes (e.g., biodegradation, hydrolysis, etc.).

10. The soil layer in contact with the structure floor and walls is isotropic with respect to permeability.

11. Both the building ventilation rate and the difference in dynamic pressure between the interior of the structure and the soil surface are constant values.

Use of the J&E Model as a first-tier screening tool to identify sites needing further assessment requires careful evaluation of the assumptions listed in the previous section to determine whether any conditions exist that would render the J&E Model inappropriate for the site. If the model is deemed applicable at the site, care must be taken to ensure reasonably conservative and self-consistent model parameters are used as input to the model. Considering the limited site data typically available in preliminary site assessments, the J&E Model can be expected to predict only whether or not a risk-based exposure level will be exceeded at the site. Precise prediction of concentration levels is not possible with this approach.

The suggested minimum site characterization information for a first tier evaluation of the vapor intrusion pathway includes: site conceptual model, nature and extent of contamination distribution, soil lithologic descriptions, groundwater concentrations, and/or possibly near source soil vapor concentrations. The number of samples and measurements needed to establish this information varies by site and it’s not possible to provide a hard and fast rule. Bulk soil concentrations should not be used unless appropriately preserved during sampling.

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

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

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

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

SECTION 3

SOIL AND GROUNDWATER MODEL APPLICATION

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

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

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

A list of reasonably conservative model input parameters for building-related parameters is provided in Table 9, which also provides the practical range, typical or mean value (if applicable), and most conservative value for these parameters. For building parameters with low uncertainty and sensitivity, only a single "fixed" value corresponding to the mean or typical value is provided in Table 9. Soil-dependent properties are provided in Table 10 for soils classified according to the US SCS system. If site soils are not classified according to the US SCS, Table 11 can be used to assist in selecting an appropriate SCS soil type corresponding to the available site lithologic information. Note that the selection of the soil texture class should be biased towards the coarsest soil type of significance, as determined by the site characterization program.

TABLE 7. RANGE OF VALUES FOR SELECTED INPUT PARAMETERS

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

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

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

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

[b] Applicable only to advanced model for soil contamination.

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

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

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

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

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

TABLE 11. GUIDANCE FOR SELECTION OF SOIL TYPE

If your boring log indicates that the following materials are the predominant soil types …	**Then you should use the following texture classification when obtaining the attenuation factor**
Sand or Gravel or **Sand and Gravel**, with less than about 12 % fines, where "fines" are smaller than 0.075 mm in size.	Sand
Sand or Silty Sand, with about 12 % to 25 % fines	Loamy Sand
Silty Sand, with about 20 % to 50 % fines	Sandy Loam
Silt and Sand or Silty Sand or Clayey, Silty Sand or Sandy Silt or Clayey, Sandy Silt, with about 45 to 75 % fines	Loam
Sandy Silt or Silt, with about 50 to 85 % fines	Silt Loam

These input parameters were developed from the best available soil-physics science, available studies of building characteristics, and international-expert opinion. Consequently, the input parameters listed in Tables 9 and 10 are considered default parameters for a first-tier assessment, which should in most cases provide a reasonably (but not overly) conservative estimate of the vapor intrusion attenuation factor for a site. Justification for the building-related and soil-dependent parameters values selected as default values for the J&E Model is described below.

3.1 JUSTIFICATION OF DEFAULT SOIL-DEPENDENT PROPERTIES

The default soil-dependent parameters recommended for a first tier assessment (Table 10) represent mean or typical values, rather than the most conservative value, in order to avoid overly conservative estimates of attenuation factors. Note, however, that the range of values for some soil properties can be very large, particularly in the case of moisture content and hydraulic conductivity. Consequently, selecting a soil type and corresponding typical soil property value may not accurately or conservatively represent a given site. Note also that Table 9 does not provide estimates of soil properties for very coarse soil types, such as gravel, gravelly sand, and sandy gravel, etc., which also may be present in the vadose zone. Consequently, in cases where the vadose zone is characterized by very coarse materials, the J&E Model may not provide a conservative estimate of attenuation factor.

As discussed above, the J&E Model is sensitive to the value of soil moisture content. Unfortunately, there is little information available on measured moisture contents below buildings. Therefore, the typical approach is to use a water retention model (e.g., van Genuchten model) to approximate moisture contents. For the unsaturated zone, the selected default value for soil moisture is a value equal to halfway between the residual saturation value and field capacity, using the van Genuchten model-predicted values for U.S. SCS soil types. For the capillary transition zone, a moisture content corresponding to the air entry pressure head is calculated by using the van Genuchten model. When compared to other available water retention models, the van Genuchten model yields somewhat lower water contents, which results in more conservative estimates of attenuation factor. The soil moisture contents listed in Table 10 are based on agricultural samples, which are likely to have higher water contents than soils below building foundations and, consequently result in less-conservative estimates of the attenuation factor.

3.2 JUSTIFICATION OF DEFAULT BUILDING-RELATED PROPERTIES

Building Air Exchange Rate (Default Value = 0.25 AEH)

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

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

The crack width and crack ratio are related. Assuming a square house and that the only crack is a continuous edge crack between the foundation slab and wall ("perimeter crack"), the crack ratio and crack width are related as follows:

Crack Ratio = Crack Width x 4 x (Subsurface Foundation Area)^0.5/Subsurface Foundation Area

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

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

The default building area is based on the following information:

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

The Michigan guidance document indicates that the 111.5 m^2 area approximately corresponds to the 10th percentile floor space area for a residential single-family dwelling, based on statistics compiled by the U.S. Department of Commerce (DOC) and U.S. Housing and Urban Development (HUD). The typical, upper, and lower ranges presented in Table 9 are subjectively chosen values. The subsurface foundation area is a function of the building area, and depth to the base of the foundation, which is fixed.

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

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

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

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

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

An alternate empirical approach is to select a Q_{soil} value on the basis of tracer tests (i.e., mass balance approach). When soil gas advection is the primary mechanism for tracer intrusion into a building, the Q_{soil} can be estimated by measuring the concentrations of a chemical tracer in indoor air, in outdoor air, and in soil vapor below a building, and by measuring the building ventilation rate (Hers et al. 2000a; Fischer et al. 1996; Garbesi et al. 1993; Rezvan et al. 1991; Garbesi and Sextro, 1989). For sites with coarse-grained soils (Table 10). The Q_{soil} values measured using this technique are compared to predicted rates using the Perimeter Crack model. The Perimeter Crack model predictions are both higher and lower than the measured values, but overall are within one order of magnitude of the measured values. Although the Q_{soil} values predicted by the models and measured using field tracer tests are uncertain, the results suggest that a "typical" range for houses on coarse-grained soils is on the order of 1 to 10 L/min. A disadvantage with the tracer test approach is that only limited data are available and there do not appear to be any tracer studies for field sites with fine-grained soils.

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

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

3.3 RUNNING THE MODELS

Eight different models are provided in MICROSOFT EXCEL formats.

1. Models for Soil Contamination:
   SL-SCREEN-Feb 04.XLS
   SL-ADV-Feb 04.XLS

2. Models for Groundwater Contamination:
   GW-SCREEN-Feb 04.XLS
   GW-ADV-Feb 04.XLS

3. Model for Soil Gas Contamination
   SG-SCREEN-Feb 04.xls
   SG-ADV-Feb 04.xls

4. Models for Non Aqueous Phase Liquids
   NAPL-SCREEN-Feb 04.xls

NAPL-ADV-Feb 04.xls

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

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

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

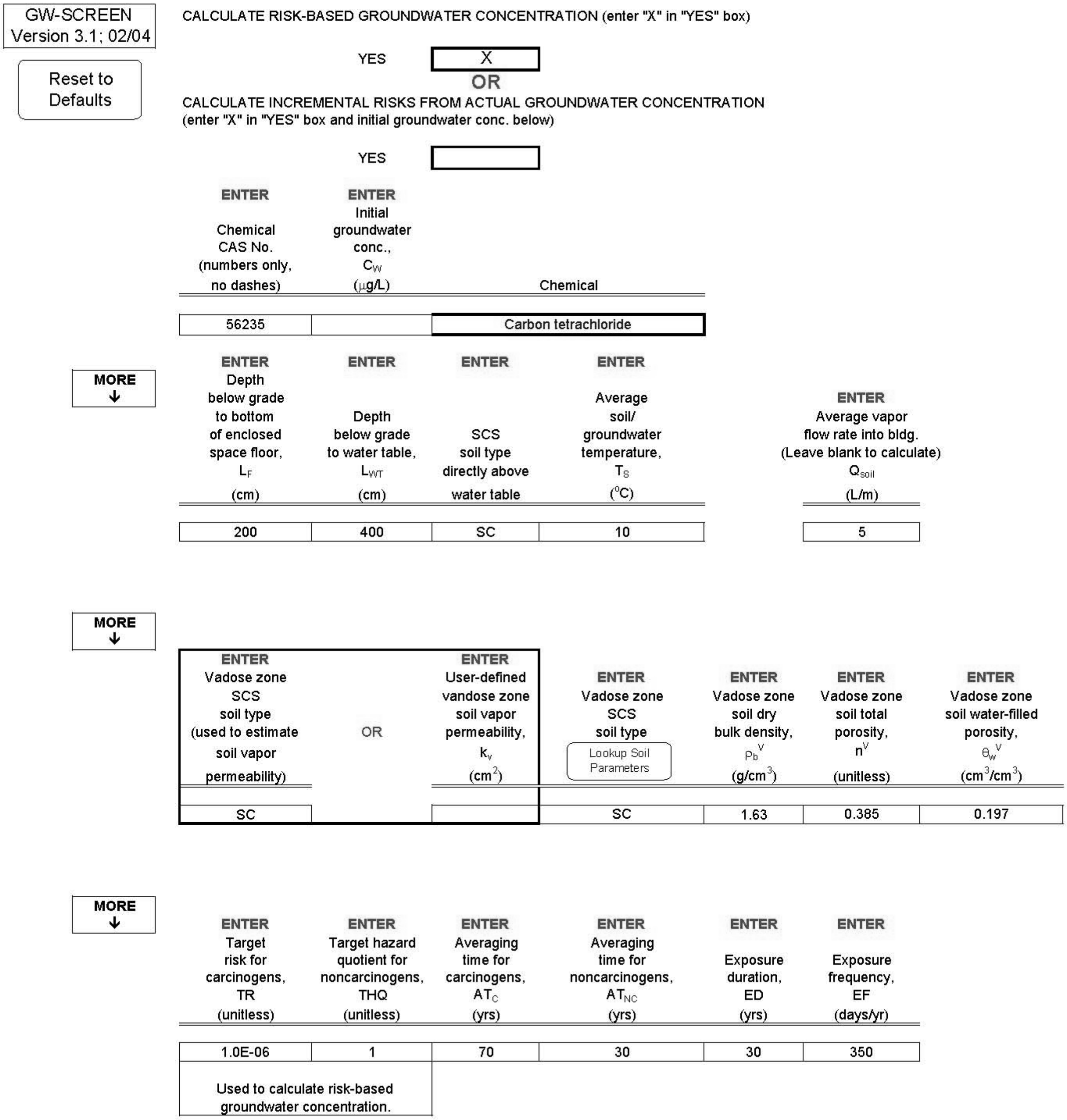
The following is an explanation of what is contained in each worksheet, how to enter data, how to interpret model results, and how to add/revise the chemical properties data found in the VLOOKUP Tables. As examples, Appendix C contains all the worksheets for the advanced soil contamination model SL-ADV.

3.4 THE DATA ENTRY SHEET (DATENTER)

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

Error Messages

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



GW-SCREEN
Version 3.1; 02/04

Reset to Defaults

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

YES X

OR

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

YES ☐

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_W (μg/L)	Chemical
56235		Carbon tetrachloride

MORE ↓

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

MORE ↓

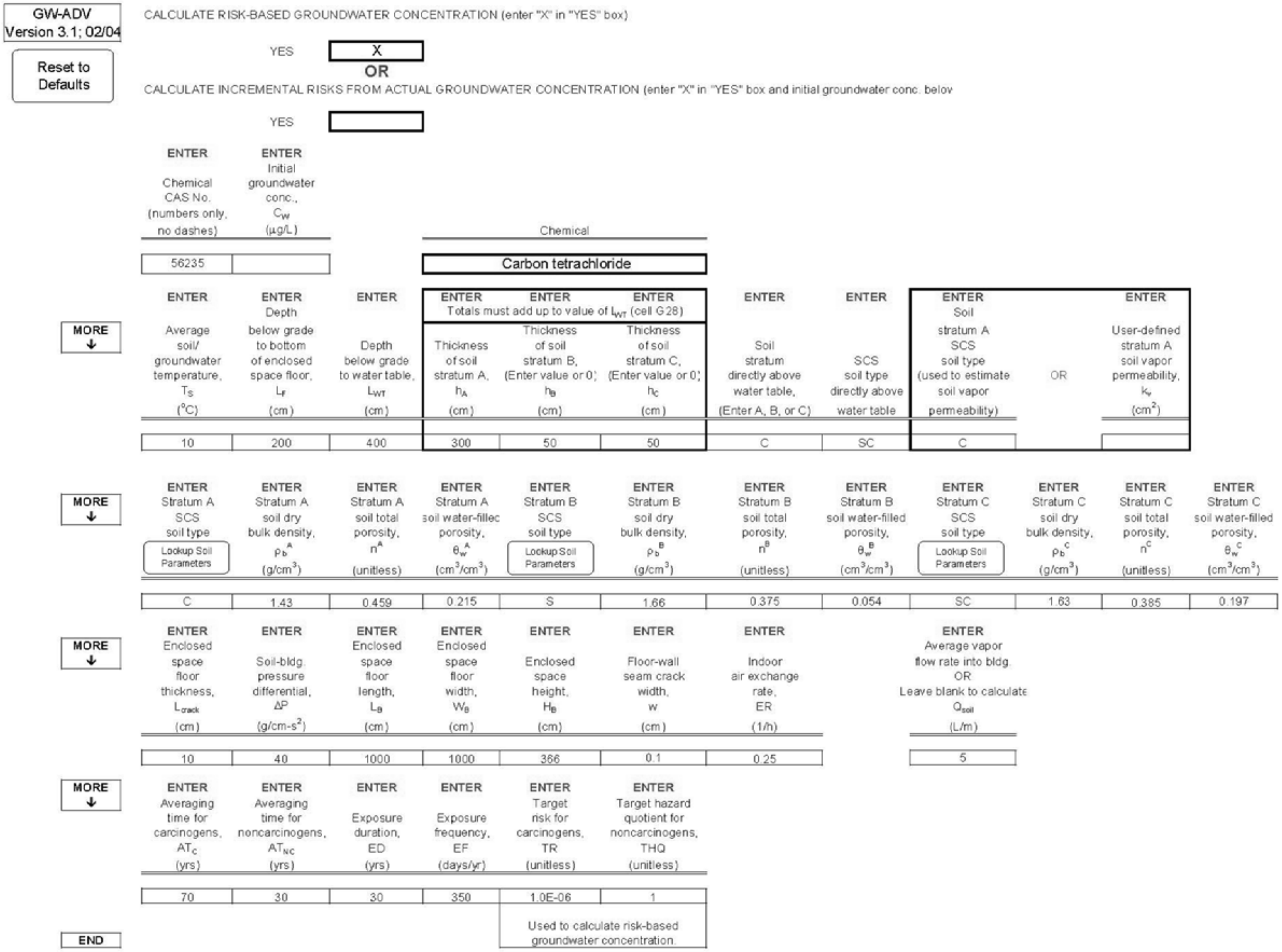
ENTER Vadose zone SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined vandose zone soil vapor permeability, k_v (cm^2)	ENTER Vadose zone SCS soil type Lookup Soil Parameters	ENTER Vadose zone soil dry bulk density, ρ_b^V (g/cm^3)	ENTER Vadose zone soil total porosity, n^V (unitless)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

MORE ↓

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

Used to calculate risk-based groundwater concentration.

Figure 4. GW-SCREEN Data Entry Sheet



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. belov

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)		ENTER User-defined stratum A soil vapor permeability, k_v (cm^2)
			Totals must add up to value of L_{WT} (cell G28)						OR	
10	200	400	300	50	50	C	SC	C		

ENTER Stratum A SCS soil type	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-fillec porosity, θ_w^A (cm^3/cm^3)	ENTER Stratum B SCS soil type	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	ENTER Stratum C SCS soil type	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)
C	1.43	0.459	0.215	S	1.66	0.375	0.054	SC	1.63	0.385	0.197

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP (g/cm-s^2)	ENTER Enclosed space floor length, L_B (cm)	ENTER Enclosed space floor width, W_B (cm)	ENTER Enclosed space height, H_B (cm)	ENTER Floor-wall seam crack width, w (cm)	ENTER Indoor air exchange rate, ER (1/h)	ENTER Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
10	40	1000	1000	366	0.1	0.25	5

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. GW-ADV Data Entry Sheet

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

Entering Data

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

Model Variables--

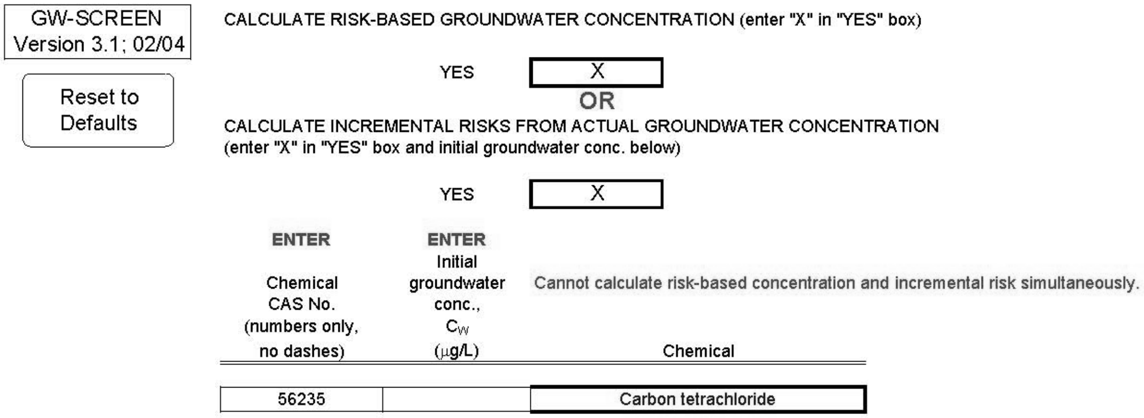
The following is a list of all data entry variables required for evaluating either a risk-based media concentration or the incremental risks due to actual contamination. A description for which model(s) the variable is appropriate is given in parenthesis after the name of the variable. In addition, notes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

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

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

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

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



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

YES X

OR

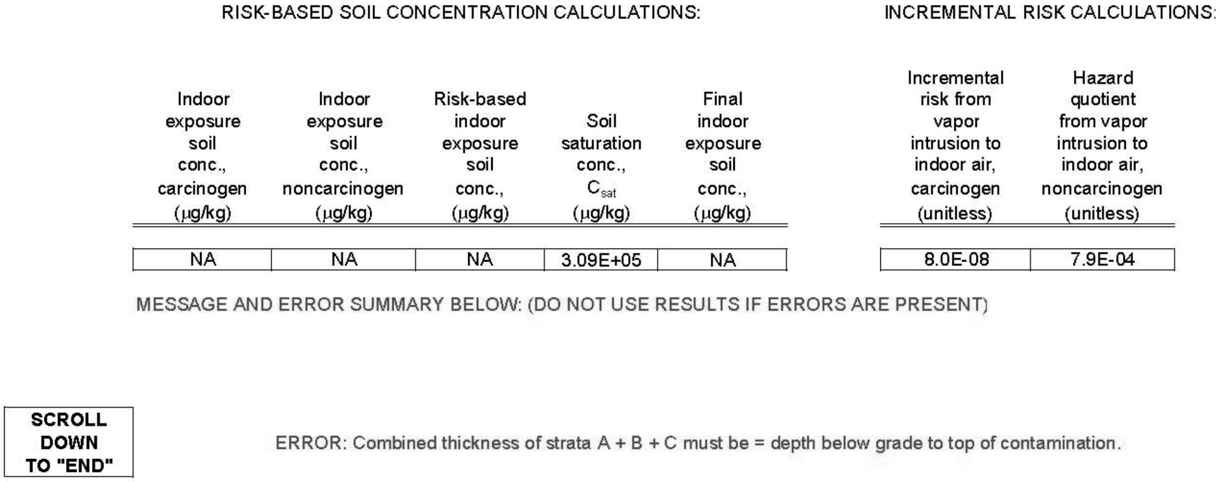
CALCULATE INCREMENTAL RISKS FROM ACTUAL GROUNDWATER CONCENTRATION
(enter "X" in "YES" box and initial groundwater conc. below)

YES X

Cannot calculate risk-based concentration and incremental risk simultaneously.

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Initial groundwater conc., C_W (μg/L)	Chemical
56235		Carbon tetrachloride

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	3.09E+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)
8.0E-08	7.9E-04

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

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

Figure 7. Example Error Message on Results Sheet

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

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

   The soil/groundwater temperature is used to correct the Henry's law constant to the specified temperature. Figure 8 from U.S. EPA (1995) shows the average temperature of shallow groundwater in the continental United States. Shallow groundwater temperatures may be used to approximate subsurface soil temperatures greater than 1 to 2 meters below the ground surface. Another source of information may be your State groundwater protection regulatory agency.

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

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

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

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

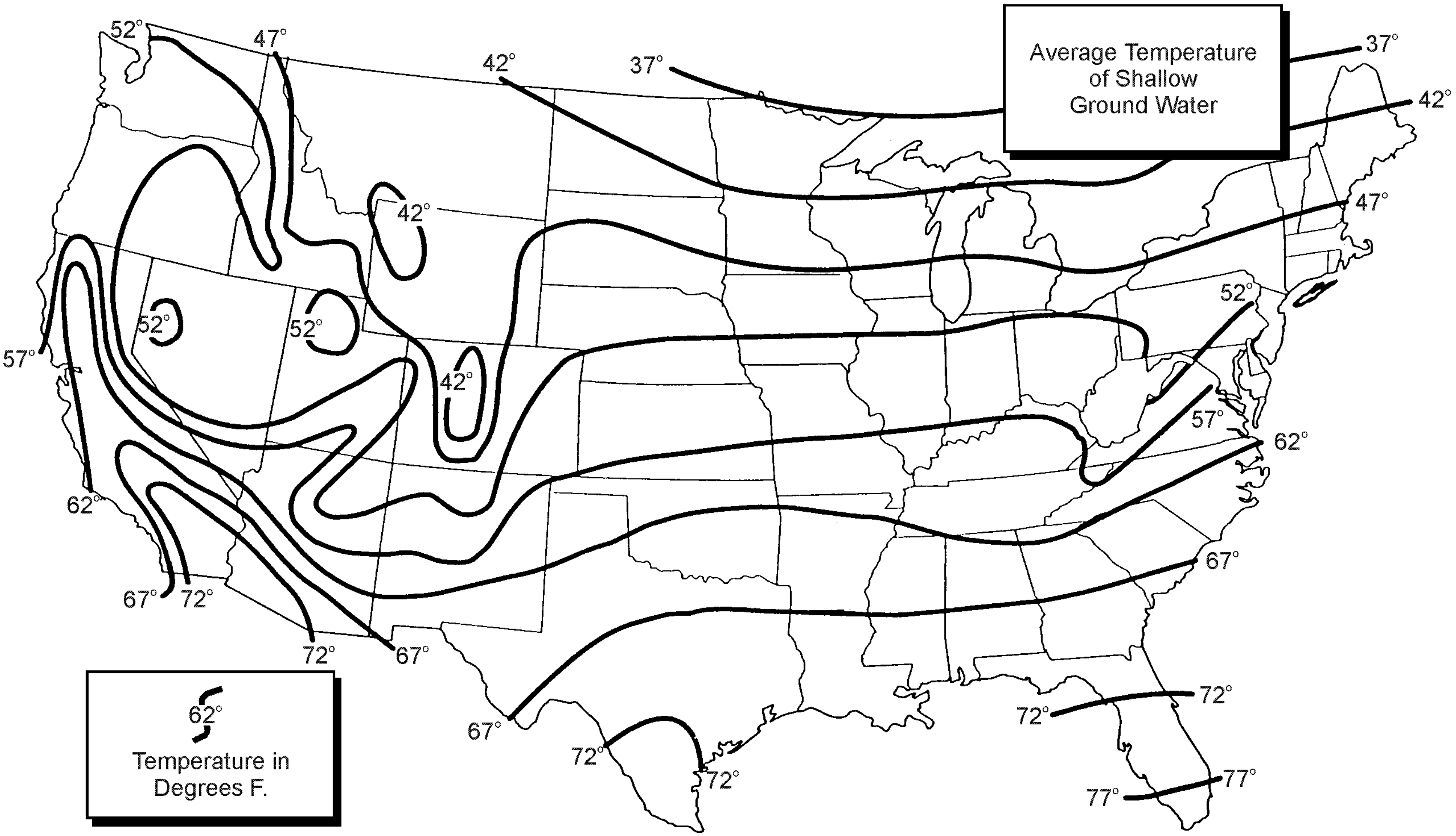


Figure 8. Average Shallow Groundwater Temperature in the United States

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

Enter the depth to the top of the water table (i.e., where the pressure head is equal to zero and the pressure is atmospheric).

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

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

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

1. Entering a value of zero will automatically invoke the infinite source model.

2. Enter the depth to the top of the water table. This will invoke the finite source model under the assumption that contamination extends from the top of contamination previously entered down to the top of the water table.

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

In the advanced models, the user can define up to three soil strata between the soil surface and the top of contamination or to the soil gas sampling depth, as appropriate. These strata are listed as A, B, and C. Stratum A extends down from the soil surface, Stratum B is below Stratum A, and Stratum C is the deepest stratum. The thickness of Stratum A must be at least as thick as the depth below grade to the bottom of the enclosed space floor. The combined thickness of all strata must be equal to the depth to the top of contamination, or to the soil gas sampling depth, as appropriate. If soil strata B and/or C are not to be considered, a value of zero must be entered for each stratum not included in the analysis.

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

Enter one of the following SCS soil type abbreviations:

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	Silty loam
SL	Sandy loam

The SCS soil textural classification can be determined by using either the ATSM Standard Test Method for Particle-Size Analysis of Soils (D422-63) or by using the analytical procedures found in the U.S. Natural Resources Conservation Service (NRCS) Soil Survey Laboratory Methods Manual, Soil Survey Laboratory Investigations Report No. 42. After determining the particle size distribution of a soil sample, the SCS soil textural classification can be determined using the SCS classification chart in Figure 7.

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

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

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

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) (SCS – soil)

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

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

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

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

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

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

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

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

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

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

Total soil porosity (n) is determined as:

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

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

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

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

One option is to use a model to estimate the long-term average soil water-filled porosities of each soil stratum between the enclosed space floor and the top of contamination. The HYDRUS model version 5.0 (Vogel et al., 1996) is a public domain code for simulating one-dimensional water flow, solute transport, and heat movement in variably-saturated soils. The water flow simulation module of HYDRUS will generate soil water content as a function of depth and time given actual daily precipitation data. Model input requirements include either the soil hydraulic properties of van Genuchten (1980) or those of Brooks and Corey (1966). The van Genuchten soil hydraulic properties required are the same as those given in Tables 3 and 4 (i.e., θ_s, θ_r, N, α_1, and K_s). The HYDRUS model is available from the U.S. Department of Agriculture (USDA) - Agricultural Research Service in Riverside, California via their internet website at http://www.ussl.ars.usda.gov/MODELS/HYDRUS.HTM. One and two-dimensional commercial versions of HYDRUS (Windows versions) are available at the International Ground Water Modeling Center website at http://www.mines.edu/research/igwmc/software/. Schaap and Leij (1998) have recently developed a Windows program entitled ROSETTA for estimating the van Genuchten soil hydraulic properties based on a limited or more extended set of input data. The ROSETTA program can be found at the USDA website: http://www.ussl.ars.usda.gov/MODELS/rosetta/rosetta.htm. The van Genuchten hydraulic properties can then be input into HYDRUS to estimate soil moisture content.

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

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

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

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

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

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

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

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

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

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

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

    Enter the thickness of the floor slab. All models operate under the assumption that the floor in contact with the underlying soil is composed of impermeable concrete whether constructed as a basement floor or slab-on-grade. The default value is 10 cm, which is consistent with J&E (1991).

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

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

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

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

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

28. *Enclosed Space Height* (Advanced Models Only) (H_B)

For a single story home, the variation in mixing height will be the greatest for houses with HVAC systems that result in significant air circulation (e.g., forced air heat pump). Mixing heights would be less for houses with electrical baseboard heaters. The mixing height is approximated by the room height. The default value is 2.44 meters for a single story house without a basement.

For a single story house with a basement less mixing would be expected because of the cross floor connections. The default values for a house with a basement is 3.66 m. This value represents a two-fold reduction in vapor concentrations between the floors.

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

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

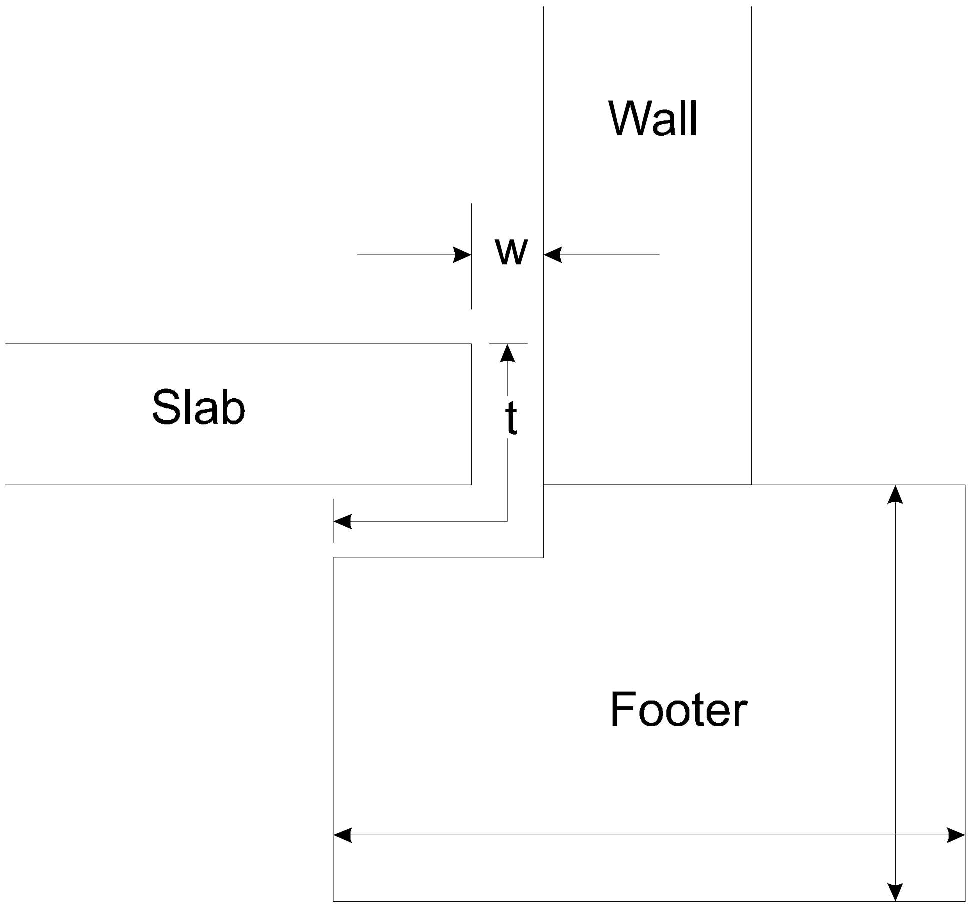


Figure 9. Floor Slab and Foundation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.5 THE RESULTS SHEET (RESULTS)

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

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

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

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

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

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

3.6 THE CHEMICAL PROPERTIES SHEET (CHEMPROPS)

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

3.7 THE INTERMEDIATE CALCULATIONS SHEET (INTERCALS)

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

3.8 THE LOOKUP TABLES (VLOOKUP)

The VLOOKUP sheet contains two lookup tables from which individual data are retrieved for a number of model calculations. The first table is the Soil Properties Lookup Table. This table contains the average soil water retention curve data of Hers (2002) and Schaap and Leij (1998) and the mean grain diameter data of Nielson and Rogers (1990) by SCS soil type, and the mean dry bulk density from Leij, Stevens, et al (1994).

3.9 ADDING, DELETING, OR REVISING CHEMICALS

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

SECTION 4

SOIL GAS MODEL APPLICATION

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

4.1 RUNNING THE MODELS

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

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

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

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

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

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

$$C_g' = \frac{C_g \times MW}{R \times T_S} \tag{33}$$

where C_g' = Soil gas concentration, μg/m^3

C_g = Soil gas concentration, ppmv

MW = Molecular weight, g/mol

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

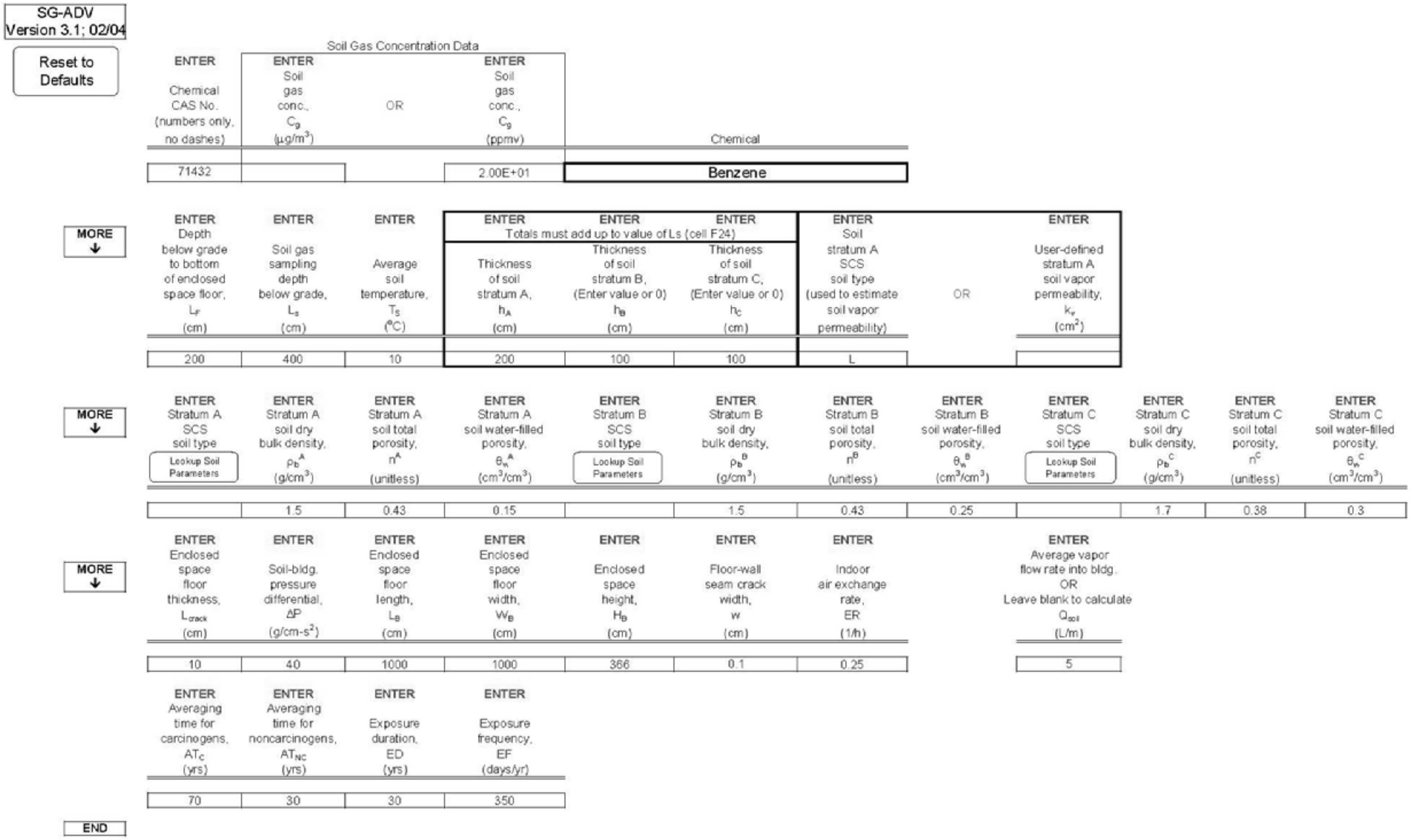
T_S = System (soil) temperature, ^{o}K.

In the soil gas models, the steady-state indoor air concentration is calculated by Equation 19 (i.e., $C_{building} = \alpha\ C_{source}$). The value of the vapor concentration at the source of emissions (C_{source}) is assigned the value of the user-defined soil gas concentration. The value of the steady-state attenuation coefficient (α) in Equation 19 is calculated by Equation 13. Because no evaluation has been made of the extent of the source of emissions, steady-state conditions (i.e., a non-diminishing source) must be assumed.

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

4.2 SOIL GAS SAMPLING

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



Soil Gas Concentration Data

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Soil gas conc., C_g (μg/m^3)	OR	ENTER Soil gas conc., C_g (ppmv)	Chemical
71432			2.00E+01	Benzene

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 Totals must add up to value of Ls (cell F24) 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)
200	400	10	200	100	100	L		

ENTER Stratum A SCS soil type	ENTER Stratum A soil dry bulk density, ρ_b^A (g/cm^3)	ENTER Stratum A soil total porosity, n^A (unitless)	ENTER Stratum A soil water-filled porosity, θ_w^A (cm^3/cm^3)	ENTER Stratum B SCS soil type	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	ENTER Stratum C SCS soil type	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	0.25		1.7	0.38	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)		ENTER Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
10	40	1000	1000	366	0.1	0.25		5

ENTER Averaging time for carcinogens, AT_C (yrs)	ENTER Averaging time for noncarcinogens, AT_{NC} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)
70	30	30	350

Figure 10. SG-ADV Data Entry Worksheet

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

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

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

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

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

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

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

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

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

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

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

http://www.astm.org.

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

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

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

Data Quality and Data Quality Objectives

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

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

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

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

4.3 ASSUMPTIONS AND LIMITATIONS OF THE SOIL GAS MODEL

As discussed previously, the soil gas models operate under the assumption of steady-state conditions. This means that enough time has passed for the vapor plume to have reached the building of interest directly above the source of contamination and that the vapor concentrations have reached their maximum values. Depending on the depth at which the soil gas is sampled, diffusion of the soil gas toward the building is a function of the soil properties between the building floor in contact with the soil and the sampling depth. Convection of the soil gas into the structure is a function of the building properties and the effective soil vapor permeability. Assumptions and limitations of the soil gas models are the same as those in Section 2.11 with the exception of the source vapor concentration that is determined empirically through soil gas sampling.

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

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

SECTION 5

ASSUMPTIONS AND LIMITATIONS OF THE J&E MODEL

The J&E Model is a one-dimensional analytical solution to diffusive and convective transport of vapors into indoor spaces. The model is formulated as an attenuation factor that relates the vapor concentration in the indoor space to the vapor concentration at the source. It was developed for use as a screening level model and consequently is based on a number of simplifying assumptions regarding contaminant distribution and occurrence, subsurface characteristics, transport mechanisms, and building construction.

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

The J&E Model as implemented by EPA assumes homogeneous soil layers with isotropic properties that characterize the subsurface. The first tier spreadsheet versions allow only one layer; the advanced spreadsheet versions allow up to three layers. Sources of contaminants that can be modeled include dissolved, sorbed, or vapor sources where the concentrations are below the aqueous solubility limit, the soil saturation concentration, and/or the pure component vapor concentration. The contaminants are assumed to be homogeneously distributed at the source. All but one of the spreadsheets assumes an infinite source. The exception is the advanced model for a bulk soil source, which allows for a finite source. For the groundwater and bulk soil models, the vapor concentration at the source is calculated assuming equilibrium partitioning. Vapor from the source is assumed to diffuse directly upward (one-dimensional transport) through uncontaminated soil (including an uncontaminated capillary fringe if groundwater is the vapor source) to the base of a building foundation, where convection carries the vapor through cracks and openings in the foundation into the building. Both diffusive and convective transport processes are assumed to be at steady state. Neither sorption nor biodegradation is accounted for in the transport of vapor from the source to the base of the building.

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

TABLE 12. ASSUMPTIONS AND LIMITATIONS OF THE VAPOR INTRUSION MODEL

Assumption	Implication	Field Evaluation
Contaminant		
No contaminant free-liquid/precipitate phase present	J&E Model not representative of NAPL partitioning from source	NAPL or not at site–easier to evaluation for floating product or soil contamination sites. Most DNAPL sites with DNAPL below the water table defy easy characterization.
Contaminant is homogeneously distributed within the zone of contamination		
No contaminant sources or sinks in the building.	Indoor sources of contaminants and/or sorption of vapors on materials may confound interpretation of results.	Survey building for sources, assessment of sinks unlikely
Equilibrium partitioning at contaminant source.	Groundwater flow rates are low enough so that there are no mass transfer limitations at the source.	Not likely
Chemical or biological transformations are not significant (model will predict more intrusion)	Tendency to over predict vapor intrusion for degradable compounds	From literature
Subsurface Characteristics		
Soil is homogeneous within any horizontal plane	Stratigraphy can be described by horizontal layers (not tilted layers)	Observe pattern of layers and unconformities Note: In simplified J&E Model layering is not considered
All soil properties in any horizontal plane are homogeneous		
The top of the capillary fringe must be below the bottom of the building floor in contact with the soil.		
EPA version of JE Model assumes the capillary fringe is uncontaminated.		
Transport Mechanisms		
One-dimensional transport	Source is directly below building, stratigraphy does not influence flow direction, no effect of two- or three-dimensional flow patterns.	Observe location of source, observe stratigraphy, pipeline conduits, not likely to assess two- and three-dimensional pattern.
Two separate flow zones, one diffusive one convective.	No diffusion (dispersion) in the convective flow zone. Plug flow in convective zone	Not likely
Vapor-phase diffusion is the dominant mechanism for transporting contaminant vapors from contaminant sources located away from the foundation to the soil region near the foundation	Neglects atmospheric pressure variation effects, others?	Not likely

(continued)

Assumption	Implication	Field Evaluation
Straight-line gradient in diffusive flow zone.	Inaccuracy in flux estimate at match point between diffusive and convective sections of the model.	Not likely
Diffusion through soil moisture will be insignificant (except for compounds with very low Henry's Law Constant	Transport through air phase only. Good for volatiles. Only low volatility compounds would fail this and they are probably not the compounds of concern for vapor intrusion	From literature value of Henry's Law Constant.
Convective transport is likely to be most significant in the region very close to a basement, or a foundation, and vapor velocities decrease rapidly with increasing distance from a structure		Not likely
Vapor flow described by Darcy's law	Porous media flow assumption.	Observations of fractured rock, fractured clay, karst, macropores, preferential flow channels.
Steady State convection	Flow not affected by barometric pressure, infiltration, etc.	Not likely
Uniform convective flow near the foundation	Flow rate does not vary by location	Not likely
Uniform convective velocity through crack or porous medium	No variation within cracks and openings and constant pressure field between interior spaces and the soil surface	Not likely
Significant convective transport only occurs in the vapor phase	Movement of soil water not included in vapor impact	Not likely
All contaminant vapors originating from directly below the basement will enter the basement, unless the floor and walls are perfect vapor barriers. (Makes model over est. vapors as none can flow around the building)	Model does not allow vapors to flow around the structure and not enter the building	Not likely
Contaminant vapors enter structures primarily through cracks and openings in the walls and foundation	Flow through the wall and foundation material itself neglected	Observe numbers of cracks and openings. Assessment of contribution from construction materials themselves not likely

- The presence or suspected presence of residual or free-product non-aqueous phase liquids (LNAPL, DNAPL, fuels, solvents, etc.) in the subsurface.
- The presence of heterogeneous geologic materials (other than the three layers allowed in the advanced spreadsheets) between the vapor source and building. The J&E Model does not apply to geologic materials that are fractured, contain macropores or other preferential pathways, or are composed of karst.

- Sites where significant lateral flow of vapors occurs. These can include geologic layers that deflect contaminants from a strictly upward motion and buried pipelines or conduits that form preferential paths. Significantly different permeability contrasts between layers are likely to cause lateral flow of vapors. The model assumes the source of contaminants is directly below the potential receptors.
- Very shallow groundwater where the building foundation is wetted by the groundwater.
- Very small building air exchange rates (e.g., < 0.25/h)
- Buildings with crawlspace structures or other significant openings to the subsurface (e.g., earthen floors, stone buildings, etc.). The EPA spreadsheet only allows for either slab on grade or basement construction.
- Contaminated groundwater sites with large fluctuations in the water table elevation. In these cases, the capillary fringe is likely to be contaminated; whereas in the groundwater source spreadsheets, the capillary fringe is assumed to be uncontaminated.

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

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

In the case of contaminated groundwater, the vapor equilibrium model operates under the assumption that the contaminant is present at levels below the water solubility limit. If the user-defined soil concentration is greater than the soil saturation concentration (C_{sat}) or if the groundwater concentration is greater than the solubility limit (S), the equilibrium vapor concentration will be calculated at the value of C_{sat} or S as appropriate.

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

Likewise, the groundwater models will compare the calculated risk-based groundwater concentration to the aqueous solubility limit of the compound. If the risk-based groundwater concentration is greater than the solubility limit, the contaminant is not of concern for the vapor intrusion pathway.

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

The procedures used to estimate the soil vapor permeability of the soil stratum in contact with the building floor and walls assume isotropic soils and steady-state soil moisture content. In addition, the calculations do not account for preferential vapor pathways due to soil fractures, vegetation root pathways, or the effects of a gravel layer below the floor slab or backfill. These items may act to increase the vapor permeability of in situ soils.

If in situ pneumatic tests are used to measure site vapor permeability, care must be taken to ensure adequate sampling to reduce the possibility of missing important soil structure effects due to anisotropy.

Single-point in situ pneumatic tests are typically conducted by measuring the pressure in a probe as a metered flow of air is passed through the probe and into the soil. Garbesi et al. (1996), however, demonstrated that soil vapor permeability increases with the sampling length scale. Using a dual-probe dynamic pressure sampling apparatus, Garbesi et al. (1996) demonstrated that the average soil vapor permeability typically increases up to a constant value as the distance between the source probe and detector probe increases. On a length scale typical of a house (3 to 10 m), use of the dual-probe sampling technique found that the soil permeability was approximately 10 to 20 times higher than that measured by the single-point method. Although arguably the most accurate means of determining in situ soil vapor permeability, the techniques of Garbesi et al. (1996) are complex and require specialized equipment.

Another method for determining the intrinsic permeability of soil is to conduct empirical measurements of the saturated hydraulic conductivity (K_s). These data are then input into Equation

26. The resulting value of k_i is then multiplied by the relative air permeability (k_{rg}) calculated by Equation 27 to yield the effective air permeability of the soil.

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

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

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

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

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

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

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

5.1 SOURCE VAPOR CONCENTRATION

As applied in the accompanying spreadsheets, the vapor equilibrium model employed to estimate the vapor concentration at the source of soil contamination is applicable in the limit of "low" concentrations where compounds are sorbed to organic carbon in the soil, dissolved 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). If residual phase contaminants are present in the soil column, the user is referred to either the NAPL-SCREEN or NAPL-ADV model, as appropriate.

In the case of contaminated groundwater, the vapor equilibrium model operates under the assumption that the contaminant is present at levels below the water solubility limit. If the user-defined soil concentration is greater than the soil saturation concentration (C_{sat}) or if the groundwater concentration is greater than the solubility limit (S), the equilibrium vapor concentration will be calculated at the value of C_{sat} or S as appropriate.

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

Likewise, the groundwater models will compare the calculated risk-based groundwater concentration to the aqueous solubility limit of the compound. If the risk-based groundwater concentration is greater than the solubility limit, the contaminant is not of concern for the vapor intrusion pathway.

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

5.2 SOIL VAPOR PERMEABILITY

The procedures used to estimate the soil vapor permeability of the soil stratum in contact with the building floor and walls assumes isotropic soils and steady-state soil moisture content. In addition, the calculations do not account for preferential vapor pathways due to soil fractures, vegetation root pathways, or the effects of a gravel layer below the floor slab or backfill which may act to increase the vapor permeability with respect to in situ soils.

If in situ pneumatic tests are used to measure site vapor permeability, care must be taken to ensure adequate sampling to reduce the possibility of missing important soil structure effects due to anisotropy.

Single point in situ pneumatic tests are typically conducted by measuring the pressure in a probe as a metered flow of air is passed through the probe and into the soil. Garbesi et al. (1996), however, demonstrated that soil vapor permeability increases with the sampling length scale. Using a dual-probe dynamic pressure sampling apparatus, Garbesi et al. (1996) demonstrated that the average soil vapor permeability typically increases up to a constant value as the distance between the source probe and detector probe increases. On a length scale typical of a house (3 to 10 m) use of the dual-probe sampling technique found that the soil permeability was approximately 10 to 20 times higher than that measured by the single point method. Although arguably the most accurate means of determining in situ soil vapor permeability, the techniques of Garbesi et al. (1996) are complex and require specialized equipment.

Another method for determining the intrinsic permeability of soil is to conduct empirical measurements of the saturated hydraulic conductivity (K_s). These data are then input into Equation 26. The resulting value of k_i is then multiplied by the relative air permeability (k_{rg}) calculated by Equation 27 to yield the effective air permeability of the soil.

5.3 RISE OF AND DIFFUSION ACROSS THE CAPILLARY ZONE

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

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

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

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

5.4 DIFFUSIVE AND CONVECTIVE TRANSPORT INTO THE STRUCTURE

The following is a discussion of the major assumptions and limitations of the J&E Model for diffusive and convective vapor transport into buildings.

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

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

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

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

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

SECTION 6

INTERPRETATION OF RESULTS

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

From a conceptual point of view, the vapor intrusion model provides a theoretical description of the processes involved in vapor intrusion from subsurface soils or groundwater into indoor structures. A combination of modeling and sampling methods is also possible to reduce the uncertainty of the calculated indoor air concentrations. Typically this involves field methods for measuring soil gas very near or below an actual structure. It should be understood, however, that soil gas sampling results outside the footprint of the building may or may not be representative of the soil gas concentrations directly below the structure. For solid building floors in contact with the soil (e.g., concrete slabs), the soil gas directly beneath the floor may be considerably higher than that adjacent to the structure. This is typically due to a vapor pooling effect underneath the near impermeable floor. Once a representative average concentration is determined, all vapor directly below the areal extent of the building is presumed to enter the structure. The soil gas concentration, along with the building ventilation rate and the soil gas flow rate into the building, will determine the indoor concentration. When using the soil gas models, it must be remembered that no analysis has been made concerning the source of contamination. Therefore, the calculated indoor concentration is assumed to be steady-state. The procedures described in API (1998) can be used to calibrate the diffusion transport considerations of the J&E Model as well as for calibrating the Model for transformation processes (e.g., biodegradation). The reader is also referred to U.S. EPA (1992) for a more detailed discussion of applying soil gas measurements to indoor vapor intrusion.

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

APPENDIX A

USER'S GUIDE FOR NON-AQUEOUS PHASE LIQUIDS

Purpose

The NAPL-SCREEN and NAPL-ADV models are designed to forward calculate incremental cancer risks or noncarcinogenic hazard quotients due to subsurface soil vapor intrusion into buildings. The models are specifically designed to handle nonaqueous phase liquids or solids in soils. The user may specify up to 10 soil contaminants, the concentrations of which form a residual phase mixture. A residual phase mixture occurs when the sorbed phase, aqueous phase, and vapor phase of each chemical have reached saturation in soil. Concentrations above this saturation limit for all of the specified chemicals of a mixture will result in a fourth or residual phase (i.e., nonaqueous phase liquid or solid).

Other vapor intrusion models (SL-SCREEN, SL-ADV, SG-SCREEN, SG-ADV, GW-SCREEN, and GW-ADV) handled only a single contaminant and only when the soil concentration was at or below the soil saturation limit (i.e., a three-phase system). Use of these models when a residual phase is present, results in an overprediction of the soil vapor concentration and subsequently the building vapor concentration.

Residual Phase Theory

The three-phase system models estimate the equilibrium soil vapor concentration at the emission source (C_{source}) using the procedures from Johnson et al. (1990):

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

where: C_{source} = Vapor concentration at the source of contamination, g/cm^3
H'_{TS} = Henry's law constant at the soil temperature, dimensionless
C_R = Initial soil concentration, g/g
ρ_b = Soil dry bulk density, g/cm^3
θ_w = Soil water-filled porosity, cm^3/cm^3
K_d = Soil-water partition coefficient, cm^3/g (= $K_{oc} \times f_{oc}$)
θ_a = Soil air-filled porosity, cm^3/cm^3
K_{oc} = Soil organic carbon partition coefficient, cm^3/g
f_{oc} = Soil organic carbon weight fraction.

In Equation 1, the equilibrium vapor concentration is proportional to the soil concentration up to the soil saturation limit. When a residual phase is present, however, the vapor concentration is independent of the soil concentration but proportional to the mole fraction of the individual component of the residual phase mixture. In this case, the equilibrium vapor concentration must be calculated numerically for a series of time-steps. For each time-step, the mass of each constituent that is volatilized is calculated using Raoult's law and the appropriate mole fraction. At the end of each time-step, the total mass lost is subtracted from the initial mass and the mole fractions are recomputed for the next time-step.

The NAPL-SCREEN and NAPL-ADV models use the procedures of Johnson et al. (2001) to calculate the equilibrium vapor concentration at the source of emissions for each time-step. Within each model, the user-defined initial soil concentration of each component in the mixture is checked to see if a residual phase is present. This is done by calculating the product of the activity coefficient of component *i* in water (α_i) and the mole fraction of *i* dissolved in soil moisture (y_i) such that:

$$\alpha_i y_i = \frac{M_i}{\left[\left(P_i^v(T_S)\theta_a V / RT_S\right) + \left(M^{H2O}/\alpha_i\right) + \left(K_{d,i}M_{soil}/\alpha_i MW_{H2O}\right)\delta\left(M^{H2O}\right)\right]} \quad (2)$$

where:
M_i = Initial moles of component *i* in soil, moles
$P_i^v(T_S)$ = Vapor pressure of *i* at the average soil temperature, atm
θ_a = Soil air-filled porosity, cm^3/cm^3
V = Volume of contaminated soil, cm^3
R = Ideal gas constant, 82.05 atm-cm^3/mol-^{o}K
T_S = Average soil temperature, ^{o}K
M^{H_2O} = Total moles in soil moisture dissolved phase, moles
α_i = Activity coefficient of *i* in water, unitless
$K_{d,i}$ = Soil-water partition coefficient of *i*, cm^3/g
M_{soil} = Total mass of contaminated soil, g
MW_{H2O} = Molecular weight of water, 18 g/mol
$\delta(M^{H_2O})$ = 1 if $M^{H_2O} > 0$, and
$\delta(M^{H_2O})$ = 0 if $M^{H_2O} = 0$.

If the sum of all the values of $\alpha_i y_i$ for all of the components of the mixture is less than 1, the mixture does not contain a residual phase and the models are not applicable. In such cases, the SL-SCREEN or SL-ADV model can be used to estimate the building concentration.

Once it has been determined that a residual phase does exists, the mole fraction of each component (x_i) is determined by iteratively solving Equations 3 and 4 subject to the constraint that the sum of all the mole fractions equals unity ($\Sigma x_i = 1$):

$$x_i = \frac{M_i}{\left[\left(P_i^v(T_S)\theta_a V / RT_S\right) + M^{HC} + \left(M^{H2O}/\alpha_i\right) + \left(K_{d,i}M_{soil}/\alpha_i MW_{H2O}\right)\delta\left(M^{H2O}\right)\right]} \quad (3)$$

and,

$$x_i = \frac{M_i^{HC}}{M^{HC}} \quad (4)$$

where M_i^{HC} is the number of moles of component *i* in residual phase and M^{HC} is the total number of moles of all components in residual phase. The solution is simplified by assuming that M^{H_2O} is approximately equal to the number of moles of water in the soil moisture. With the mole fraction of each component at the initial time-step, the equilibrium vapor concentration at the source of emissions is calculated by Raoult's law:

$$C_{source} = \frac{x_i P_i^v(T_S) MW_i}{RT_S} \qquad (5)$$

where MW_i is the molecular weight of component *i* (g/mol).

At the beginning of each succeeding time-step, the number of moles of each chemical remaining in the soil from the previous time-step are again checked to see if a residual phase is present using Equation 2. When a residual phase is no longer present, the equilibrium vapor concentration at the source of emissions is calculated by:

$$C_{source} = \frac{\alpha_i y_i P_i^v(T_S) MW_i}{RT_S}. \qquad (6)$$

Ancillary Calculations

The activity coefficient of component *i* in water (α_i) is estimated from its solubility. Because hydrocarbons are typically sparingly soluble in water, the following generalization has been applied to compounds that are liquid or solid at the average soil temperature:

$$\alpha_i = (1/y_i) = (55.55 \text{ moles/L}) MW_i / S_i \qquad (7)$$

where S_i is the solubility of component *i* (g/L). For gases at the average soil temperature, the corresponding relationship is:

$$\alpha_i = (1/y_i)\left(1 atm / P_i^v(T_S)\right) = (55.55 \text{ moles}/L)\left(MW_i(1\ atm)/S_i P_i^v(T_S)\right). \qquad (8)$$

Assuming that the vapor behaves as an ideal gas with a relatively constant enthalpy of vaporization between 70°F and the average soil temperature, the Claussius-Clapeyron equation can be used to estimate the vapor pressure at the desired temperature:

$$P^v(T_S) = P^v(T_R) \times \exp\left[\left(\frac{T_B \times T_R}{(T_B - T_R)}\right)\left(\frac{1}{T_S} - \frac{1}{T_R}\right)\ln\left(\frac{P^v(T_R)}{P_B}\right)\right] \qquad (9)$$

where:
$P^v(T_S)$ = Vapor pressure at the desired temperature T_S, atm
$P^v(T_R)$ = Vapor pressure at the reference temperature T_R, atm

T_B = Normal boiling point, ^{o}K
T_R = Vapor pressure reference temperature, ^{o}K
T_S = The desired temperature, ^{o}K
P_B = Normal boiling point pressure = 1 atm.

Building Concentration

The vapor concentration within the building or enclosed space ($C_{building}$) is calculated using the steady-state solution of Johnson and Ettinger (1991) such that:

$$C_{building} = \alpha C_{source} \,. \qquad (10)$$

The steady-state attenuation coefficient (α) is calculated by:

$$\alpha = \frac{\left[\left(\dfrac{D_T^{eff} A_B}{Q_{building} L_T}\right) \times \exp\left(\dfrac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right]}{\left[\exp\left(\dfrac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left(\dfrac{D_T^{eff} A_B}{Q_{building} L_T}\right) + \left(\dfrac{D_T^{eff} A_B}{Q_{soil} L_T}\right)\left[\exp\left(\dfrac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) - 1\right]\right]} \qquad (11)$$

where:
α = Steady-state attenuation coefficient, unitless
D_T^{eff} = Total overall effective diffusion coefficient, cm^2/s
A_B = Area of the enclosed space below grade, cm^2
$Q_{building}$ = Building ventilation rate, cm^3/s
L_T = Source-building separation, cm
Q_{soil} = Volumetric flow rate of soil gas into the enclosed space, cm^3/s
L_{crack} = Enclosed space foundation or slab thickness, cm
A_{crack} = Area of total cracks, cm^2
D^{crack} = Effective diffusion coefficient through the cracks, cm^2/s.

The reader is referred to Section 2.5 of this Guidance for a more detailed discussion of the derivation of Equation 11 and procedures for determining values for model input parameters. Except for the calculation of the equilibrium vapor concentration at the source of emissions, NAPL-SCREEN is identical to the three-phase model SL-SCREEN and NAPL-ADV is identical to the three-phase model SL-ADV.

The NAPL-SCREEN and NAPL-ADV models explicitly solve for the time-averaged building concentration over the exposure duration using a forward finite-difference numerical approach. For each time-step δt:

$$M_i(t + \delta t) = M_i(t) - \delta t\left(C_{building} \times Q_{building} / MW_i\right) \qquad (12)$$

where $M_i\,(t)$ is the number of moles of component i in soil at the previous time and $M_i(t+\delta t)$ is the number of moles at the new time. The time-step interval is variable as a function of the percent of mass lost over the time-step. The user may specify a minimum and maximum percent loss allowed; these values are applied to the single component of the residual phase mixture with the highest mass loss rate during each time-step interval. If the user-specified maximum percent loss is exceeded, the next time-step interval is reduced by half; likewise, if the user-specified minimum percent loss is not achieved, the next time-step interval is increased by a factor of two. The instantaneous building concentration at time = t is calculated using Equation 10 for each time-step. The time-averaged building concentration is estimated using a trapezoidal approximation of the integral.

Model Assumptions and Limitations

The NAPL-SCREEN and NAPL-ADV models operate under the assumption that sufficient time has elapsed since the time of initial soil contamination for steady-state conditions to have been achieved. This means that the subsurface vapor plume has reached the bottom of the enclosed space floor and that the vapor concentration has reached its maximum value. An estimate of the time required to reach near steady-state conditions (τ_{ss}) can be made using the following equations from API (1998):

$$\tau_{ss} \cong \frac{R_v \theta_a L_T^{\,2}}{D^{eff}} \qquad (13)$$

and,

$$R_v = 1 + \frac{\theta_w}{\theta_a H'_{TS}} + \frac{\rho_b K_d}{\theta_a H'_{TS}} \qquad (14)$$

and,

$$D^{eff} = D_a \frac{\theta_a^{\,10/3}}{n^2} + \left(\frac{D_w}{H'_{TS}}\right)\frac{\theta_w^{\,10/3}}{n^2} \qquad (15)$$

where R_v is the unitless vapor phase retardation factor, L_T is the source-building separation (cm), D^{eff} is the effective diffusion coefficient (cm^2/s), D_a is the diffusivity in air (cm^2/s), D_w is the diffusivity in water (cm^2/s), and n is the soil total porosity (cm^3/cm^3). The NAPL-SCREEN and NAPL-ADV models are applicable only when the elapsed time since initial soil contamination meets or exceeds the value of τ_{ss} (see **Using the Models**).

Emission source depletion is calculated by estimating the rate of vapor loss as a function of time such that the mass lost at each time-step is subtracted from a finite mass of contamination at the source. This requires the model user to estimate the dimensions of the emission source, e.g., the length, width, and thickness of the contaminated zone. The model should only be used, therefore, when the extent of soil contamination has been sufficiently determined. It should be noted that because the NAPL-SCREEN and NAPL-ADV models are one-dimensional, the areal extent of soil contamination (i.e., length × width) can be less than but not greater than the areal extent of the building floor in contact with the soil.

Each model treats the contaminated zone directly below the building as a box containing a finite mass of each specified compound. The initial contamination contained within the box is assumed to be homogeneously distributed. After each time-step, the remaining contamination is assumed to be instantaneously redistributed within the box to homogeneous conditions. The diffusion path length from the top of contamination to the bottom of the enclosed space floor therefore remains constant with time. Use of this simplifying assumption means that the degree of NAPL soil saturation is not required in the calculation of the total overall effective diffusion coefficient (D_T^{eff}).

As time proceeds, the concentration of the mixture of compounds within the soil column may reach the soil saturation limit. Below this point, a residual phase will cease to exist and the vapor concentration of each chemical will decrease proportional to its total volume soil concentration. Theoretically, the vapor concentration will decrease asymptotically, approaching but never reaching zero. Because of the nature of the numerical solution to equilibrium vapor concentration, however, compounds with high effective diffusion coefficients (e.g., vinyl chloride) may reach zero soil concentrations while other less volatile contaminants will not. If the initial soil concentrations are significantly higher than their respective values of the soil saturation concentration, a residual phase may persist up to the user-defined exposure duration.

Model assumptions and limitations concerning vapor transport and vapor intrusion into buildings are those specified for the three-phase models.

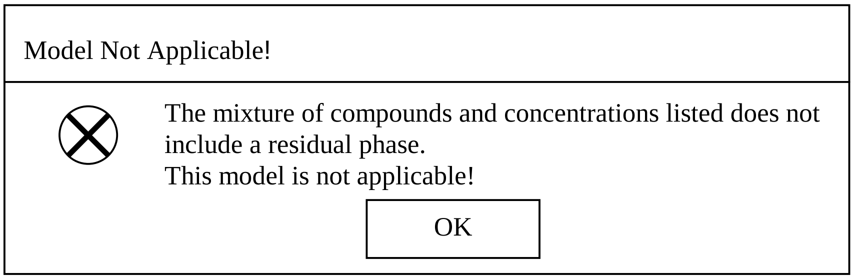
Using the Models

Each model is constructed as a Microsoft® Excel workbook containing five worksheets. The DATENTER worksheet is the data entry worksheet and also provides model results. The VLOOKUP worksheet contains the “Chemical Properties Lookup Table” with listed chemicals and associated chemical and toxicological properties. It should be noted that the toxicological properties for many of these chemicals were derived by route-to-route extrapolation. In addition, the VLOOKUP worksheet includes the “Soil Properties Lookup Table” containing values for model intermediate variables used in estimating the soil vapor permeability. The CHEMPROPS worksheet provides a summary of the chemical and toxicological properties of the soil contaminants selected by the user. In addition, the CHEMPROPS worksheet provides calculated values for the soil saturation concentration (C_{sat}) and the time to reach steady-state conditions (τ_{ss}) once all required data are entered into the DATENTER worksheet. The INTERCALCS worksheet contains calculated values of intermediate model variables. Finally, the COMPUTE worksheet contains the numerical solutions for equilibrium vapor concentration and building vapor concentration as a function of time.

Both models use the Microsoft® SOLVER add-in algorithms to simultaneously solve Equations 3 and 4 for each of up to 10 chemicals specified by the user. In order to run NAPL-SCREEN or NAPL-ADV, the SOLVER add-in must be loaded into EXCEL. The user is referred to the EXCEL instructions for loading the SOLVER add-in.

On the DATENTER worksheet, the user may specify up to 10 soil contaminants by CAS number along with associated soil concentrations in units of mg/kg. The CAS number entered must match exactly one of the 93 chemicals listed in the VLOOKUP worksheet or the error message "CAS No. not found" will appear in the "Chemical" box. If the list of chemicals and concentrations entered does not constitute a residual phase, the error message in Figure 1 will appear after starting the model.

Figure 1. Residual Phase Error Message



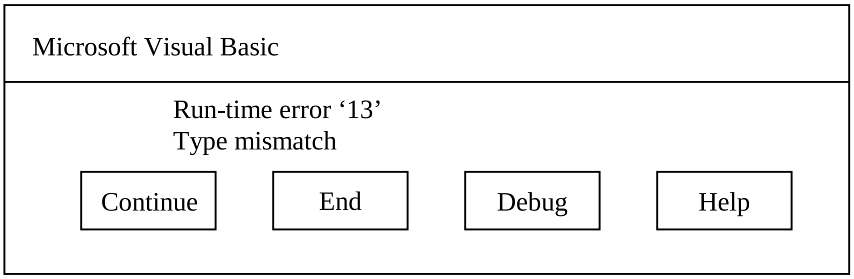
Model Not Applicable!

The mixture of compounds and concentrations listed does not include a residual phase.
This model is not applicable!

If this error message box appears, use either the SL-SCREEN or SL-ADV model to estimate subsurface vapor intrusion into the building.

After starting the model calculations, other error message boxes may appear if data entry values are missing on the DATENTER worksheet or if entered values do not conform to model assumptions. If such an error message box appears, fill-in missing data or re-enter data as appropriate. If entered data values are outside the expected range or if text values are entered where numeric values are expected, the model calculation macro will be suspended and the run-time error message in Figure 2 will appear.

Figure 2. Run-Time Error Message



Microsoft Visual Basic

Run-time error '13'
Type mismatch

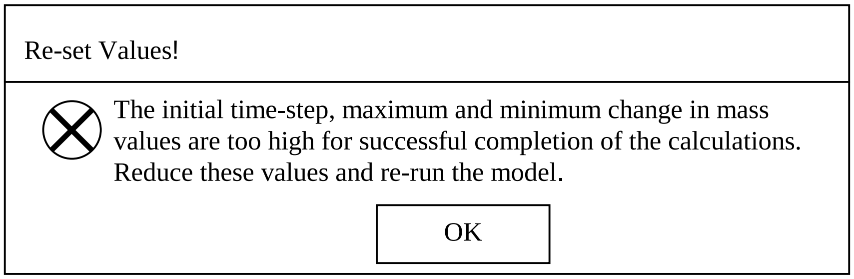
Should this error message appear, click on the "End" button to terminate the macro and return to the DATENTER worksheet. At this point, the user should review all of the entered values and make the appropriate corrections.

In addition to contaminant data, soil properties data, zone of contamination data, and exposure assumptions must also be specified in the DATENTER worksheet. Similar to the SL-SCREEN three-phase model, the NAPL-SCREEN model allows for only one soil stratum between the top of contamination and the bottom of the building floor in contact with the soil. In addition, the NAPL-SCREEN model uses built-in default values for all building variables (e.g., building dimensions, air exchange rate, total crack area, etc.). These default values are for single-family detached residences; therefore, the NAPL-SCREEN model should only be used for the residential exposure scenario.

The NAPL-ADV model, like the SL-ADV model, allows for up to three different soil strata between the top of contamination and the bottom of the building floor. In addition, the NAPL-ADV model allows the user to enter values for all model variables. This allows for the estimation of soil vapor intrusion into buildings other than single-family residences.

For each model, the user must also enter the duration of the first (initial) time-step interval. The maximum and minimum change in mass for each time-step must also be specified. The values of the initial time-step interval, and the maximum and minimum change in mass are important. If these values are too low, the model will calculate very small increments in the mass lost over time which will greatly extend the run-time of the model. In general, if the concentrations of the least volatile chemicals in the mixture are well above their respective values of the soil saturation concentration, a relatively large initial time-step interval, and maximum and minimum change in mass should be specified (e.g., 4 days, 10%, and 5%, respectively). For comparison, the value of the soil saturation concentration (C_{sat}) for each chemical specified by the user may be found in the CHEMPROPS worksheet after all data have been entered on the DATENTER worksheet. If, however, the soil concentrations of the most volatile constituents are very close to their respective saturation limits, large values of the initial time-step interval, and the maximum and minimum change in mass will result in the error message in Figure 3 after starting the model.

Figure 3. Time-Step and Change in Mass Error Message

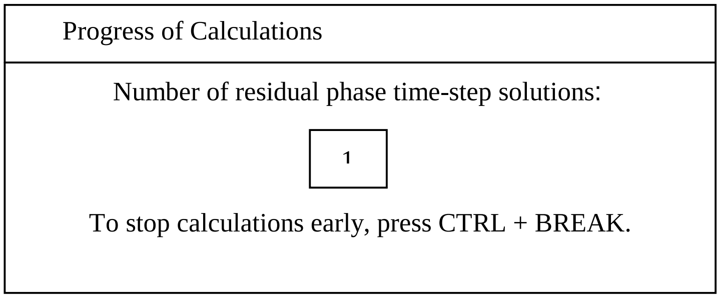


The initial time-step, maximum and minimum change in mass values are too high for successful completion of the calculations. Reduce these values and re-run the model.

Should this error message occur, reduce the value of the initial time-step interval and the values of the maximum and minimum change in mass to smaller values and re-run the model. The error message will be repeated until the values of these variables are sufficiently small.

After all required data are entered into the DATENTER worksheet, the model is run by clicking on the “Execute Model” button which will change from reading “Execute” to “Stand by...”. In addition, the message box in Figure 4 will appear keeping a running count of the number of residual phase time-step solutions achieved by the model.

Figure 4. Progress of Calculations Message Box



Progress of Calculations

Number of residual phase time-step solutions:

1

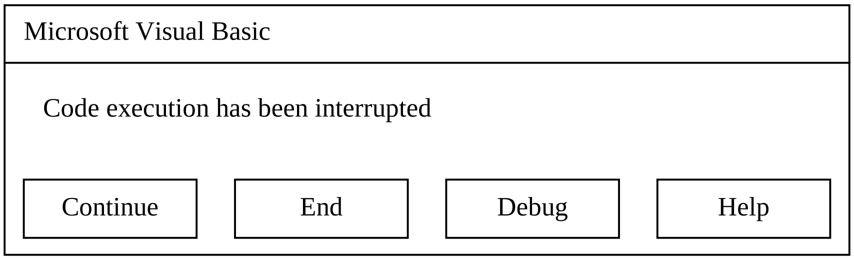
To stop calculations early, press CTRL + BREAK.

Each SOLVER trial solution can also be seen running in the status bar at the bottom of the screen. When the model is finished calculating, the “Execute Model” button will read “Done” and the Progress of Calculations message box in Figure 4 will disappear. The time-averaged building concentrations, incremental cancer risks, and/or hazard quotients will then be displayed under the “RESULTS” section of the DATENTER worksheet. In addition, an “X” will appear beside the calculated risk or hazard quotient of each contaminant for which a route-to-route extrapolation was employed. It should be noted that a route-to-route extrapolation was used for any chemical without a unit risk factor (URF) or a reference concentration (RfC). Therefore, the user should evaluate the resulting cancer risks and/or hazard quotients of such chemicals. Once a solution has been achieved and the user wishes to save the results, the file should be saved under a new file name. If the user wishes to delete <u>all</u> of the data previously entered on the DATENTER worksheet, this may be accomplished by clicking on the “Clear Data Entry Sheet” button.

Stopping Calculations Early

As mentioned previously, the user-defined values of the initial time-step interval, and the maximum and minimum change in mass should be chosen carefully. If the model run-time is excessive or if the user simply wishes to terminate the calculations, the model may be stopped by pressing CTRL + BREAK. If termination occurs in-between SOLVER solutions, the message box in Figure 5 will appear.

Figure 5. Code Interruption Message Box

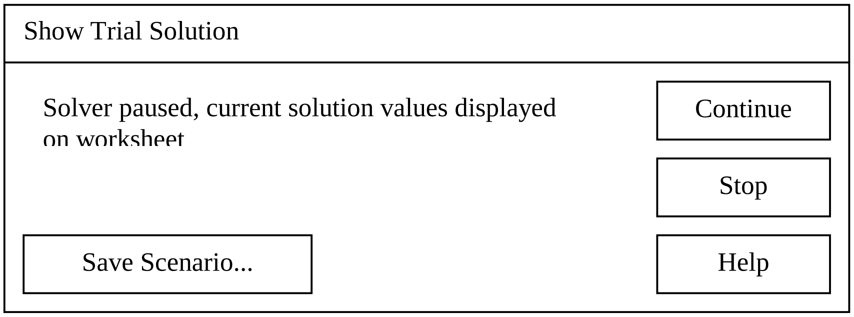


Code execution has been interrupted

If this message box appears, click on the "End" button to terminate the macro.

If the termination occurs during a SOLVER solution, the message box in Figure 6 will appear. If this message box appears, click on the "Stop" button. This will stop the SOLVER solution but not the program macro. Depending on where in the macro code the interruption occurs, the model may continue to operate after clicking on the "Stop" button in Figure 6. If this happens, press CTRL + BREAK again. At this point, the message box in Figure 5 will appear; click on the "End" button to terminate the macro.

Figure 6. Solver Interruption Message Box



Solver paused, current solution values displayed on worksheet

At this point, the user may examine the model results up to the point of termination on the COMPUTE worksheet. The values of the "Change in mass", the "Time-step interval", and the "Cumulative time" should be examined to determine if changes are necessary in the values of the initial time-step interval, and the maximum and minimum change in mass. After these or any other values are changed on the DATENTER worksheet, the model may be re-run by clicking on the "Execute Model" button.

Step-By-Step Procedures for Running the Models

The following gives the step-by-step procedures for running either the NAPL-SCREEN or the NAPL-ADV model.

1. On the DATENTER worksheet, enter the CAS number of each soil contaminant in the residual phase mixture (do not include dashes in the CAS numbers). After the CAS numbers have been entered, the respective chemical names will appear in the "Chemical" box.

2. On the DATENTER worksheet, enter the soil concentration of each contaminant in units of mg/kg as well as values for all remaining variables except the "Initial time-step", the "Maximum change in mass", and the "Minimum change in mass".

3. On the CHEMPROPS worksheet, note the calculated values of the "Time to steady state" (τ_{ss}) for each contaminant. Calculated values of the time-averaged building concentration and associated risks for contaminants with values of τ_{ss} greater than the actual elapsed time since initial soil contamination will be artificially high.

4. On the CHEMPROPS worksheet, note the calculated values of the "Soil saturation concentration" (C_{sat}) for each contaminant. Use these data to help determine appropriate user-defined values for the initial time-step, and the maximum and minimum change in mass. Typical values for these variables might be 2 days, 7%, and 4%, respectively, but may be considerably higher or lower depending on the number of chemicals in the analysis and the starting soil concentrations (see the discussion on page 8).

5. Click on the "Execute Model" button to begin the model calculations. If data are missing on the DATENTER worksheet, or entered values do not conform to model assumptions, an error message box will appear after the model is started informing the user of the type of error encountered. Enter the appropriate values on the DATENTER worksheet and re-run the model. Once the model has successfully started, note the number of residual phase time-step solutions achieved by the model in the Progress of Calculations message box (Figure 4). Use this information to help establish new values for the initial time-step interval and the maximum and minimum change in mass if the number of time-steps needs to be increased or decreased.

6. When the NAPL-SCREEN model has finished calculating, check column "O" on the COMPUTE worksheet to determine how many time-steps were calculated while a residual phase was present; one time-step is equal to one row (when using the NAPL-ADV model check column "P"). A residual phase is present when the value in column "O" or "P", as appropriate, is equal to 1.000. In general, a greater number of time-steps means a more accurate estimate of the time-averaged building concentration. If the starting soil concentrations of the most volatile contaminants are very close to their respective values of C_{sat}, a minimum of 5 to 10 time-steps should be calculated by the model. For all other cases, a reasonable number of time-steps is between 40 and 70. To increase the number of time-steps calculated by the model, decrease the values of the initial time-step interval and the maximum and minimum change in mass. The opposite is true when the number of time-steps is to be decreased.

7. If the message box in Figure 1 appears after starting the model, the mixture of compounds and concentrations specified does not include a residual phase. Use the SL-SCREEN or SL-ADV model to calculate indoor air concentrations and risks for each contaminant separately.

8. If the message box in Figure 3 appears after starting the model, reduce the input values of the initial time-step, and maximum and minimum change in mass and re-run the model.

9. If the run-time of the model is excessive, terminate the model macro by pressing CTRL + BREAK (see the discussion under **Stopping Calculations Early** on pages 9 and 10). Examine the calculated values of the "Change in mass", the "Time-step interval", and the "Cumulative time" on the COMPUTE worksheet. Re-enter new lower values for the initial time-step interval, and the maximum and minimum change in mass and re-run the model.

10. After successful completion of a model run, note the calculated values of the "Time-averaged building concentration", "Incremental cancer risk", and/or "Hazard quotient" in the "RESULTS" section of the DATENTER worksheet. Also note for which contaminants a route-to-route extrapolation was employed. <u>If the model results are to be retained, save the file under a new file name</u>.

Adding, Deleting or Revising Chemical Data

Additional chemicals can be listed in the "Chemical Properties Lookup Table" within the VLOOKUP worksheet. To add, delete or revise chemicals, the VLOOKUP worksheet must be unprotected using the password "ABC" in capital letters. Row number 171 is the last row that may be used to add new chemicals. If new chemicals are added or chemicals deleted, the user must sort all the data in the "Chemical Properties Lookup Table" (except the column headers) in ascending order by CAS number. After sorting is complete, the worksheet should again be protected.

APPENDIX E

BIBLIOGRAPHY AND REFERENCE LIST

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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

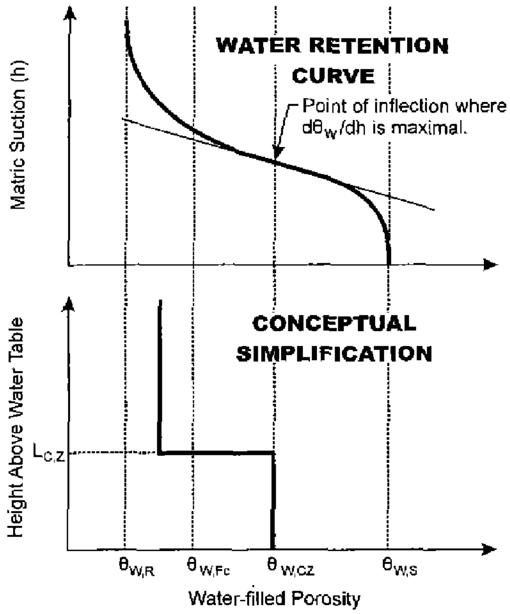

Figure 1. Conceptual simplification of water retention curve for purposes of estimating moisture contents and capillary rise ($\theta_{W,R}$, $\theta_{W,FC}$, $\theta_{W,CZ}$, $\theta_{W,S}$ are the residual, field capacity, capillary zone, and saturated water contents).

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

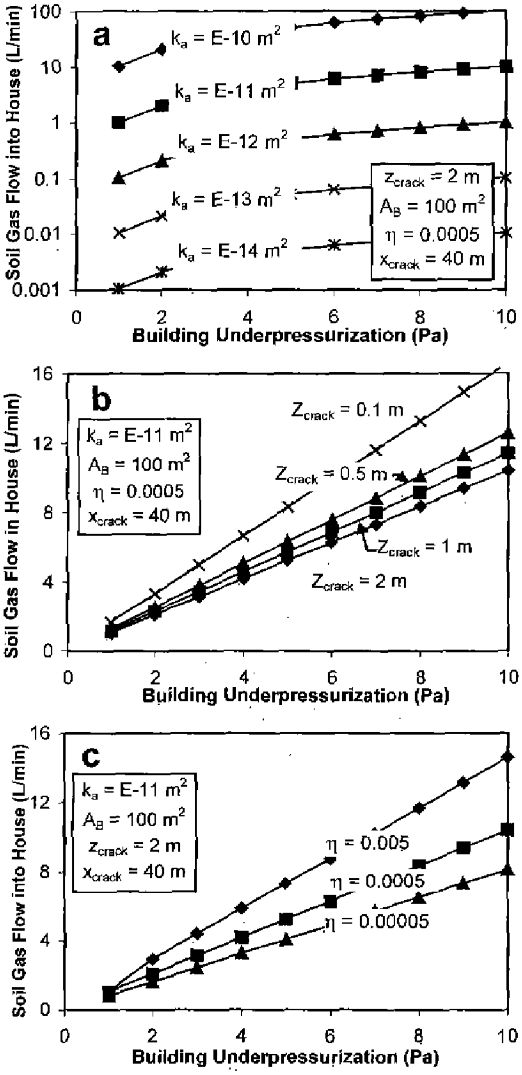

Figure 2. Sensitivity of soil gas flow to perimeter crack model (used in J&E model) to (a) soil-air permeability (k_a), (b) depth to perimeter crack (z_{crack}), and (c) crack ratio (η). X_{crack} = perimeter crack length, A_b = subsurface foundation area.

$$\eta = \frac{r_{crack}\,X_{crack}}{A_B} \qquad (3)$$

where A_B is the subsurface foundation area (L^2). The perimeter crack model accounts for both soil gas flow through soil and the foundation, but is most sensitive to the soil-air permeability based on the analysis presented in Figure 2. For the range of values chosen for k_a, η, ΔP, and z_{crack}, by far the greatest variation is obtained for k_a with the predicted Q_{soil} ranging between ~0.001 and 100 L/min.

One method of estimating soil-air permeability is to use published values for saturated hydraulic conductivity and water retention parameters for a particular soil type (EQM 2000). This method involves the following steps: (1) obtain saturated hydraulic conductivity for soil texture type (Schaap and Leij 1998); (2) estimate intrinsic permeability from saturated hydraulic conductivity; (3) estimate effective total fluid saturation at field capacity;

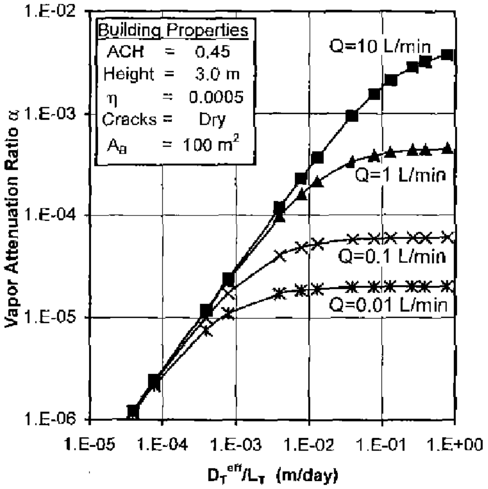

Figure 3. Sensitivity of vapor attenuation ratio (benzene) to soil-gas flow rate (Q) into building using perimeter crack model with dry dust-filled concrete cracks with total porosity = 0.3 Height = building height, Q = Q_{soil} ACH = air exchanges per hour (other symbols previously defined).

(4) estimate relative air permeability using the relationship proposed by Parker et al. (1987); and (5) calculate effective soil-air permeability (relative air permeability multiplied by intrinsic permeability). The soil-air permeability can also be measured in the field (Garbesi and Sextro 1995; Hers and Zapf-Gilje 1998); however, this type of testing is rarely performed.

The Q_{soil} can also be estimated from a tracer test mass balance. When soil-gas advection is the primary mechanism for tracer intrusion into a building, the Q_{soil} can be estimated by measuring the concentrations of a chemical tracer in indoor air, outdoor air, and in soil vapor below a building, and measuring the building ventilation rate (Hers et al. 2002; Fischer et al. 1996; Garbesi et al. 1993; Rezvan et al. 1991; Garbesi and Sextro, 1989). The Q_{soil} values measured using this technique are compared to predicted rates using the perimeter crack model, for sites with coarse-grained soils (Table 1). The perimeter crack model predictions are both higher and lower than the measured values, but overall are within one order of magnitude of the measured values. Although the Q_{soil} predicted by models and measured using field tracer tests are uncertain, the results suggest that a "typical" range for houses on coarse-grained soils is on the order of 1 to 10 L/min.

J&E Model Sensitivity for Key Input Parameters

The sensitivity of the benzene α_p predicted by the J&E model is evaluated as a function of soil gas flow (Q_{soil}), the effective diffusion coefficient (D_T^{eff}), and contamination depth (L_T) (Figure 3). The D_T^{eff}/L_T ratio captures the influence of soil properties and depth to contamination source on α_p. For BTEX and most chlorinated solvent compounds, chemical-specific variation in the D_T^{eff}/L_T ratio is not significant because the free-air diffusion coefficients vary by only a factor of two, and the Henry's law constants vary by a factor of 10 (D_T^{eff}/L_T is less sensitive to H′ than D_{air}). Because the effective diffusion coefficient is calculated using the Millington and 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.

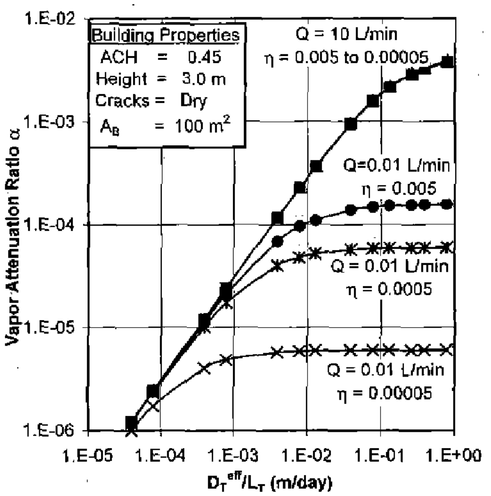

Figure 4. Sensitivity of vapor attenuation ratio (benzene) to soil-gas flow rate (Q) using perimeter crack model and foundation crack ratio (η) (other symbols previously defined).

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.

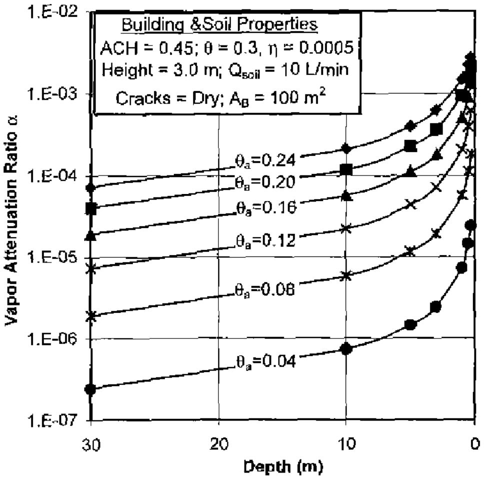

Figure 5. Sensitivity of vapor attenuation ratio (benzene) to water-filled porosity (θa). Other symbols previously defined.

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

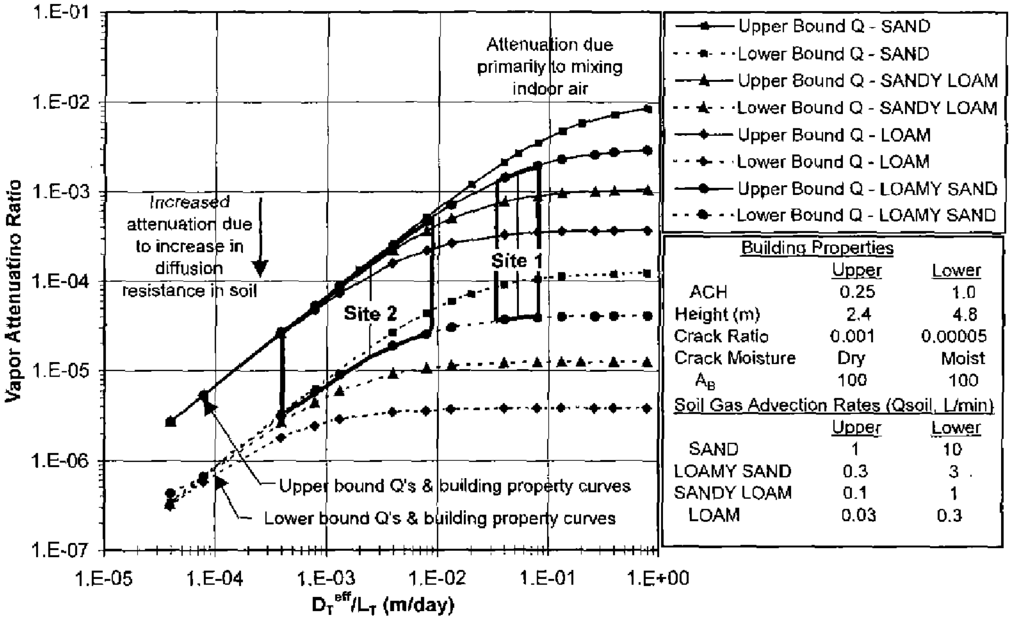

Figure 6. Predicted vapor attenuation ratio (benzene) for vapor concentrations at source and indoor air using Johnson and Ettinger (1991) model. Figure adapted from Johnson et al. (1998). Dry dust-filled cracks: Total porosity = 0.3; moist dust-filled cracks: water-filled porosity = 0.1, and total porosity = 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 petrochemical plant, NAPL above water table	research greenhouse slab-on-grade poured concrete 2 mm edge crack	surface silt to f. sand, underlain 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	benzene	V: 200	1	N/A	<9E-6	2.45E-04	
				0.7	iso-pentene	V: 28,000	1	N/A	< 9E-7	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, crawlspace, large paved area	sand & gravel, discontinuous clay lenses	~ 3	benzene	N/A	N/A	N/A	HC-like odours -- 1E-4	INS	crawlspace conc.: benzene ~ 8.3 mg/m^3, Total HC ~ 500 mg/m^3
					total HC						
"CDOT HDQ Site" Colorado, USA Johnson et al. (2000)	chlorinated solvents, dissolved plume	mostly apartments, few SFRs, mostly slab-on-grade, few crawlspaces & basements, AC mostly window units, heating natural gas,baseboard, and/or fireplaces	weathered & fractured claystone above water table	4.6	1,1 DCE	G: 10-10,000	115-	Geom	4.8E-06		a_m values for houses above plume with DCE groundwater concentration > 10 ug/L
					1,1 DCE	G: 10-10,000	150	90th	2.0E-05		
					TCE	G: 3-3,000	115-	Geom	1.4E-05		
					TCE	G: 3-3,000	150	90th	7.0E-05		
					1,1,1 TCA	G: 10-1,000	115-	Geom	1.7E-05		
					1,1,1 TCA	G: 10-1,000	150	90th	6.6E-05		
					above 3 CS		115-	Geom	1.2E-05	8.6E-05	average for 3 chlorinated solvents (CS)
					above 3 CS		150	90th	5.2E-05	2.4E-04[4]	
"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	G: 10-1,000	65	50th	1.50E-05	INS	a_m values for houses above plume with DCE groundwater concentration > 10 ug/L
					1,1 DCE	G: 10-1,000	65	Avg	7.60E-05		
					1,1 DCE	G: 10-1,000	65	90th	1.20E-04		
Hamilton Site Colorado, USA (2001), unpublished	chlorinated solvents, dissolved plume	SFRs built 50's most basements	primarily sand & & gravel, some clay & silt layers	9.7 to 11	1,1 DCE	G: 15-30	32	50th	6.80E-05	INS	Gravel at water table
						G: 15-30	32	90th	1.40E-04		
"Lowry (Air Force Base) Site" Colorado, USA Versar (2000)	chlorinated solvents, dissolved	SFR: mostly basements some crawlspaces	silty sand to silt, generally silty sand near water table	6.1 to 7	1,1 DCE	G: 1.4-1.9	>50	50th	2.20E-05	INS	max G a_m = 6.2E-04
					TCE	G: 120-170	>50	50th	2.20E-05		max G a_m = 1.2E-03
					1,1 DCE	V: > 29	>50	50th	6.50E-04		max V_{SS} a_m = 8.3E-03
					TCE	V: > 1,000	>50	50th	7.70E-04		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	TCE	V: 84	14	Max	2.80E-04	INS	a_m shallow vapour
						V: 84	14	2nd[6]	<1.3E-5		
				10.7	TCE	G: 735	14	Max	7.80E-05		a_m groundwater, depth to groundwater = 10.7 m
						G: 735	14	2nd	<3.6E-5		
"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 m^3, 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); [6]N/A = not available or applicable, SFR = single family residence, SF_6 = sulpher 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[4]	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 etimated 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

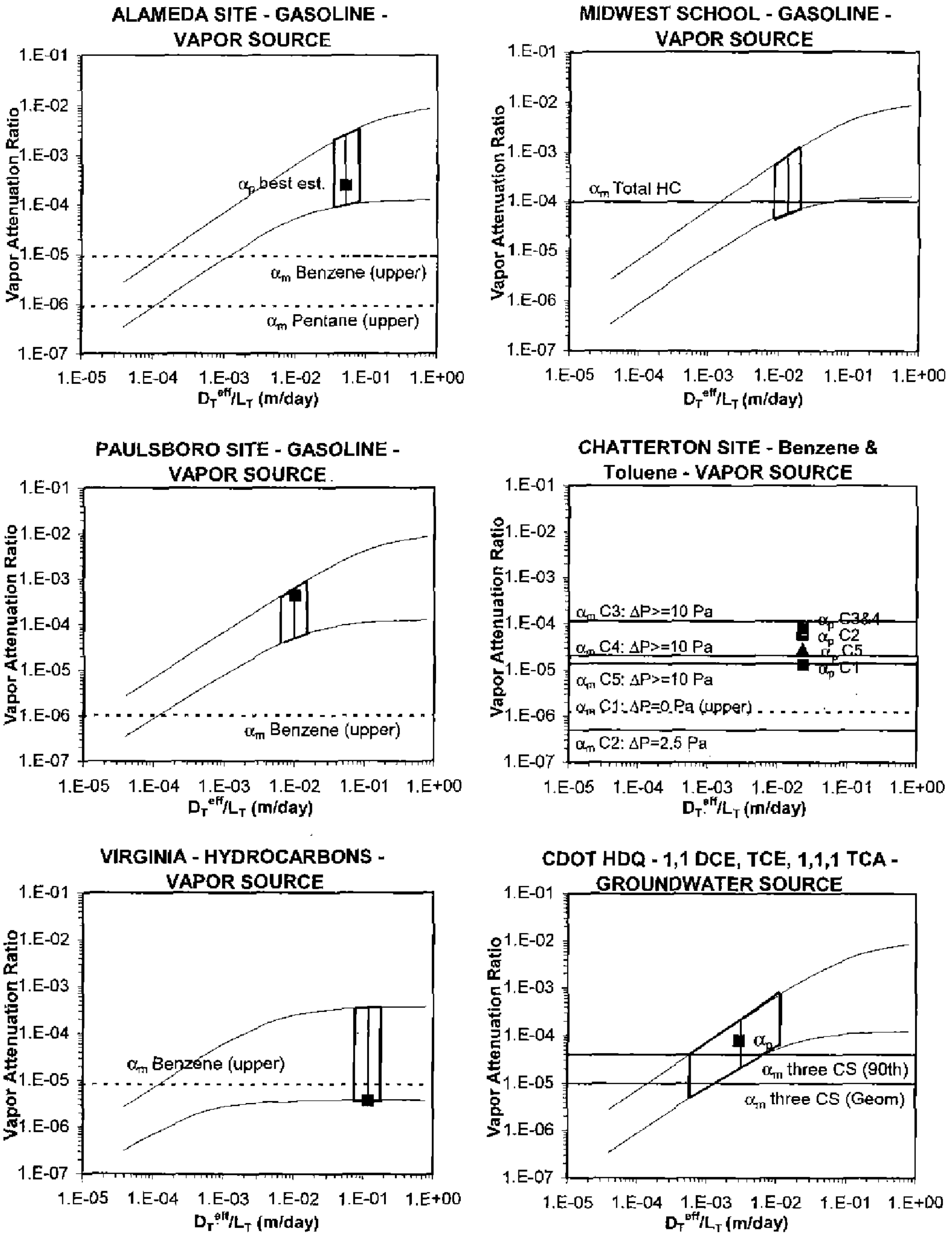

Figure 7a. Comparison between measured and J&E model-predicted vapor attenuation ratio (benzene). Upper and lower bound curves from Figure 6 are included. Dashed lines indicate that α_m is upper bound value. Symbols are best estimate α_p values.

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_m calculated using the measured indoor air concentrations are upper-bound values and range from $< 4.0 \times 10^{-7}$ to $< 9.0 \times 10^{-6}$. For the Chatterton ΔP = 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 ΔP = 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

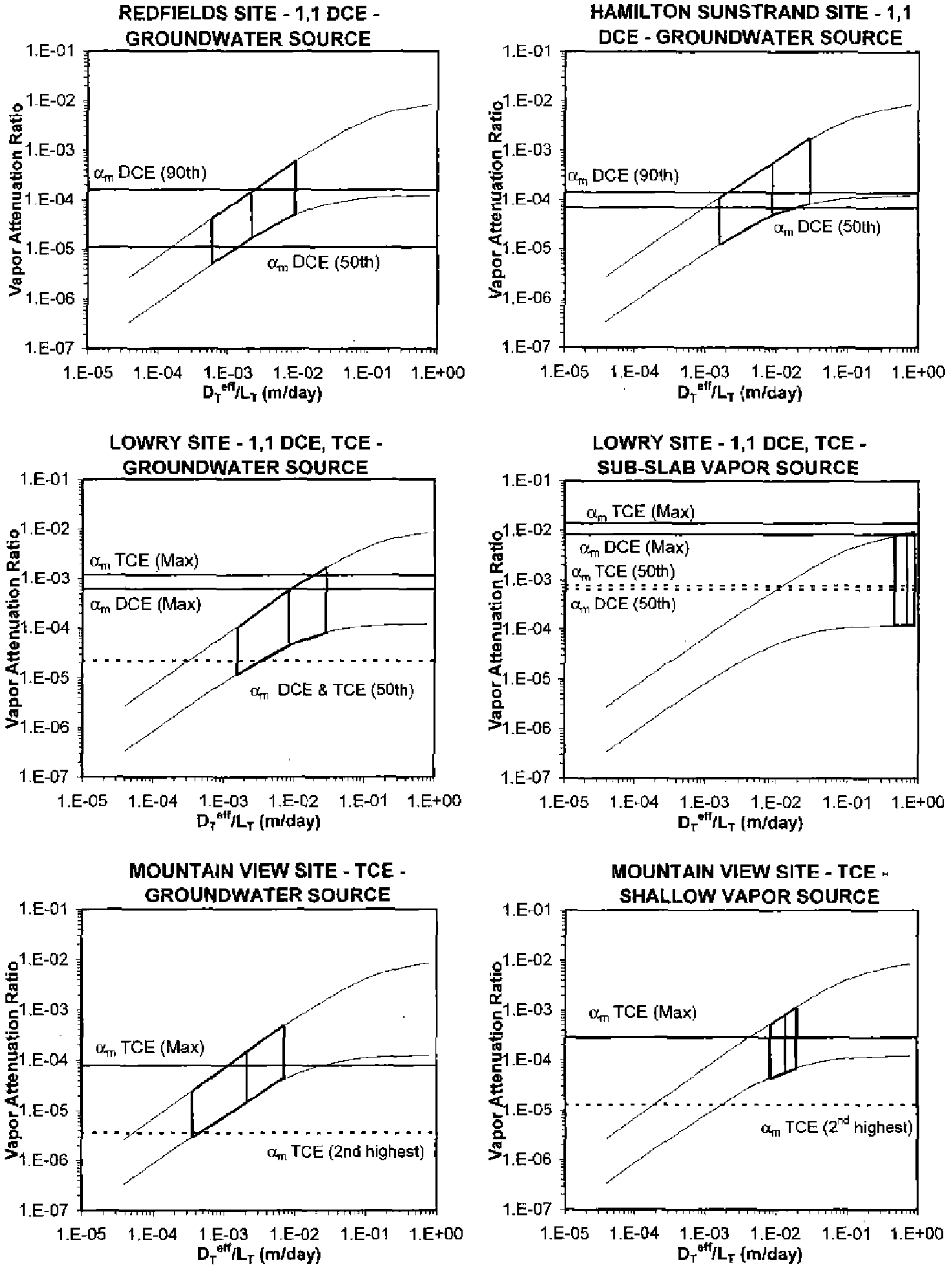

Figure 7b. Comparison between measured and J&E model-predicted vapor attenuation ratio (benzene). Upper and lower bound curves from Figure 6 are included. Dashed lines indicate that α_m is upper bound.

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.

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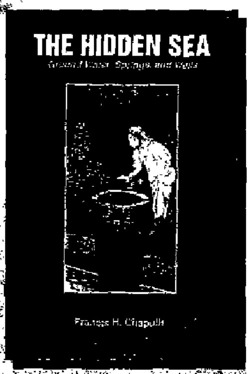

APPENDIX 4

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.

DATA ENTRY SHEET

GW-ADV
Version 3.0; 02/03

Reset to Defaults

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

YES X

OR

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

YES ☐

Groundwater Vapor Emissions To Indoor Air
Residential Exposure Scenario
High Permeability Soil Scenario

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

MORE ↓

ENTER Average soil/ groundwater temperature, T_S ($^{\circ}$C)	ENTER Depth below grade to bottom of enclosed space floor, L_F (cm)	ENTER Depth below grade to water table, L_{WT} (cm)	ENTER Totals must add up to value of L_{WT} (cell G28) 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)
15	15	300	100	200		B	CL	S		

MORE ↓

ENTER Stratum A SCS soil type	ENTER Stratum A soil dry bulk density, ρ_b^A (g/cm^3)	ENTER Stratum A soil total porosity, n^A (unitless)	ENTER Stratum A soil water-filled porosity, θ_w^A (cm^3/cm^3)	ENTER Stratum B SCS soil type	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	ENTER Stratum C SCS soil type	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)
Lookup Soil Parameters				Lookup Soil Parameters				Lookup Soil Parameters			
S	1.50	0.430	0.15	CL	1.5	0.43	0.3				

MORE ↓

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP (g/cm-s^2)	ENTER Enclosed space floor length, L_B (cm)	ENTER Enclosed space floor width, W_B (cm)	ENTER Enclosed space height, H_B (cm)	ENTER Floor-wall seam crack width, w (cm)	ENTER Indoor air exchange rate, ER (1/h)	ENTER Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
15	40	961	961	244	0.1	1	5

MORE ↓

ENTER Averaging time for carcinogens, AT_C (yrs)	ENTER Averaging time for noncarcinogens, AT_{NC} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)	ENTER Target risk for carcinogens, TR (unitless)	ENTER Target hazard quotient for noncarcinogens, THQ (unitless)
70	30	30	350	1.0E-06	0.2
				Used to calculate risk-based groundwater concentration.	

END

DATA ENTRY SHEET

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H ($atm\text{-}m^3/mol$)	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	6.0E-06	3.5E-02

END

DATA ENTRY SHEET

Exposure duration, τ (sec)	Source-building separation, L_T (cm)	Stratum A soil air-filled porosity, θ_a^A (cm^3/cm^3)	Stratum B soil air-filled porosity, θ_a^B (cm^3/cm^3)	Stratum C soil air-filled porosity, θ_a^C (cm^3/cm^3)	Stratum A effective total fluid saturation, S_{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} (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)	Unit risk factor, URF (μg/m^3)$^{-1}$	Reference conc., RfC (mg/m^3)
15	4.46E+02	0.10	8.33E+01	5.62E-03	3.84E+02	2.87E+251	7.30E-06	3.26E-03	6.0E-06	3.5E-02

END

DATA ENTRY SHEET

RISK-BASED GROUNDWATER CONCENTRATION CALCULATIONS:

Indoor exposure groundwater conc., carcinogen (μg/L)	Indoor exposure groundwater conc., noncarcinogen (μg/L)	Risk-based indoor exposure groundwater conc., (μg/L)	Pure component water solubility, S (μg/L)	Final indoor exposure groundwater conc., (μg/L)
1.25E+02	2.24E+03	1.25E+02	2.00E+05	1.25E+02

INCREMENTAL RISK CALCULATIONS:

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

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

MESSAGE: The values of Csource and Cbuilding on the INTERCALCS worksheet are based on unity and do not represent actual values.

SCROLL DOWN TO "END"

END

DATA ENTRY SHEET

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α_1 (1/cm)	N (unitless)	M (unitless)	n (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)	Bulk Density (g/cm^3)	θ_w (cm^3/cm^3)	SCS Soil Name
C	0.61	0.01496	1.253	0.2019	0.459	0.098	0.0092	1.43	0.215	Clay
CL	0.34	0.01581	1.416	0.2938	0.442	0.079	0.016	1.48	0.168	Clay Loam
L	0.50	0.01112	1.472	0.3207	0.399	0.061	0.020	1.59	0.148	Loam
LS	4.38	0.03475	1.746	0.4273	0.390	0.049	0.040	1.62	0.076	Loamy Sand
S	26.78	0.03524	3.177	0.6852	0.375	0.053	0.044	1.66	0.054	Sand
SC	0.47	0.03342	1.208	0.1722	0.385	0.117	0.025	1.63	0.197	Sandy Clay
SCL	0.55	0.02109	1.330	0.2481	0.384	0.063	0.029	1.63	0.146	Sandy Clay Loam
SI	1.82	0.00658	1.679	0.4044	0.489	0.050	0.0046	1.35	0.167	Silt
SIC	0.40	0.01622	1.321	0.2430	0.481	0.111	0.0039	1.38	0.216	Silty Clay
SICL	0.46	0.00839	1.521	0.3425	0.482	0.090	0.0056	1.37	0.198	Silty Clay Loam
SIL	0.76	0.00506	1.663	0.3987	0.439	0.065	0.011	1.49	0.180	Silt Loam
SL	1.60	0.02667	1.449	0.3099	0.387	0.039	0.030	1.62	0.103	Sandy Loam

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 ($atm\text{-}m^3/mol$)	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)	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	4.3E-05	4.0E-02		
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		3.2E+00		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	5.4E-06	4.9E-02		
71432	Benzene	5.90E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.56E-03	25	353.24	562.16	7,342	2.9E-05	6.0E-02		
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		2.2E+00		
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		4.9E-03		
74873	Methyl chloride (chloromethane)	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	249.00	416.25	5,115	7.4E-06	3.0E-01		
75003	Chloroethane (ethyl chloride)	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.30	460.40	5,879	8.3E-07	1.0E+01	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	7.7E-05	1.0E-01		
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	1.0E-06	3.0E+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	7,800	3.7E-05	7.0E-02	X	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	1.6E-06	4.9E-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		2.0E-01		
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	1.0E-05	3.9E-03	X	
78933	Methylethylketone (2-butanone)	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	352.50	536.78	7,481		1.0E+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		X
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	2.0E-06	6.0E-01	X	
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	5.7E-05	2.1E-01		X
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		2.1E-01		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		1.4E-01		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.26	761.00	12,600		1.4E-01		X
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	3.4E-05	9.0E-03		
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		
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		1.8E-02		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	739.13	13,000		3.5E-01		
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		2.0E+00		
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		1.0E+00		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	452.00	685.00	8,773		7.0E-02	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	1.1E-05	8.1E-01		
106934	1,2-Dibromoethane (ethylene dibro	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.60	583.00	8,310	7.1E-05	9.1E-03		
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	2.1E-05	4.9E-03		
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		8.1E-02		
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		7.0E-01		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		3.0E-01		
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		6.0E-02		
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	10,803	7.1E-04			
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		1.1E+00		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		3.5E-03		
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	5,900	2.7E-05	7.0E-02	X	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	6.0E-06	3.5E-02		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936	14370		1.1E-01		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	7192		3.5E-02		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	516.5	6717		7.0E-02		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	7900	1.6E-05	7.0E-02		
1634044	MTBE	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.3	497.1	6677.66	2.6E-07	8.0E+00		

DATA ENTRY SHEET

GW-ADV
Version 3.0; 02/03

Reset to Defaults

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

YES ☒ X

OR

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

YES ☐

Groundwater Vapor Emissions To Indoor Air
Commercial/Industrial Exposure Scenario
High Permeability Soil Scenario

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

MORE ↓

ENTER Average soil/ groundwater temperature, T_S ($^{\circ}$C)	ENTER Depth below grade to bottom of enclosed space floor, L_F (cm)	ENTER Depth below grade to water table, L_{WT} (cm)	ENTER Totals must add up to value of L_{WT} (cell G28) 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)
15	15	300	100	200		B	CL	S		

MORE ↓

ENTER Stratum A SCS soil type Lookup Soil Parameters	ENTER Stratum A soil dry bulk density, ρ_b^A (g/cm^3)	ENTER Stratum A soil total porosity, n^A (unitless)	ENTER Stratum A soil water-filled porosity, θ_w^A (cm^3/cm^3)	ENTER Stratum B SCS soil type Lookup Soil Parameters	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	ENTER Stratum C SCS soil type Lookup Soil Parameters	ENTER Stratum C soil dry bulk density, ρ_b^C (g/cm^3)	ENTER Stratum C soil total porosity, n^C (unitless)	ENTER Stratum C soil water-filled porosity, θ_w^C (cm^3/cm^3)
S	1.50	0.430	0.15	CL	1.5	0.43	0.3				

MORE ↓

ENTER Enclosed space floor thickness, L_{crack} (cm)	ENTER Soil-bldg. pressure differential, ΔP (g/cm-s^2)	ENTER Enclosed space floor length, L_B (cm)	ENTER Enclosed space floor width, W_B (cm)	ENTER Enclosed space height, H_B (cm)	ENTER Floor-wall seam crack width, w (cm)	ENTER Indoor air exchange rate, ER (1/h)	ENTER Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
15	40	961	961	244	0.1	2	5

MORE ↓

ENTER Averaging time for carcinogens, AT_C (yrs)	ENTER Averaging time for noncarcinogens, AT_{NC} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)	ENTER Target risk for carcinogens, TR (unitless)	ENTER Target hazard quotient for noncarcinogens, THQ (unitless)
70	25	25	250	1.0E-06	0.2

Used to calculate risk-based groundwater concentration.

END

DATA ENTRY SHEET

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H ($atm\text{-}m^3/mol$)	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	6.0E-06	3.5E-02

END

DATA ENTRY SHEET

Exposure duration, τ (sec)	Source-building separation, L_T (cm)	Stratum A soil air-filled porosity, θ_a^A (cm^3/cm^3)	Stratum B soil air-filled porosity, θ_a^B (cm^3/cm^3)	Stratum C soil air-filled porosity, θ_a^C (cm^3/cm^3)	Stratum A effective total fluid saturation, S_{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} ($atm\text{-}m^3/mol$)	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	8.33E+01	5.62E-03	3.84E+02	2.87E+251	3.65E-06	1.63E-03	6.0E-06	3.5E-02

END

DATA ENTRY SHEET

RISK-BASED GROUNDWATER CONCENTRATION CALCULATIONS:

Indoor exposure groundwater conc., carcinogen (μg/L)	Indoor exposure groundwater conc., noncarcinogen (μg/L)	Risk-based indoor exposure groundwater conc., (μg/L)	Pure component water solubility, S (μg/L)	Final indoor exposure groundwater conc., (μg/L)
4.18E+02	6.28E+03	4.18E+02	2.00E+05	4.18E+02

INCREMENTAL RISK CALCULATIONS:

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

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

MESSAGE: The values of Csource and Cbuilding on the INTERCALCS worksheet are based on unity and do not represent actual values.

SCROLL DOWN TO "END"

END

DATA ENTRY SHEET

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α_1 (1/cm)	N (unitless)	M (unitless)	n (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)	Bulk Density (g/cm^3)	θ_w (cm^3/cm^3)	SCS Soil Name
C	0.61	0.01496	1.253	0.2019	0.459	0.098	0.0092	1.43	0.215	Clay
CL	0.34	0.01581	1.416	0.2938	0.442	0.079	0.016	1.48	0.168	Clay Loam
L	0.50	0.01112	1.472	0.3207	0.399	0.061	0.020	1.59	0.148	Loam
LS	4.38	0.03475	1.746	0.4273	0.390	0.049	0.040	1.62	0.076	Loamy Sand
S	26.78	0.03524	3.177	0.6852	0.375	0.053	0.044	1.66	0.054	Sand
SC	0.47	0.03342	1.208	0.1722	0.385	0.117	0.025	1.63	0.197	Sandy Clay
SCL	0.55	0.02109	1.330	0.2481	0.384	0.063	0.029	1.63	0.146	Sandy Clay Loam
SI	1.82	0.00658	1.679	0.4044	0.489	0.050	0.0046	1.35	0.167	Silt
SIC	0.40	0.01622	1.321	0.2430	0.481	0.111	0.0039	1.38	0.216	Silty Clay
SICL	0.46	0.00839	1.521	0.3425	0.482	0.090	0.0056	1.37	0.198	Silty Clay Loam
SIL	0.76	0.00506	1.663	0.3987	0.439	0.065	0.011	1.49	0.180	Silt Loam
SL	1.60	0.02667	1.449	0.3099	0.387	0.039	0.030	1.62	0.103	Sandy Loam

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)	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	4.3E-05	4.0E-02		
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		3.2E+00		X
67663	Chloroform	3.98E+01	1.04E-01	1.00E-05	7.92E+03	1.50E-01	3.67E-03	25	329.20	508.10	6,955	5.4E-06	4.9E-02		
71432	Benzene	5.90E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.56E-03	25	353.24	562.16	7,342	2.9E-05	6.0E-02		
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		2.2E+00		
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		4.9E-03		
74873	Methyl chloride (chloromethane)	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	249.00	416.25	5,115	7.4E-06	3.0E-01		
75003	Chloroethane (ethyl chloride)	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.30	460.40	5,879	8.3E-07	1.0E+01	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	7.7E-05	1.0E-01		
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	1.0E-06	3.0E+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	7,800	3.7E-05	7.0E-02	X	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	1.6E-06	4.9E-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		2.0E-01		
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	1.0E-05	3.9E-03	X	
78933	Methylethylketone (2-butanone)	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	352.50	536.78	7,481		1.0E+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		X
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	2.0E-06	6.0E-01	X	
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	5.7E-05	2.1E-01		X
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		2.1E-01		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		1.4E-01		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.26	761.00	12,600		1.4E-01		X
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	3.4E-05	9.0E-03		
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		
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		1.8E-02		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	739.13	13,000		3.5E-01		
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		2.0E+00		
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		1.0E+00		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	452.00	685.00	8,773		7.0E-02	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	1.1E-05	8.1E-01		
106934	1,2-Dibromoethane (ethylene dibro	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.60	583.00	8,310	7.1E-05	9.1E-03		
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	2.1E-05	4.9E-03		
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		8.1E-02		
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		7.0E-01		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		3.0E-01		
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		6.0E-02		
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	10,803	7.1E-04			
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		1.1E+00		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		3.5E-03		
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	5,900	2.7E-05	7.0E-02	X	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	6.0E-06	3.5E-02		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936	14370		1.1E-01		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	7192		3.5E-02		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	516.5	6717		7.0E-02		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	7900	1.6E-05	7.0E-02		
1634044	MTBE	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.3	497.1	6677.66	2.6E-07	8.0E+00		

DATA ENTRY SHEET

SL-ADV
Version 3.0; 02/03

Reset to Defaults

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 ☐

Soil Vapor Emissions To Indoor Air
Residential Exposure Scenario

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** Totals must add up to value of L_t (cell G28) 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)		**ENTER** User-defined stratum A soil vapor permeability, k_v (cm^2)
20	15	15	215	15			S	OR	

MORE ↓

ENTER Stratum A SCS soil type (Lookup Soil Parameters)	**ENTER** Stratum A soil dry bulk density, ρ_b^A (g/cm^3)	**ENTER** Stratum A soil total porosity, n^A (unitless)	**ENTER** Stratum A soil water-filled porosity, θ_w^A (cm^3/cm^3)	**ENTER** Stratum A soil organic carbon fraction, f_{oc}^A (unitless)	**ENTER** Stratum B SCS soil type (Lookup Soil Parameters)	**ENTER** Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	**ENTER** Stratum B soil total porosity, n^B (unitless)	**ENTER** Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	**ENTER** Stratum B soil organic carbon fraction, f_{oc}^B (unitless)	**ENTER** Stratum C SCS soil type (Lookup Soil Parameters)	**ENTER** Stratum C soil dry bulk density, ρ_b^C (g/cm^3)	**ENTER** Stratum C soil total porosity, n^C (unitless)	**ENTER** Stratum C soil water-filled porosity, θ_w^C (cm^3/cm^3)	**ENTER** Stratum C soil organic carbon fraction, f_{oc}^C (unitless)
S	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-s^2)	**ENTER** Enclosed space floor length, L_B (cm)	**ENTER** Enclosed space floor width, W_B (cm)	**ENTER** Enclosed space height, H_B (cm)	**ENTER** Floor-wall seam crack width, w (cm)	**ENTER** Indoor air exchange rate, ER (1/h)	**ENTER** Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
15	40	961	961	244	0.1	1	5

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

DATA ENTRY SHEET

Diffusivity in air, D_a (cm^2/s)	Diffusivity in water, D_w (cm^2/s)	Henry's law constant at reference temperature, H (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	6.0E-06	3.5E-02	L

END

DATA ENTRY SHEET

Exposure duration, τ (sec)	Source-building separation, L_T (cm)	Stratum A soil air-filled porosity, θ_a^A (cm^3/cm^3)	Stratum B soil air-filled porosity, θ_a^B (cm^3/cm^3)	Stratum C soil air-filled porosity, θ_a^C (cm^3/cm^3)	Stratum A effective total fluid saturation, S_{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)	Floor-wall seam perimeter, X_{crack} (cm)	Initial soil concentration used, C_R ($\mu g/kg$)	Bldg. ventilation rate, $Q_{building}$ (cm^3/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, A_B (cm^2)	Crack-to-total area ratio, η (unitless)	Crack depth below grade, Z_{crack} (cm)	Enthalpy of vaporization at ave. soil temperature, $\Delta H_{v,TS}$ (cal/mol)	Henry's law constant at ave. soil temperature, H_{TS} ($atm\text{-}m^3/mol$)	Henry's law constant at ave. soil 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)
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, K_d (cm^3/g)	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., $C_{building}$ ($\mu g/m^3$)	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)
9.30E-01	5.12E+02	0.10	8.33E+01	5.62E-03	3.84E+02	2.88E+251	NA	NA	6.32E+01	1.92E-03	1.70E+07	YES

Finite source indoor attenuation coefficient, $<\alpha>$ (unitless)	Mass limit bldg. conc., $C_{building}$ ($\mu g/m^3$)	Finite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Final finite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
NA	4.68E-03	NA	4.68E-03	6.0E-06	3.5E-02

END

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)
8.67E+01	1.56E+03	8.67E+01	2.28E+05	8.67E+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

DATA ENTRY SHEET

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α_1 (1/cm)	N (unitless)	M (unitless)	n (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)	Bulk Density (g/cm^3)	θ_w (cm^3/cm^3)	SCS Soil Name
C	0.61	0.01496	1.253	0.2019	0.459	0.098	0.0092	1.43	0.215	Clay
CL	0.34	0.01581	1.416	0.2938	0.442	0.079	0.016	1.48	0.168	Clay Loam
L	0.50	0.01112	1.472	0.3207	0.399	0.061	0.020	1.59	0.148	Loam
LS	4.38	0.03475	1.746	0.4273	0.390	0.049	0.040	1.62	0.076	Loamy Sand
S	26.78	0.03524	3.177	0.6852	0.375	0.053	0.044	1.66	0.054	Sand
SC	0.47	0.03342	1.208	0.1722	0.385	0.117	0.025	1.63	0.197	Sandy Clay
SCL	0.55	0.02109	1.330	0.2481	0.384	0.063	0.029	1.63	0.146	Sandy Clay Loam
SI	1.82	0.00658	1.679	0.4044	0.489	0.050	0.0046	1.35	0.167	Silt
SIC	0.40	0.01622	1.321	0.2430	0.481	0.111	0.0039	1.38	0.216	Silty Clay
SICL	0.46	0.00839	1.521	0.3425	0.482	0.090	0.0056	1.37	0.198	Silty Clay Loam
SIL	0.76	0.00506	1.663	0.3987	0.439	0.065	0.011	1.49	0.180	Silt Loam
SL	1.60	0.02667	1.449	0.3099	0.387	0.039	0.030	1.62	0.103	Sandy Loam

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 ($atm\text{-}m^3/mol$)	Henry's law constant reference temperature, T_R (^oC)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	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)	Physical state at soil temperature, (S,L,G)	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	4.3E-05	4.0E-02	L		
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		3.2E+00	L		X
71432	Benzene	5.90E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.56E-03	25	353.24	562.16	7,342	2.9E-05	6.0E-02	L		
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		2.2E+00	L		
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		4.9E-03	L		
74873	Methyl chloride (chloromethane)	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	249.00	416.25	5,115	7.4E-06	3.0E-01	L		
75003	Chloroethane (ethyl chloride)	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.30	460.40	5,879	8.3E-07	1.0E+01	L	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	7.7E-05	1.0E-01	G		
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	1.0E-06	3.0E+00	L		
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	7,800	3.7E-05	7.0E-02	L	X	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	1.6E-06	4.9E-01	L		
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		2.0E-01	L		
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	1.0E-05	3.9E-03	L	X	
78933	Methylethylketone (2-butanone)	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	352.50	536.78	7,481		1.0E+00	L		
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	L		X
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	2.0E-06	6.0E-01	L	X	
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	5.7E-05	2.1E-01	L		X
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		2.1E-01	S		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		1.4E-01	S		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.26	761.00	12,600		1.4E-01	S		X
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	3.4E-05	9.0E-03	S		
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	L		
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		1.8E-02	L		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	739.13	13,000		3.5E-01	L		
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		2.0E+00	L		
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		1.0E+00	L		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	452.00	685.00	8,773		7.0E-02	L	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	1.1E-05	8.1E-01	L		
106934	1,2-Dibromoethane (ethylene dibr	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.60	583.00	8,310	7.1E-05	9.1E-03	L		
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	2.1E-05	4.9E-03	L		
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		8.1E-02	L		
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		7.0E-01	L		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		3.0E-01	L		
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		6.0E-02	L		
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	10,803	7.1E-04		L		
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		1.1E+00	S		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		3.5E-03	L		
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	5,900	2.7E-05	7.0E-02	L	X	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	6.0E-06	3.5E-02	L		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936	14370		1.1E-01	S		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	7192		3.5E-02	L		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	516.5	6717		7.0E-02	L		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	7900	1.6E-05	7.0E-02	L		
1634044	MTBE	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.3	497.1	6677.66	2.6E-07	8.0E+00	L		

SL-ADV
Version 3.0; 02/03

Reset to
Defaults

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

Soil Vapor Emissions To Indoor Air
Commercial/Industrial Exposure Scenario

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 Totals must add up to value of L_t (cell G28) 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)
20	15	15	215	15			S		

MORE

ENTER Stratum A SCS soil type Lookup Soil Parameters	ENTER Stratum A soil dry bulk density, ρ_b^A (g/cm^3)	ENTER Stratum A soil total porosity, n^A (unitless)	ENTER Stratum A soil water-filled porosity, θ_w^A (cm^3/cm^3)	ENTER Stratum A soil organic carbon fraction, f_{oc}^A (unitless)	ENTER Stratum B SCS soil type Lookup Soil Parameters	ENTER Stratum B soil dry bulk density, ρ_b^B (g/cm^3)	ENTER Stratum B soil total porosity, n^B (unitless)	ENTER Stratum B soil water-filled porosity, θ_w^B (cm^3/cm^3)	ENTER Stratum B soil organic carbon fraction, f_{oc}^B (unitless)	ENTER Stratum C SCS soil type Lookup Soil Parameters	ENTER Stratum C soil dry bulk density, ρ_b^C (g/cm^3)	ENTER Stratum C soil total porosity, n^C (unitless)	ENTER Stratum C soil water-filled porosity, θ_w^C (cm^3/cm^3)	ENTER Stratum C soil organic carbon fraction, f_{oc}^C (unitless)
S	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-s^2)	ENTER Enclosed space floor length, L_B (cm)	ENTER Enclosed space floor width, W_B (cm)	ENTER Enclosed space height, H_B (cm)	ENTER Floor-wall seam crack width, w (cm)	ENTER Indoor air exchange rate, ER (1/h)	ENTER Average vapor flow rate into bldg. OR Leave blank to calculate Q_{soil} (L/m)
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Used to calculate risk-based soil concentration.

END

DATA ENTRY SHEET

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END

DATA ENTRY SHEET

Exposure duration, τ (sec)	Source-building separation, L_T (cm)	Stratum A soil air-filled porosity, θ_a^A (cm^3/cm^3)	Stratum B soil air-filled porosity, θ_a^B (cm^3/cm^3)	Stratum C soil air-filled porosity, θ_a^C (cm^3/cm^3)	Stratum A effective total fluid saturation, S_{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)	Floor-wall seam perimeter, X_{crack} (cm)	Initial soil concentration used, C_R ($\mu g/kg$)	Bldg. ventilation rate, $Q_{building}$ (cm^3/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, A_B (cm^2)	Crack-to-total area ratio, η (unitless)	Crack depth below grade, Z_{crack} (cm)	Enthalpy of vaporization at ave. soil temperature, $\Delta H_{v,TS}$ (cal/mol)	Henry's law constant at ave. soil temperature, H_{TS} ($atm\text{-}m^3/mol$)	Henry's law constant at ave. soil 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)
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, K_d (cm^3/g)	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., $C_{building}$ ($\mu g/m^3$)	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)
9.30E-01	5.12E+02	0.10	8.33E+01	5.62E-03	3.84E+02	2.88E+251	NA	NA	6.32E+01	1.92E-03	1.70E+07	YES

Finite source indoor attenuation coefficient, $<\alpha>$ (unitless)	Mass limit bldg. conc., $C_{building}$ ($\mu g/m^3$)	Finite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Final finite source bldg. conc., $C_{building}$ ($\mu g/m^3$)	Unit risk factor, URF $(\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
NA	2.81E-03	NA	2.81E-03	6.0E-06	3.5E-02

END

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)
2.43E+02	3.64E+03	2.43E+02	2.28E+05	2.43E+02

INCREMENTAL RISK CALCULATIONS:

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

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

MESSAGE: The values of Csource and Cbuilding on the INTERCALCS worksheet are based on unity and do not represent actual values.

SCROLL DOWN TO "END"

END

DATA ENTRY SHEET

Soil Properties Lookup Table

SCS Soil Type	K_s (cm/h)	α_1 (1/cm)	N (unitless)	M (unitless)	n (cm^3/cm^3)	θ_r (cm^3/cm^3)	Mean Grain Diameter (cm)	Bulk Density (g/cm^3)	θ_w (cm^3/cm^3)	SCS Soil Name
C	0.61	0.01496	1.253	0.2019	0.459	0.098	0.0092	1.43	0.215	Clay
CL	0.34	0.01581	1.416	0.2938	0.442	0.079	0.016	1.48	0.168	Clay Loam
L	0.50	0.01112	1.472	0.3207	0.399	0.061	0.020	1.59	0.148	Loam
LS	4.38	0.03475	1.746	0.4273	0.390	0.049	0.040	1.62	0.076	Loamy Sand
S	26.78	0.03524	3.177	0.6852	0.375	0.053	0.044	1.66	0.054	Sand
SC	0.47	0.03342	1.208	0.1722	0.385	0.117	0.025	1.63	0.197	Sandy Clay
SCL	0.55	0.02109	1.330	0.2481	0.384	0.063	0.029	1.63	0.146	Sandy Clay Loam
SI	1.82	0.00658	1.679	0.4044	0.489	0.050	0.0046	1.35	0.167	Silt
SIC	0.40	0.01622	1.321	0.2430	0.481	0.111	0.0039	1.38	0.216	Silty Clay
SICL	0.46	0.00839	1.521	0.3425	0.482	0.090	0.0056	1.37	0.198	Silty Clay Loam
SIL	0.76	0.00506	1.663	0.3987	0.439	0.065	0.011	1.49	0.180	Silt Loam
SL	1.60	0.02667	1.449	0.3099	0.387	0.039	0.030	1.62	0.103	Sandy Loam

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 ($atm\text{-}m^3/mol$)	Henry's law constant reference temperature, T_R (^oC)	Normal boiling point, T_B (^oK)	Critical temperature, T_C (^oK)	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)	Physical state at soil temperature, (S,L,G)	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	4.3E-05	4.0E-02	L		
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		3.2E+00	L		X
71432	Benzene	5.90E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.56E-03	25	353.24	562.16	7,342	2.9E-05	6.0E-02	L		
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		2.2E+00	L		
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		4.9E-03	L		
74873	Methyl chloride (chloromethane)	3.50E+01	1.10E-01	6.50E-06	8.20E+03	9.84E-01	2.40E-02	25	249.00	416.25	5,115	7.4E-06	3.0E-01	L		
75003	Chloroethane (ethyl chloride)	1.47E+01	1.04E-01	1.15E-05	5.70E+03	4.51E-01	1.10E-02	25	285.30	460.40	5,879	8.3E-07	1.0E+01	L	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	7.7E-05	1.0E-01	G		
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	1.0E-06	3.0E+00	L		
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	7,800	3.7E-05	7.0E-02	L	X	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	1.6E-06	4.9E-01	L		
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		2.0E-01	L		
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	1.0E-05	3.9E-03	L	X	
78933	Methylethylketone (2-butanone)	4.50E+00	8.95E-02	9.80E-06	2.68E+05	1.12E-03	2.74E-05	25	352.50	536.78	7,481		1.0E+00	L		
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	L		X
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	2.0E-06	6.0E-01	L	X	
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	5.7E-05	2.1E-01	L		X
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		2.1E-01	S		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		1.4E-01	S		X
90120	1-(2-) Methylnaphthalene	7.20E+02	5.90E-02	7.50E-06	2.60E+01	1.19E-02	2.90E-04	25	514.26	761.00	12,600		1.4E-01	S		X
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	3.4E-05	9.0E-03	S		
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	L		
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		1.8E-02	L		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	739.13	13,000		3.5E-01	L		
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		2.0E+00	L		
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		1.0E+00	L		
105679	2,4-Dimethylphenol	4.00E+01	5.84E-02	8.69E-06	7.87E+03	6.97E-04	1.70E-05	25	452.00	685.00	8,773		7.0E-02	L	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	1.1E-05	8.1E-01	L		
106934	1,2-Dibromoethane (ethylene dibro	2.81E+01	7.33E-02	8.06E-06	3.40E+03	1.31E-02	3.20E-04	25	404.60	583.00	8,310	7.1E-05	9.1E-03	L		
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	2.1E-05	4.9E-03	L		
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		8.1E-02	L		
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		7.0E-01	L		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		3.0E-01	L		
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		6.0E-02	L		
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	10,803	7.1E-04		L		
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		1.1E+00	S		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		3.5E-03	L		
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	5,900	2.7E-05	7.0E-02	L	X	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	6.0E-06	3.5E-02	L		
129000	Pyrene	1.05E+05	2.72E-02	7.24E-06	1.35E-01	4.51E-04	1.10E-05	25	667.95	936	14370		1.1E-01	S		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	7192		3.5E-02	L		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	516.5	6717		7.0E-02	L		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	7900	1.6E-05	7.0E-02	L		
1634044	MTBE	6.00E+00	8.00E-02	1.00E-05	1.50E+05	2.41E-02	5.87E-04	25	328.3	497.1	6677.66	2.6E-07	8.0E+00	L		

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 ↓

			Totals must add up to value of Ls (cell C24)					
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)
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	5.9E-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 (ug/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	0.0000059	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)
1.0E-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 ($atm\text{-}m^3/mol$)	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	4.2E-05	2.5E-03	153.82		+	Cal EPA URF
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	5.3E-06	3.0E-03	119.38		+	Cal EPA URF
71432	Benzene	5.90E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.56E-03	25	353.24	562.16	7,342	2.9E-05	6.0E-03	78.11		+	Cal EPA URF
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			No Cal EPA URF
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	4.9E-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	No Cal EPA URF
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	No Cal EPA URF
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	7.8E-05	0.0E+00	62.50			Cal EPA URF
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	1.0E-06	3.0E+00	84.93			Cal EPA URF
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	3.7E-05	7.0E-02	163.83	X	+	Cal EPA URF
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	1.6E-06	5.0E-01	98.96			Cal EPA URF
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	0.0E+00	2.0E-01	96.94			No Cal EPA URF
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	1.0E-05	4.0E-03	112.99			Cal EPA URF
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			No Cal EPA URF
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	2.0E-06	3.5E-02	131.39			Cal EPA URF
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		+	Cal EPA URF = USEPA
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			USEPA
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			No Cal EPA URF
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			USEPA IX PRGs
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	1.1E-05	8.0E-01	147.00			Cal EPA URF
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	7.1E-05	2.0E-04	188.00			Cal EPA URF
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	2.1E-05	4.9E-03	98.96			Cal EPA URF
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	USEPA Region IX
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			USEPA Region IX
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	7.1E-04	0.0E+00	143.11			CAEPA URF
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			No Cal EPA URF
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	2.7E-05	7.0E-02	208.28	X		Cal EPA URF
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	5.9E-06	6.0E-01	165.83			Cal EPA URF
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	No Cal EPA URF
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	No Cal EPA URF
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	1.6E-05	2.0E-02	110.97			Cal EPA URF
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	2.6E-07	3.0E+00	98.00			Cal EPA URF

Notes:

URF from CalEPA if available: Criteria for Carcinogens: California Environmental Protection Agency, Office of Environmental Health Hazard Assessment, Standards and Criteria Work Group, January 2003 (CalEPA 2003).
"+" 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 $(^{\circ}C)$	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 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	5.9E-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	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	0.0000059	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)
1.0E-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 ($atm\text{-}m^3/mol$)	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	4.2E-05	2.5E-03	153.82		+	Cal EPA URF
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	5.3E-06	3.0E-03	119.38		+	Cal EPA URF
71432	Benzene	5.90E+01	8.80E-02	9.80E-06	1.75E+03	2.28E-01	5.56E-03	25	353.24	562.16	7,342	2.9E-05	6.0E-03	78.11		+	Cal EPA URF
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			No Cal EPA URF
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	4.9E-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	No Cal EPA URF
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	No Cal EPA URF
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	7.8E-05	0.0E+00	62.50			Cal EPA URF
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	1.0E-06	3.0E+00	84.93			Cal EPA URF
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	3.7E-05	7.0E-02	163.83	X	+	Cal EPA URF
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	1.6E-06	5.0E-01	98.96			Cal EPA URF
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	0.0E+00	2.0E-01	96.94			No Cal EPA URF
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	1.0E-05	4.0E-03	112.99			Cal EPA URF
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			No Cal EPA URF
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	2.0E-06	3.5E-02	131.39			Cal EPA URF
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		+	Cal EPA URF = USEPA
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			USEPA
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			No Cal EPA URF
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			USEPA IX PRGs
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	1.1E-05	8.0E-01	147.00			Cal EPA URF
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	7.1E-05	2.0E-04	188.00			Cal EPA URF
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	2.1E-05	4.9E-03	98.96			Cal EPA URF
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	USEPA Region IX
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			USEPA Region IX
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	7.1E-04	0.0E+00	143.11			CAEPA URF
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			No Cal EPA URF
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	2.7E-05	7.0E-02	208.28	X		Cal EPA URF
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	5.9E-06	6.0E-01	165.83			Cal EPA URF
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	No Cal EPA URF
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	No Cal EPA URF
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	1.6E-05	2.0E-02	110.97			Cal EPA URF
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	2.6E-07	3.0E+00	98.00			Cal EPA URF

Notes:

URF from CalEPA if available: Criteria for Carcinogens: California Environmental Protection Agency, Office of Environmental Health Hazard Assessment, Standards and Criteria Work Group, January 2003 (CalEPA 2003).
"+" 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

- Massachusetts Department of Environment Protection (MADEP 1994)
- USEPA Soil Screening Level Guidance (USEPA 1996)
- Hawai'i Department of Health (HDOH 1995)

BACKGROUND DOCUMENTATION
FOR THE DEVELOPMENT OF THE
MASSACHUSETTS MCP NUMERICAL STANDARDS

Massachusetts Department of Environmental Protection
Bureau of Waste Site Cleanup
and
Office of Research and Standards

April 1994

Note: 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". The MADEP method was also adopted for use by the Ontario Ministry of Environment and Energy (MOEE 1996) to develop soil screening levels for leaching concerns.

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

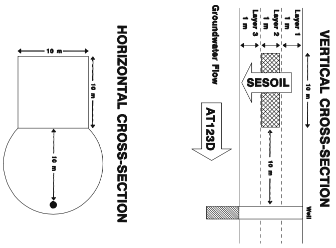
The Massachusetts Department of Environmental Protection has developed dilution attenuation factors (DAFs) in order to establish soil cleanup criteria for the protection of groundwater from leaching of residual contaminants in soil. DEP has adopted the modeling approach utilized by the State of Oregon 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:

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

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

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Reference: USEPA, 1996a, *Soil Screening Guidance: Technical Background Document*: U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Publication 9355.4-17A, May, 1996.

(Draft 2001 update)

United States
Environmental Protection
Agency

Solid Waste and
Emergency Response

OSWER 9355.4-24
March 2001

Superfund

SUPPLEMENTAL GUIDANCE FOR DEVELOPING SOIL SCREENING LEVELS FOR SUPERFUND SITES

Peer Review Draft

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Peer Review Draft

Office of Emergency and Remedial Response
U.S. Environmental Protection Agency
Washington, DC 20460

Disclaimer

This document provides guidance to EPA Regions concerning how the Agency intends to exercise its discretion in implementing one aspect of the CERCLA remedy selection process. The guidance is designed to implement national policy on these issues.

The statutory provisions and EPA regulations described in this document contain legally binding requirements. However, this document does not substitute for those provisions or regulations, nor is it a regulation itself. Thus, it cannot impose legally-binding requirements on EPA, States, or the regulated community, and may not apply to a particular situation based upon the circumstances. Any decisions regarding a particular remedy selection decision will be made based on the statute and regulations, and EPA decisionmakers retain the discretion to adopt approaches on a case-by-case basis that differ from this guidance where appropriate. EPA may change this guidance in the future.

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APPENDICES

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LIST OF ACRONYMS

ABS	Absorption fraction
AF	Skin-soil Adherence Factor
ARAR	Applicable or Relevant and Appropriate Requirement
AT	Averaging Time
ATSDR	Agency for Toxic Substances and Disease Registry
BW	Body Weight
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
C_{sat}	Soil Saturation Limit
CSF	Cancer Slope Factor
CSGWPP	Comprehensive State Ground Water Protection Plan
CSM	Conceptual Site Model
DAF	Dilution Attenuation Factor
DDT	p,p'-Dichlorodiphenyltrichloroethane
DOD	Department of Defense
DOE	Department of Energy
DQO	Data Quality Objectives
ED	Exposure Duration
EF	Exposure Frequency
EPA	Environmental Protection Agency
EV	Event Frequency
HBL	Health Based Level
HEAST	Health Effects Assessment Summary Tables
HI	Hazard Index
HQ	Hazard Quotient
IC	Institutional Control
IF	Age-adjusted Soil Ingestion Factor
IR	Soil Ingestion Rate
IRIS	Integrated Risk Information System
ISC3	Industrial Source Complex Dispersion Model
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal
MRL	Minimal Risk Level
NPL	National Priorities List
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PAH	Polycyclic Aromatic Hydrocarbon
PEF	Particulate Emission Factor
PRG	Preliminary Remediation Goal

LIST OF ACRONYMS
(Continued)

QA/QC	Quality Assurance/Quality Control
Q/C	Site-Specific Dispersion Factor
RAGS	Risk Assessment Guidance for Superfund
RBCA	Risk-based Corrective Action
RfC	Reference Concentration
RfD	Reference Dose
RI/FS	Remedial Investigation/Feasibility Study
RME	Reasonable Maximum Exposure
SA	Surface Area
SAP	Sampling and Analysis Plan
SCDM	Superfund Chemical Data Matrix
SCS	Soil Classification System
SPLP	Synthetic Precipitation Leachate Procedure
SSG	Soil Screening Guidance
SSL	Soil Screening Level
TBD	Technical Background Document
TC	Soil-to-dust Transfer Coefficient
THQ	Target Hazard Quotient
TR	Target Cancer Risk
TRW	Technical Review Workgroup for Lead
UCL	Upper Confidence Limit
URF	Unit Risk Factor
VF	Volatilization Factor
VOC	Volatile Organic Compound

Migration to Ground Water.

This guidance calculates commercial/industrial SSLs for the ingestion of leachate-contaminated ground water using the same set of equations and default input values presented in the 1996 *SSG*. Thus, the generic SSLs for this pathway are the same under commercial/industrial and residential land use scenarios.

EPA has adopted this approach for two reasons. First, it protects off-site receptors, including residents, who may ingest contaminated ground water that migrates from the site. Second, it protects potentially potable ground water aquifers that may exist beneath commercial/ industrial properties (see text box for EPA's policy on ground water classification). Thus, this approach is appropriate for protecting ground water resources and human health; however, it may necessitate that sites meet stringent SSLs if the migration to ground water pathway applies, regardless of future land use.

The simple site-specific ground water approach consists of two steps. First, it employs a simple linear equilibrium soil/water partition equation to estimate the contaminant concentration in soil leachate. Alternatively, the synthetic precipitation leachate procedure (SPLP) can be used to estimate this concentration. Next, a simple water balance equation is used to calculate a dilution factor to account for reduction of soil leachate concentration from mixing in an aquifer. This calculation is based on conservative, simplified assumptions about the release and transport of contaminants in the subsurface (see Exhibit 4-3). These assumptions should be reviewed for consistency with the CSM to determine the applicability of SSLs to the migration to ground water pathway.

Ground Water Classification

In order to demonstrate that the ingestion of ground water exposure pathway is not applicable for a site, site managers may either perform a detailed fate and transport analysis (as discussed in the *TBD* to the 1996 *SSG*), or may show that the underlying ground water has been classified as non-potable. EPA's current policy regarding ground water classification for Superfund sites is outlined in an OSWER directive (U.S. EPA, 1997e). EPA evaluates ground water at a site according to the federal ground water classification system, which includes four classes:

1 - sole source aquifers;
2A - currently used for drinking water;
2B - potentially usable for drinking water; and
3 - not usable for drinking water.

Generally, this pathway applies to all potentially potable water (i.e., classes 1, 2A, and 2B), unless the state has made a different determination through a process analogous to the Comprehensive State Ground Water Protection Plan (CSGWPP). Through this process, ground water classification is based on an aquifer or watershed analysis of relevant hydrogeological information, with public participation, in consultation with water suppliers, and using a methodology that is consistently applied throughout the state. If a state has no CSGWPP or similar plan, EPA will defer to the state's ground water classification only if it is more protective than EPA's. As of February 2001, 11 states (AL, CT, DE, GA, IL, MA, NH, NV, OK, VT, and WI) have approved CSGWPP plans.

Equation 4-10 is the soil/water partition equation; it is appropriate for calculating SSLs corresponding to target leachate contaminant concentrations in the zone of contamination. Equations 4-11 and 4-12 are appropriate for determining the dilution attenuation factor (DAF) by which concentrations are reduced when leachate mixes with a clean aquifer. Because of the wide variability in subsurface conditions that affect contaminant migration in ground water, default values are not provided for input parameters for these dilution equations. Instead, EPA has developed two possible default DAFs (DAF=20 and DAF=1) that are appropriate for deriving generic SSLs for this pathway. The selection of a default DAF is discussed in Appendix A, and the derivation of these defaults is described in the *TBD* to the 1996 *SSG*. The default DAFs also can be used for calculating simple site-specific SSLs, or the site manager can develop a site-specific DAF using equations 4-11 and 4-12.

To calculate SSLs for the migration to ground water pathway, the acceptable ground water concentration is multiplied by the DAF to obtain a target soil leachate concentration (C_w).[20] For example, if the DAF is 20 and the acceptable ground water concentration is 0.05 mg/L, the target soil leachate concentration would be 1.0 mg/L. Next, the partition equation is used to calculate the total soil concentration (i.e., SSL) corresponding to this soil leachate concentration. Alternatively, if a leach test is used, the target soil leachate concentration is compared directly to extract concentrations from the leach tests.

Exhibit 4-3

Simplifying Assumptions for the SSL Migration to Ground Water Pathway

- Infinite source (i.e., steady-state concentrations are maintained over the exposure period)
- Uniformly distributed contamination from the surface to the top of the aquifer
- No contaminant attenuation (i.e., adsorption, biodegradation, chemical degradation) in soil
- Instantaneous and linear equilibrium soil/water partitioning
- Unconfined, unconsolidated aquifer with homogeneous and isotropic hydrologic properties
- Receptor well at the downgradient edge of the source and screened within the plume
- No contaminant attenuation in the aquifer
- No NAPLs present (if NAPLs are present, the SSLs do not apply)

For more information on the development of SSLs for this pathway, please consult the 1996 *SSG*.

Mass-Limit SSLs. Equations 4-13 and 4-14 present models for calculating mass-limit SSLs for the outdoor inhalation of volatiles and migration to ground water pathways, respectively. These models can be used only if the depth and area of contamination are known or can be estimated with confidence. These equations are identical to those in the 1996 *SSG*. Please consult that guidance for information on using mass-limit SSL models.

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[20] The acceptable ground water concentration is, in order of preference: a non-zero Maximum Contaminant Level Goal (MCLG), a Maximum Contaminant Level (MCL), or a health-based level (HBL) calculated based on an ingestion rate of 2L/day and a target cancer risk of $1x10^{-6}$ or an HQ of 1. These values are presented in Appendix C.

Equation 4-10
Soil Screening Level Partitioning Equation for Migration to Ground Water

$$\text{Screening Level in Soil (mg/kg)} = C_w \left[K_D + \frac{(\theta_w + \theta_a H')}{\rho_b} \right]$$

Parameter/Definition (units)	Default
C_w/target soil leachate concentration (mg/L)	(nonzero MCLG, MCL, or HBL)[a] × dilution factor
K_d/soil-water partition coefficient (L/kg)	for organics: $K_d = K_{oc} \times f_{oc}$ for inorganics: see Appendix C[b]
K_{oc}/soil organic carbon/water partition coefficient (L/kg)	chemical-specific[c]
f_{oc}/fraction organic carbon in soil (g/g)	**0.002 (0.2%)**
θ_w/water-filled soil porosity (L_{water}/L_{soil})	**0.3**
θ_a/air-filled soil porosity (L_{air}/L_{soil})	$n - \theta_w$
ρ_b/dry soil bulk density (kg/L)	**1.5**
n/soil porosity (L_{pore}/L_{soil})	$1 - (\rho_b/\rho_s)$
ρ_s/soil particle density (kg/L)	2.65
H'/dimensionless Henry's law constant	chemical-specific[c] (assume to be zero for inorganic contaminants except mercury)

[a] Chemical-specific (see Appendix C).

[b] Assume a pH of 6.8 when selecting default K_d values for metals.

[c] See Appendix C.

Equation 4-11
Derivation of Dilution Attenuation Factor

$$\text{Dilution Attenuation Factor (DAF)} = 1 + \frac{K \times i \times d}{I \times L}$$

Parameter/Definition (units)	Default
DAF/dilution attenuation factor (unitless)	**20 or 1 (0.5-acre source)**
K/aquifer hydraulic conductivity (m/yr)	**Site-specific**
i/hydraulic gradient (m/m)	**Site-specific**
I/infiltration rate (m/yr)	**Site-specific**
d/mixing zone depth (m)	**Site-specific**
L/source length parallel to ground water flow (m)	**Site-specific**

Equation 4-12
Estimation of Mixing Zone Depth

$$d = (0.0112\,L^{2})^{0.5} + d_a(1 - \exp[(-L \times I)/(K \times i \times d_a)])$$

Parameter/Definition (units)	**Default**
d/mixing zone depth (m)	**Site-specific**
L/source length parallel to ground water flow (m)	**Site-specific**
I/infiltration rate (m/yr)	**Site-specific**
K/aquifer hydraulic conductivity (m/yr)	**Site-specific**
i/hydraulic gradient (m/m)	**Site-specific**
d_a/aquifer thickness (m)	**Site-specific**

Equation 4-13
Mass-Limit Volatilization Factor - Commercial/Industrial Scenario

$$VF = Q/C_{vol} \times \frac{[T \times (3.15 \times 10^{7}\,s/yr)]}{(D_b \times d_s \times 10^{6}\,g/Mg)}$$

Parameter/Definition (units)	**Default**
d_s/average source depth (m)	**site-specific**
T/exposure interval (yr)	**30**
Q/C_{vol} /inverse of mean conc. at center of a square source (g/m^2-s per kg/m^3)	**68.18 (for 0.5 acre source)**
D_b/dry soil bulk density (kg/L or Mg/m^3)	**1.5**

Equation 4-14
Mass-Limit Soil Screening Level for Migration to Ground Water

$$\text{Screening Level in Soil (mg/kg)} = \frac{(C_w \times I \times ED)}{D_b \times d_s}$$

Parameter/Definition (units)	**Default**
C_w/target soil leachate concentration (mg/L)	(nonzero MCLG, MCL, or HBL)[a] × dilution factor
d_s/depth of source (m)	**site-specific**
I/infiltration rate (m/yr)	**0.18**
ED/exposure duration (yr)	70
D_b/dry soil bulk density (kg/L)	**1.5**

[a] Chemical-specific, see Appendix C.

Hawai'i Department of Health RBCA Guidance (Tier 2 methodology for evaluation of leaching of chemicals from soil)

Reference:	HIDOH, 1995, *Risk-Based Corrective Action and Decision Making at Sites With Contaminated Soil and Groundwater*: State of Hawai'i, Department of Health, December, 1995 (revised June, 1996).

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

VOLUME I

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Errata:

Table of Contents; Addenda noted.

Chapter 1, table 1-1 and 1-2, Chapter 2, Table 2-2, Appendix F, Table 1; drinking water standard for vinyl chloride corrected.

Chapter 1, pages 3-4; groundwater action level discussion revised for clarity.

Chapter 1, page 7; text in paragraph three revised to describe Table 1-1.

Chapter 1, page 13; NS term defined in Table 1-1 notes.

Chapter 2, page 17; introduction revised for clarity.

Chapter 2, pages 20-21; groundwater action level discussion revised for clarity.

Chapter 2, page 28, Appendix E, page E-1; definition of volatile contaminant corrected.

Chapter 2, Table 2-6, Appendix C, Table 3, Appendix E, Table 2; molecular weight for toluene corrected.

Chapter 2, Table 2-9, Appendix E, Table 4; soil and particle density units corrected to kg/m^3.

Appendix F, Table 1; revised for clarity with respect maximum groundwater protection soil action level, SESOIL model results for benzene and toluene in Table 1d corrected.

QUIKSOIL spreadsheet; SAL calculation corrected to match equation in RBCA manual.

Addenda:

Addendum # 1 (February 1996): Provides additional guidance on determining the extent of soil contamination at sites and choosing soil contaminant concentrations for use in RBCA models.

Addendum #2 (June 1996, second update): February, 1996, version of addendum added nine contaminants to Tier 1 lookup tables. June, 1996, updates include: text revised for clarity; dioxin (2,3,7,8 TCDD), chlordane, and carbon tetrachloride added to Tier 1 lookup tables; soil action levels for Di-n-octyl phthalate corrected; groundwater action levels for 4,4 DDE corrected; molecular weight for 4,4 DDE corrected; physio-chemical constants for PCBs noted (for potential use in modeling).

Addendum # 3 (June 1996): RBCA manual Appendix K: Supporting Data for Tier 1 Soil Action Levels Generated Using SESOIL.

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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.

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).

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 any site 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.

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, Lāna'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 - Mānoa 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.

GENERATION OF TIER 2 SALs FOR GROUNDWATER-PROTECTION CONCERNS - QUIKSOIL SPREADSHEET

The QUIKSOIL spreadsheet model is based on a simple contaminant partitioning equation that approximates the dissolved-phase ("leachate") concentration of the contaminant in impacted soil based on the physio-chemical nature of the contaminant and the soil. The model is based on an equation presented in ASTM's "Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites (Table X2.1, ASTM, 1994)" for calculation of soil leaching factors:

$$SAL = C_w \text{ x } (Kd + (\theta_w + (\theta_a \text{ x } H'))/\rho_b),$$

where C_w is the target groundwater action level for the site (mg/L), Kd is the soil-water partition coefficient (L/Kg), θ_w and θ_a are the water- and air-filled porosities, H' is the Henry's law constant (unitless) and ρ_b is the soil bulk density.

Procedures regarding use of the QUIKSOIL spreadsheet to generate Tier 2 SALs are as follows:

Step 1. Check with the DOH Solid and Hazardous Waste Branch to ensure that the spreadsheet you have is the most up-to-date version.

Step 2. Input physio-chemical constants for the contaminant being evaluated. Constants for common contaminants are provided at the end of the spreadsheet (use "cut & paste" function of spreadsheet; refer also to Table 2-6). Contact the DOH Solid and Hazardous Waste Branch to obtain constants for contaminants not listed.

Step 3. Input site data where available. (Model will use default, conservative parameter values where site data is not available.)

Step 4. Input the target groundwater standard for the site (refer to Table 2-2). Do not include assumptions regarding dilution of leachate. Contact the DOH Solid and Hazardous Waste Branch to obtain groundwater criteria for contaminants not listed in Table 2-2.

Step 5. Spreadsheet generates the contaminants Tier 2 SAL for groundwater-protection concerns at the site. Complete the information at the end of the first page of the spreadsheet. Include a copy of the spreadsheet for each contaminant modeled with the Tier 2 report submitted to DOH for review and approval.

An example printout of the QUIKSOIL spreadsheet is provided in Appendix H.

Users of the QUIKSOIL spreadsheet should be aware that the model does not incorporate DOH-acceptable assumptions regarding the fate and transport of the "leachate" in the vadose zone. With respect to the more comprehensive SESOIL application, the QUIKSOIL spreadsheet generates overly conservative SALs for contaminants that are highly biodegradable (e.g., half-life < 50 days) or highly volatile (e.g., Henry's Law constant > 0.01atm-m^3/mol) or sites where the base of the impacted soil is situated greater than ten meters from groundwater. For contaminants or sites with these attributes, DOH strongly encourages use of the SESOIL application to generate groundwater-protection SALs.

CALCULATION OF FINAL SALs FOR GROUNDWATER-PROTECTION CONCERNS

SALs generated with SESOIL (either Tier 1 SESOIL SALs provided in Appendix F or Tier 2, site-specific SESOIL SALs) or QUIKSOIL should be further refined on a site-specific basis to account for dilution of leachate as it mixes with groundwater. Because the relationship between leachate concentration and soil concentration is assumed to be linear (i.e., Freundich number in SESOIL application set to "1"), refinement of a SESOIL- or QUIKSOIL-generated SAL is a simple matter of multiplying the SAL by a leachate dilution attenuation factor (DAF) calculated for the site.

Site-specific dilution attenuation factors are generated using the DOH spreadsheet entitled "DAF" (refer to example in Appendix I). The DAF equation relates the volume of recharge water infiltrating into groundwater beneath a site during a year to the volume of impacted groundwater passing beneath the site during that year as follows:

$$\mathrm{DAF} = 1 + ((V_s \times d_m) \text{ x } n_{eff})/(I \times L),$$

where "V_s" (meters/year) is groundwater seepage velocity, "D_m" (meters) is the mixing depth of the leachate in groundwater, "n_{eff}" (m^3/m^3) is the fraction effective porosity, "I" (meters/year) is infiltration rate, and "L" (meters) is source length parallel to groundwater flow.

Annual groundwater recharge is reported in the yearly summaries of SESOIL output files. If Tier 1, SESOIL-generated SALs or SALs based on the QUIKSOIL spreadsheet are used for the site then groundwater recharge can be estimated as an island-specific fraction of total annual rainfall. Assume the following recharge with respect to the location of the site (data from Atlas of Hawai'i, 1983): Ni'ihau: 5% total rainfall, Kaua'i: 16% total rainfall, O'ahu: 36% total rainfall, Moloka'i: 16% total rainfall, Maui: 30% total rainfall, Lāna'i: 12% total rainfall, Kaho'olawe: 10% total rainfall, and Hawai'i: 31% total rainfall.

The spreadsheet calculates groundwater velocity (seepage) as:

$$V_s = (K \times h)/n_{eff}$$

where "K" is the hydraulic conductivity of the groundwater bearing media in meters per year, "h" is the hydraulic gradient.

Mixing zone depth is calculated by relating source length parallel to groundwater flow, aquifer thickness (d_a, meters), and the hydraulic conductivity of the groundwater-bearing media as follows:

$$d_m = (0.0112 \times L^2)^{0.5} + d_a(1 - \exp[(-L \times I)/(K \times h \times d_a)]).$$

The dilution factor equation presented above is used in ASTM's "Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites" (Table X2.1, ASTM, 1994). The mixing-zone depth equation is based on an equation published in EPA's *Technical Background Document for Soil Screening Guidance* (USEPA, 1994d).

Mixing-zone depths calculated using the equation will typically range between one and ten meters. The ASTM document referenced recommends a default mixing-zone depth of two meters. DAFs generated by the equations presented typically range from 1 to 10, dependent largely on annual rainfall, the hydraulic conductivity of the groundwater-bearing media, and the hydraulic gradient of the groundwater.

GENERATION OF TIER 2 SALs FOR DIRECT-EXPOSURE CONCERNS

Direct-Exposure Model Equations

The risk-based, deterministic models incorporated into the DETIER2 spreadsheet are based on slight modifications of direct-exposure models presented in the Second Half, 1994, and First Half, 1995, editions of EPA Region IX's "Preliminary Remediation Goals (PRGs)" (Appendix E, USEPA, 1994a, 1995). The equations used in the PRG models reflect guidance provided in the California EPA document entitled "Preliminary Endangerment Guidance Manual, January, 1994" (CAEPA, 1994). A copy of this

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:

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Version 1.1

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LIST OF FIGURES

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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):

$\mathrm{EDFI} = \mathrm{DTED} \times \mathrm{BW}/\mathrm{FIR}$

$= 0.0028\ \text{mg Cd kg-1BW} \times \text{day-1} \times 100\text{kg} / 3\text{kg day-1}$

$= 0.093\ \text{mg/kg dw food}$

$\mathrm{SQCfi} = \mathrm{EDFI} \times \mathrm{AFfi}/\mathrm{BCF}$

$= 0.093\ \text{mg/kg} \times 0.85/0.025$

$= 3.16\ \text{mg/kg}$

CCME calculation of soil quality criteria based on soil ingestion by animals

$\mathrm{EDFI} = \mathrm{DTED} \times \mathrm{BW}/\mathrm{SIR}$

= 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

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

SUPPLEMENTAL REFERENCE DOCUMENTS FOR PETROLEUM

- Summary of MADEP Carbon Range and Total Petroleum Hydrocarbon Risk-Based Screening Levels
- Overview of gasoline composition (NEIWPCC, 2003)

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

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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

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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

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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.

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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.

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Commission

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A Report On Federal & State Programs To Control Leaking Underground Storage Tanks

A Hot Dog by Any Other Name Could Be Your Drinking Water

by Patricia Ellis

"Hot dogs, getcher hot dogs!"

The cry of the hot dog vendor at the ballpark. The steaming hot frank with your choice of mustard, ketchup, relish...the captivating aroma and the even more satisfying taste! But let's not stop to think about what's actually in a hot dog. Sure, some of us take comfort in consuming only hot dogs that are "all beef" or "chicken" or Kosher. But what's really in a hot dog? Do we really want to know? And just what has the composition of hot dogs got to do with an article that is ostensibly about leaking underground storage tanks, anyway? Well, it has to do with this propensity to not want to know about those ingredients…even the ingredients in our own drinking water.

■ *continued on page 2*

Inside

■ **Hot Dogs** *from page 1*

Is Ignorance Bliss?

The drinking water supply systems in the United States are unquestionably the best in the world. Most people can simply turn on the faucet and draw a glass of fresh, clear water that they can put unflinchingly to their lips and drink. Yet, a growing segment of the population uses a filter of some sort, and increasing numbers of people buy bottled water. In fact, in the last 40 years, it is estimated that the U.S. drinking water industry has lost nearly 60 percent of its customers to competitors (currently unregulated) who are "bottled water and point-of-use/point-of-entry providers." (Means et al., 2002) Why?

The reasons are many—taste, odor, color, fad/style, fear (justified or imagined). For those of us on public water supplies, our water suppliers provide us with annual Consumer Confidence Reports (CCRs) that show us that our water has been tested for a variety of contaminants and is safe to drink. But most water suppliers analyze for a couple dozen contaminants at most. The CCRs tell us whether or not these contaminants were detected and at what concentrations.

LUSTLine

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When these contaminants are detected, even when their concentration may from time to time exhibit a spike above a regulatory threshold, this water is still distributed to us. Generally an accounting gimmick, such as 30-day average concentration, is employed so that it can be claimed that although detected above the limit, the concentration did not exceed "permissible" levels and the water is safe to drink.

For example, if the analytical report for a sample indicates that each of the BTEX compounds is present but at concentrations below their MCLs (5 ppb, 1,000 ppb, 700 ppb, and 10,000 ppb, respectively), is water with up to 11,705 ppb of BTEX really safe to drink? Do we want to drink it knowing that although the levels are reportedly safe, these contaminants are present at all? Do we want our children drinking it? And, health concerns aside, how does it taste? What about other contaminants that are not on this list of only a couple dozen? Are some of them present and, if so, what do we know about them?

Petroleum Cocktail Hour

Petroleum (and the various fuels distilled from petroleum) is composed of hundreds to thousands of individual organic compounds. (Although this article focuses on gasoline, much of the discussion is applicable to other fuels as well.) "Gasoline" is a complex blend of several hundred hydrocarbons (i.e., compounds that contain only hydrogen and carbon atoms) and other organic compounds that typically contain nitrogen, oxygen, or sulfur. The specific composition of any particular blend of gasoline is a function of the petroleum source, refining and blending processes, and additives (Kreamer and Stetzenbach, 1990). The composition also varies with geographic location and from season to season to maintain performance specifications and comply with regulatory requirements.

The primary groups of hydrocarbons in gasoline are the paraffins, olefins, naphthenes, and aromatics (Youngless et al., 1985). Table 1 lists some representative examples for each of the various classes of these organic compounds. Additive packages (which are generally proprietary) vary considerably and typically include compounds that function as antioxidants, antiicers, metal deactivators, detergents, and corrosion inhibitors, among others (Youngless et al., 1985). Some of these compounds are extremely large, complex molecules.

Some components of gasoline may also contain metal species. The most familiar of these, but not the only ones, are the organic lead compounds, which are no longer used in modern unleaded gasolines. In the past, especially with leaded fuels, a wide variety of dyes were incorporated into gasoline blends as well. Table 2 lists a few of the many gasoline additives.

In addition, a significant number of the compounds in gasoline are *unknown* (or unidentified), except for the number of carbon atoms they contain (Kreamer and Stetzenbach, 1990). What do we know about the toxicity of each of the compounds in gasoline? How do they behave in the environment? Which ones are in our drinking water and at what levels?

For an organic contaminant to show up in a water sample, it must be water soluble. It is well known that aromatic hydrocarbons (of which BTEX is probably the best recognized) are the most soluble constituents of gasoline. Table 3 lists 43 common gasoline constituents with solubility greater than 1 mg/L. Two of the nonaromatic compounds in this table have a higher solubility than ethylbenzene (the "E" in BTEX). This list isn't comprehensive, and there are undoubtedly other compounds with similar properties and, hence, significant water solubility.

While these constituents represent pure compound solubility, and individual solubilities from a mixture would be somewhat lower, the point is that there are lots of soluble constituents in gasoline that can appear in groundwater. If a sample is only analyzed for the aromatic fraction, how do we know that some of these other constituents are not also present?

Toxicity of Petroleum Constituents

It should come as no surprise to anyone that exposure (e.g., through inhalation, ingestion, or dermal contact) to any of the constituents of gasoline (or any other fuel) at any concentration should be avoided. Exposure to the vapors from most gasoline constituents can cause dizziness, drowsiness, unconsciousness, and other adverse effects on the central nervous system. Prolonged exposure to low concentrations, or brief exposure to higher concentrations, may damage internal organs, cause cancer or birth defects, or may even be fatal. Ingestion of the liquid phase of neat gasoline (and most, if not all, of its individual constituents) is acutely toxic.

So where do we find information on the toxicity of specific constituents? We would expect that one of the best sources is a material safety data sheet (MSDS), and there are many places to find them on the Internet. But they are readily available only for a small percentage of the constituents of gasoline, and, as they only pertain to exposure to a single compound, the effects of exposure to dilute aqueous mixtures are entirely unknown. (This issue is likely to be one of the important public health challenges of this century, and further discussion is way beyond the scope of this article.)

One of the current ways to deal with a large number of organic compounds is to distribute them into smaller groups, each of which has a designated "surrogate." This is the approach adopted by the Total Petroleum Hydrocarbon Criteria Working Group (TPHCWG). In this method, it is presumed that all members of the group have properties that are similar to the surrogate.

But the approach has several drawbacks. First, compound toxicity isn't necessarily the same for each of the group members, and often the toxic characteristics of a significant proportion of the group are unknown. Second, the presence of the surrogate in a sample may not necessarily mean that there are any other compounds in the sample; if they are, they are probably not at the same concentration. Third, the absence of the surrogate in a sample may not necessarily mean that all of the other compounds in the class are also absent from the sample. Fourth, many states are statutorily authorized to regulate only those contaminants that appear on EPA's list (i.e., 40 CFR 302.4, discussed in the "Regulation…" section below).

Sadly, the focus on compound toxicity has been so narrowly concentrated on human carcinogenicity that adverse effects other than cancer are usually conveniently ignored. In almost any discussion of risk management, there is no consideration of the teratogenic (birth defect) or mutagenic (mutation) effects of these toxic compounds—not to mention taste or odor!

> ***We have no idea what contaminants are really in the water we drink (or the hot dogs we eat). Simply because a contaminant isn't listed on an analytical report does not mean that the contaminant is not present in the sample. The truth is that we just don't know, but what we don't know can potentially hurt us.***

The issue of exposure to multiple toxicants is likewise given short shrift—exposure to multiple toxic compounds is limited to presumed simple additive effects, if it's considered at all. Yet, it is well recognized that the toxicity of a chemical may be increased (or in some cases even decreased) by simultaneous or consecutive exposure to another chemical (Lu, 1991). There is no consideration of synergistic (multiplicative) effects, or whether mixtures may contain procarcinogens, cocarcinogens, or cancer promoters.

And then there's the issue of whether or not a specific compound is a human carcinogen or just an animal carcinogen. Too often an animal carcinogen is touted as being a human noncarcinogen simply because there isn't any confirmation that the compound causes cancer in humans. However, saying that a compound is a noncarcinogen, when the truth is that there isn't enough information about it to determine whether or not it is a human carcinogen (although the compound is a known animal carcinogen), is being less than honest.

Admittedly, it is difficult (maybe even impossible) to demonstrate with 100 percent certainty that any chemical is a noncarcinogen. But for compounds that are known animal (especially mammalian) carcinogens, ordinary common sense would tell a reasonable person that these are substances with which unnecessary contact should be avoided, even at low concentrations and especially in mixtures that contain substances that may promote cancer.

In theory, a single molecule of a carcinogen can induce cancer. This means that there is no threshold dose and therefore no safe level of exposure to carcinogens. While not all cancer researchers hold this view, the opposing view (i.e., that threshold doses for carcinogens do exist) has yet to be demonstrated, even though large-scale experiments have been conducted for this purpose (Lu, 1991). Further complicating the issue is that unless a fatal quantity of pure product is ingested, most of the toxic effects are slow to develop (10 to 20 years or more in humans) and may be masked by other ailments as we age.

Regulation of Hazardous Substances

Underground storage tanks containing hazardous substances are regulated by the UST program under 40 CFR 280. Additional regulations regarding hazardous substances are found in 40 CFR 302.4 and 40 CFR 261.24. The first of these, CFR 302.4 (U.S. EPA, 2001a), is U.S. EPA's list of approximately 800 Hazardous Substances. Of these substances, only a handful are petroleum hydrocarbons found in fuels, and even fewer are fuel additives. (See Table 4.)

The second regulation, 40 CFR 261.24, is the Toxicity Characteristics (TC) rule for identifying RCRA hazardous wastes. The TC rule specifically exempts "petroleum contaminated" media and debris that fail the test for the toxicity characteristic of 40 CFR 261.24 (U.S. EPA, 2001b). Section 261.24(b) refers to 25 contami-

■ *continued on page 4*

■ **Hot Dogs** *from page 3*

nants (but actually lists 26) that are specifically exempt from consideration as "hazardous wastes," provided they are subject to the corrective action regulations under 40 CFR 280 (the UST regulations). This list of 26 contaminants includes benzene and only two additional chemicals (cresol and pyridine) that *may* be present in gasoline or other petroleum fuels.

We all know that none of the components of gasoline (or other petroleum fuels) are healthy for us, so why is it that so few fuel constituents are officially designated as "toxic" or "hazardous"? Part of the answer is that there are simply too many potentially toxic substances to list; some are unidentified, and adequate toxicity testing hasn't been conducted on others. Although not limited to organic compounds, the Chemical Abstract Service (CAS) assigns unique registration numbers (known as CAS or CASRN) to new chemicals at a rate of about 4,000 per day!!! (See *http://www.cas.org/EO/regsys.html.*)

Another part of the answer is that petroleum fuels as a whole are a critical part of the world economy. They've been used for close to 100 years, so we're familiar with them, we need them, and we consider them to be relatively "safe." Perhaps the primary reason why gasoline is considered "safe" is because UST regulations are relatively effective—at least to the extent that there aren't daily media reports of explosions, fires, and underground rivers of gasoline flowing beneath our feet.

However, as we all know, releases from UST systems do happen, sometimes with immediate and catastrophic effect. Every day there are releases of gasoline (and other fuels) into the environment, and a significant amount of the released fuel eventually winds up in groundwater or surface water or both, some of which is used for drinking water. So how do we know what toxic compounds (if any) are actually in our drinking water?

Identification of Toxic Compounds

Let's assume that we have a water sample that may or may not be contaminated with one or more of the hundreds of petroleum constituents in gasoline. What tests can we conduct to determine what contaminants are in the sample? Several analytical methods are potentially available to us to determine if any contaminants are present in the sample and at what concentrations. Though not the sole source for analytical methods, EPA's compendium of analytical methods, SW-846, (U.S. EPA, 1997) offers us several choices of determinative analytical methods for organic compounds, including: Methods 8015, 8021, 8260, and 8270. Let's look into each of these in ascending numerical order. (See Table 5.)

- **Method 8015** (Nonhalogenated Organics Using GC/FID) explicitly lists 30 compounds, of which only four may be present in gasoline. Only one—methanol—is on the list of hazardous substances. This method may also be used for Gasoline Range Organics (GRO) and Diesel Range Organics (DRO), but other methods (which aren't specified in the scope) may be more applicable. No additional guidance is provided regarding GRO or DRO.

- **Method 8021** (Aromatic and Halogenated Volatiles by Gas Chromatography Using Photoionization and/or Electrolytic Conductivity Detectors) explicitly lists 57 compounds, of which 10 may be present in gasoline and are also on the list of hazardous substances.

- **Method 8260** (Volatile Organic Compounds by Gas Chromatography/Mass Spectrometry) explicitly lists 107 compounds, of which about a dozen may be found in gasoline and are also on the list of hazardous substances.

- **Method 8270** (Semivolatile Organic Compounds by Gas Chromatography/Mass Spectrometry) explicitly lists about 250 compounds, of which only a couple are likely to be found in gasoline (although many more could be present in diesel fuel and heavier fuel oils) and are on the list of hazardous substances.

U.S. EPA drinking water methods 502 and 524.2 contain a slightly different list of chemicals.

Of the more than 400 target compounds identified by the four 8000-series methods, approximately 5 percent may be present at any given petroleum release site. "Well and good," you're thinking, "but what's the point of this?"

Absence of Proof Is Not Proof of Absence

Well, the first point of this is that we have no idea what contaminants are really in the water we drink (or the hot dogs we eat). Simply because a contaminant isn't listed on an analytical report does not mean that the contaminant is not present in the sample. (Note that the converse is also true—that is, there is no proof that the contaminant is present.) The truth is that we just don't know, but what we don't know *can* potentially hurt us.

There are a lot of reasons why the presence of a contaminant in a sample might go unrecognized:

- There was no analysis for the contaminant.
- There was an analysis for the contaminant, but an inappropriate method was used.
- The analytical method was applied incorrectly.
- The detection limit is very high.
- Matrix interferences.

In each of these cases, a contaminant could be in a sample, but its presence (and concentration) is undetected (and undetermined). We have to do a better job than we currently do to both anticipate which potential contaminants may be present at a given site and analyze for all of them to determine whether they are in fact present or absent.

In addition to the desirability of knowing all chemicals present for the purpose of conducting a risk assessment, it is important to know all the contaminants present when developing a remediation plan.

In one of my recent projects, carbon filters used as point-of-entry treatment for domestic wells were breaking through in far shorter times than what was expected. After running Method 8260 plus requesting that all "tics" be identified by a library search, we identified a total of 45 additional chemicals, all potentially having a gasoline source, as being present in the water samples. These additional chemicals all contributed to the loading on the carbon filters and contributed to the early breakthrough. The library search gave estimated concentrations, but none of these compounds had been calibrated against a standard.

I might also have been happier if I hadn't added dissolved lead to the list of analytes because of earlier detections of EDC. Dissolved lead exceeded recommended levels in every sample (pre- and post-carbon filters), and in every well, even where no gasoline components were detected. Further analysis, this time for tetraethyl and tetramethyl lead, the organic lead that would come from leaded gasoline, was negative. Elevated lead levels appeared to be present throughout the aquifer, which would also have to be factored into a risk assessment. While the carbon filters were dealing with the gasoline contamination in the wells, albeit in an expensive manner, the filters had no effect on the dissolved lead.

Further, it isn't enough to have samples analyzed even for all potential contaminants if the samples aren't representative. Samples must be collected from locations where contaminants are most likely to be present, and they must be correctly handled during collection, transport, preparation, and analysis.

Fuel-Specific Analytical Methods

My second point is that the current analytical practices we rely on to determine whether gasoline compounds are present or absent in water (and soil) samples are incomplete and therefore inadequate. Standard operating procedures for Methods 8015, 8021, 8260, and 8270 require calibration for only a few of the many compounds that are present in gasoline, but many compounds are either not present or are unknown.

Target analyte lists must be refined so that they are more representative of the contaminants that are likely to be encountered at fuel-release sites. For example, nearly 90 percent of the analytes listed for Method 8021 are halogenated compounds that would *not* be present at fuel-release sites—why should a sample be analyzed for them and *not* for some of the few hundred other contaminants that may actually be present? If we're going to pay for an analysis for, say, 100 compounds, wouldn't it be more cost-effective if those 100 could be reasonably anticipated to be in the sample?

■ *continued on page 6*

Table 1 Representative Organic Compounds Found in "Gasoline"

Straight Chain Alkanes
- propane
- n-hexane
- n-dodecane

Branched Alkanes
- isobutane
- 2,2-dimethylbutane
- neopentane
- 3-ethylhexane

Cycloalkanes
- cyclohexane
- n-propylcyclopentane
- ethylcyclohexane

Straight Chain Alkenes
- cis-2-butene
- 1-pentene
- trans-2-heptane

Branched Alkenes
- 2-methyl-1-butene
- 4,4-dimethyl-cis-2-pentene

Cycloalkenes
- cyclopentene
- 3-methylcyclopentene

Alkyl Benzenes
- benzene
- toluene
- ethylbenzene
- o-xylene
- m-xylene
- p-xylene
- 1,2-dimethyl-3-ethylbenzene
- 1,2,3-trimethylbenzene
- 1,2,4,5-tetramethylbenzene
- n-propylbenzene

Other Aromatics
- indan
- 1-methylindan
- phenol

Polycyclic Aromatic Hydrocarbons (PAHs)
- naphthalene

Source: Adapted from Cole (1994).

Table 2 Representative Organic Compounds Used as Additives in "Gasoline"

Oxygenates
- methyl *tertiary*-butyl ether (MTBE)
- ethanol
- ethyl *tertiary*-butyl ether (ETBE)
- *tertiary*-butyl alcohol (TBA)
- *tertiary*-amyl ethyl ether (TAEE)
- diisopropyl ether (DIPE)
- *tertiary*-amyl methyl ether (TAME)
- *tertiary*-amyl alcohol (TAA)
- methanol

Anti-knock compounds
- tetra-ethyl lead (TEL)
- tetra-methyl lead (TML)
- methylcyclopentadienyl manganese tricarbonyl (MMT)

Anti-oxidant compounds
- hindered phenols
- phenylene diamines
- aminophenols

Anti-icing compounds
- isopropyl alcohol
- amides/amines
- glycols
- organophosphate ammonium salts

Corrosion inhibitors
- carboxylic acids
- sulfonates
- amine/alkyl phosphates

Metal deactivators
- disalicylidene amines
- phenolic amines
- thiourea

Ignition controller additives
- tri-*o*-cresol phosphates

Detergents
- aminohydroxyamide
- alkylphenols
- imidazolines

Lead scavengers
- 1,2-dichloroethane (EDC)
- 1,2-dibromoethane (EDB)

Dyes
- azobenzene-4-azo-2-napthol
- benzene-azo-2-napthol
- para-diethyl aminoazobenzene
- 1,4-diisopropylaminoanthraquinone

Source: Adapted from Cummings (1977) and Irwin, et. al. (1997).

■ Hot Dogs *from page 5*

And, in order to credibly evaluate the actual risk posed by contaminants in our water, we absolutely *must* know which contaminants are in the water. In a recent series of articles by Uhler and others (2002, 2003), similar suggestions were made. They suggest a suite of 109 target analytes for the analysis of automotive gasoline using a Modified 8260 method. The list contains the PIANO compounds (Paraffins, Isoparaffins, Aromatics, Naphthenes, and Olefins), useful for recognizing peculiarities that might be inherited from refinery processes (including various major and minor iso-alkanes), and gasoline additives, including the oxygenate additives (alcohols and ethers), lead scavengers (EDC and EDB), and methylcyclopentadienyl manganese tricarbonyl (MMT). Some of this list of compounds can be useful in fingerprinting gasoline for environmental forensic investigations, as well as a basis for conducting a risk assessment.

Table 3
Common Gasoline Constituents Ranked by Solubility (mg/L)

Benzene	1,780
Toluene	515
o-Xylene	220
cis-2-Pentene	203
Cyclopentane	156
Ethylbenzene	152
1-Pentene	148
3-Methyl-1-butene	130
Indan	100
1-Methyl-4-ethylbenzene	95
1,2,3-Trimethylbenzene	77
1-Methyl-2-ethylbenzene	75
Propane	62
1,2,4-Trimethylbenzene	57
Cyclohexane	55
n-Propylbenzene	52
Isopropylbenzene	50
1,3,5-Trimethylbenzene	50
Isobutane	48.9
Methylcyclopentane	42
Pentane	38.5
Naphthalene	31
1-Methyl-naphthalene	28
2-Methyl-naphthalene	25
2,2-Dimethylbutane	18.4
sec-Butylbenzene	17
Methylcyclohexane	14
Isopentane	13.8
2-Methylpentane	13.8
n-Butylbenzene	13.8
3-Methylpentane	12.8
Isobutylbenzene	10.1
Hexane	9.5
2,3-Dimethylpentane	5.25
1,2,4,5-Tetramethylbenzene	3.48
3-Methylhexane	3.3
n-Heptane	2.93
2-Methylhexane	2.54
2,2,4-Trimethylpentane	2.44
2,3,4-Trimethylpentane	2
1-Nonene	1.12

Source: Adapted from Gustafson et al. (1997).

Table 4
Hazardous Substances Listed in 40 CFR 302.4 That May be Present in "Gasoline"

SUBSTANCE	CASRN
1,2-dibromoethane	106934
1,2-dichloroethane	107062
1,3-pentadiene	504609
benzene	71432
cresols	1319773
ortho-cresol	95487
meta-cresol	108394
para-cresol	106445
cyclohexane	110827
ethylbenzene	100414
methanol	67561
naphthalene	91203
phenol	108952
toluene	108883
xylenes	1330207
ortho-xylene	95476
meta-xylene	108383
para-xylene	106423

Source: Adapted from Gustafson et al. (1997).

Just how credible, how "scientifically defensible" is a risk assessment based on omission, neglect, or wishful thinking? To only evaluate the risk posed by some, but not all, contaminants present at a site is like crossing a busy highway but only looking in one direction as you make the attempt. Sure, you may not get hit by a car coming from the direction in which you're looking, but one from the blind side is likely to spoil your day.

Appropriate analytical method(s) already exist in today's marketplace. All that is lacking are appropriate calibration standards and standard operating procedures that have been optimized for analysis of these target analytes. Once it becomes routine to use these standards, risk assessments could be conducted for the contaminants to which receptors are actually exposed, rather than presumed surrogates. This will go a long way toward bolstering the credibility of risk assessment and restoring confidence in the safety of our drinking water.

Take Me Out to the Ballgame

Alternatively, we could opt to accept the status quo…we can slump down in our bleachers, hot dog in one hand, and glass of water (OK, beer) in the other, and blissfully pass away the time. ■

Pat Ellis is a hydrologist with the Delaware Department of Natural Resources and Environmental Control, Tank Management Branch and served as a member of EPA's Blue Ribbon Panel on MTBE. She is a technical advisor and regular contributor to LUSTLine *and can be reached at* Patricia.Ellis@state.de.us.

Table 5 **Compounds Present in "Gasoline" That Appear on Target Analyte Lists for Methods in SW-846**

COMPOUND	8015*	8021	8260	8270
diethyl ether	x		x	
ethanol	x		x	
methanol	x		x	
pyridine	x		x	
benzene		x	x	
ethylbenzene		x	x	
naphthalene		x	x	x
toluene		x	x	
xylenes		x		
o-xylene		x	x	
m-xylene		x	x	
p-xylene		x	x	
1,2-dibromoethane		x	x	
1,2-dichloroethane		x	x	
tertiary-butyl alcohol			x	
phenol				x

**Method 8015 is also indicated to be applicable for GRO and DRO.*

EPA HQ UPDATE

Analytical Methods Fact Sheet Available

Analytical methods for petroleum hydrocarbons are well established; however, methods that were developed for analysis of petroleum hydrocarbons in water samples may or may not be appropriate for fuel oxygenates. A fact sheet, titled *Analytical Methodologies for Fuel Oxygenates* (EPA 510-F-03-001), outlines the potential problems of analytical methods for common fuel oxygenates and ways to address these problems. It has been distributed to states and regions and is available on the OUST Web site at *www.epa.gov/oust/mtbe/omethods.pdf.*

For more information, contact Hal White at (703) 603-7177.

Senate Passes UST Legislation

On Thursday, May 1, the U.S. Senate passed the Underground Storage Tank Compliance Act (S. 195) by unanimous vote. The legislation provides additional flexibility and authorization of appropriations for preventing and cleaning up releases from USTs. It also includes a dedicated authorization of appropriation for the cleanup of MTBE, mandatory inspection frequencies, additional enforcement tools, and operator training guidelines. Although the House has been working on its version of UST legislation, companion legislation has not been introduced. EPA OUST has been providing technical comments on the proposed legislation.

API to Present Two Free-Product Cleanup Workshops at 20th Annual API/ NGWA Groundwater Conference

For more information, go to API Conferences and Workshops link at *www.api.org/groundwater*

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APPENDIX 8

DETERMINATION OF GROUNDWATER UTILITY

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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/D~~ISAPPROVE~~D

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.

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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.

APPENDIX 9

SUPPLEMENTAL TECHNICAL GUIDANCE DOCUMENTS

- Tier 2 Soil Action Levels for Arsenic (HDOH 2008a)
- Tier 2 Soil Action Levels for TEQ Dioxins (HDOH 2008b)
- Use of Laboratory Batch Tests to Evaluate Potential Leaching of Contaminants From Soil (HDOH April 2007)
- Pesticides in Former Agricultural Lands and Related Areas (HDOH May 2007)
- Long-Term Management of Petroleum-Contaminated Soil and Groundwater
- (HDOH June 2007)
- Advisory on Methane Assessment and Common Remedies at Schools Sites

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TO: Interested Parties

FROM: Roger Brewer
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THROUGH: Barbara Brooks
Toxicologist
HEER Office

DATE: June 13, 2008

SUBJECT: Tier 2 Action Levels for Arsenic (update to August 2006 memorandum)

This technical memorandum presents Tier 2 action levels and corresponding guidance for arsenic-contaminated soils. The guidance serves as an addendum to the Hazard Evaluation and Emergency Response (HEER) office document *Evaluation of Environmental Hazards at Sites with Contaminated Soil and Groundwater* (HDOH 2008a). The guidance updates and takes precedence over guidance published in August 2006 (HDOH 2006). The update primarily addresses recommendations for the management of Category 2 soils in former agricultural fields. Similar guidance has been prepared for arsenic-contaminated soils (HDOH 2008b)

The guidance is especially intended for use during the redevelopment of former agricultural areas, although it is applicable to any site where releases of arsenic may have occurred. The action levels should be used to help determine the extent and magnitude of arsenic-contaminated soils and help guide the scope of remedial actions needed. The action levels are intended to serve as guidelines only, however, and do not represent strict, regulatory cleanup requirements. Alternative action levels may be proposed for any site in a site-specific, environmental risk assessment.

Overview

The action levels presented are based on concentrations of *bioaccessible* arsenic in soil. *Total* arsenic data are considered appropriate for comparison to anticipated background levels of arsenic in soil but not for use in human health risk assessment or for setting risk-based action levels. An action level of 4.2 mg/kg bioaccessible arsenic is recommended for residential sites. For commercial/industrial sites, an action level of 19 mg/kg bioaccessible arsenic is recommended. Remediation of sites to permit future, unrestricted, residential land use is encouraged when technically and economically feasible. “Residential” use includes both single-family homes and high-density developments, where open spaces essentially serve as residential “backyards.” Schools, parks, playgrounds, and other open public spaces that adult and child residents may visit on a regular basis should also be initially assessed under a residential use exposure scenario. Short- and long-term remedial actions in the latter areas may differ from actions recommended for high-density and single-family residential properties, however, due to greater control over digging and other activities that may expose contaminated soil.

Additional guidance and action levels are provided for sites where the preferred action levels noted above cannot be reasonably met and continued use or redevelopment of the site is still desired. Three categories of arsenic-contaminated soil are defined for both residential and commercial/industrial sites. Residential, Category 1 soils (R-1) are not considered to pose a significant risk to human health under any potential site conditions and can be reused onsite or offsite as desired. Commercial/Industrial, Category 1 soils (C-1) can be used as needed on commercial/industrial sites but should not be used as fill material offsite without prior consultation with HDOH.

Category 2 Residential (R-2) and Commercial/Industrial (C-2) soils are not considered to pose a significant risk to human health under the specified land use. As a best management practice, however, HDOH recommends the removal or capping of Category 2 soils associated with easily identifiable, localized spill areas when feasible (e.g., past pesticide mixing or storage). HDOH does not consider capping or removal of Category 2 soils in large, former field areas to be necessary or practicable.

Category 3 Residential (R-3) and Commercial/Industrial (C-3) soils are considered to pose an unacceptable risk to human health and should be removed from the site or isolated onsite under permanent structures or properly designed caps, as described below.

Remediation of residential and commercial/industrial properties to action levels for Category 2 soils is recommended to the extent technically and economically feasible, however, and should be discussed with the HEER office on a site-by-site basis. Reuse of Category 2 Commercial/Industrial soil for daily cover at a regulated landfill may be acceptable but should be discussed with the landfill operator as well as the HDOH Solid and Hazardous Waste Branch.

Background

Significantly elevated levels of arsenic have been identified in soils from former sugar cane fields and pesticide mixing areas in Hawaiʻi, as well as in and around former plantation camps. High levels of arsenic have also been identified in soil samples from at least one former golf course. The presence of the arsenic is believed to be related the use of sodium arsenite and other arsenic-based pesticides in and around the cane fields in the 1920s through 1940s. During this period, up to 200,000 acres of land in Hawaiʻi was being cultivated for sugar cane. The arsenic is generally restricted to the upper two feet of the soil column (approximate depth of plowing). Alternative action levels and approaches may be acceptable for contaminated soils situated greater than three feet below ground surface and should be discussed with HDOH on a site-by-site basis.

Current studies have focused on the Keaʻau area of the Big Island. Soils in the area have been described as stony, organic, iron-rich Andisols (Cutler et al., 2006). Concentrations of total arsenic in soils from undeveloped former sugar cane lands in this area have been reported to range from 100-400 mg/kg in the ≤2mm size fraction of the soil and >500 mg/kg in the <250µm size fraction (report pending). Concentrations greater than 1,000 mg/kg have been reported in one former plantation camp area. Background concentrations of arsenic in native soils range from 1.0 mg/kg up to 20 mg/kg. The presence of the arsenic initially posed concerns regarding potential groundwater impacts, uptake in homegrown produce and direct exposure of residents and workers to contaminated soil. Maximum-reported concentrations of bioaccessible arsenic in soil are far below levels that would cause immediate, acute health affects. Continued exposure to arsenic in heavily contaminated soils over many years or decades could pose long-term, chronic health concerns, however.

Arsenic has not been detected in municipal groundwater wells in the area. Testing of produce from gardens in the Kea‘au area by the Department of Health in 2005 also did not identify levels of arsenic above U.S. norms, even though total arsenic in the garden soils approached or exceeded 300 mg/kg in the $\leq$2mm size fraction. Uptake of the arsenic in edible produce or other plants therefore does not appear to be a significant environmental health concern. These observations suggest that the arsenic is tightly bound to the soil and not significantly mobile. This is further supported by petrologic and leaching studies as well as “bioaccessibility” tests conducted on the soils (Cutler et al., 2006). Despite being relatively immobile, however, elevated levels of arsenic in some areas could still pose a potential chronic health risk to residents and workers who come into regular contact with the soil. The action levels and soil categories discussed below are intended to address this concern.

The evaluation of soil for arsenic has traditionally focused on the *total* amount of arsenic present and comparison to action levels based on a target excess cancer risk of one-in-a-million or 10^{-6}. This has always presented a dilemma in human health risk assessments. Natural, background concentrations of arsenic in soils are typically much higher than risk-based action levels for total arsenic. For example, the residential soil action level for arsenic presented in the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* is 0.42 mg/kg (HDOH 2008a, Appendix 1, Table I-1), while background concentrations of arsenic in soil in Hawai‘i may range up to 20 mg/kg or higher. In addition, much of the arsenic in pesticide-contaminated soil appears to be tightly bound to soil particles and not *available* for uptake in the human body. This portion of the arsenic is essentially nontoxic. These two factors led to a need for further guidance, particularly with respect to the use of *bioaccessible* arsenic data in human health risk assessments and in the development of risk-based, soil action levels.

Bioavailable and Bioaccessible Arsenic

Risk to human health posed by exposure to a contaminant in soil is evaluated in terms of the average daily dose or *intake* of the contaminant for an exposed person (e.g., in milligrams or micrograms per day; USEPA 1989, 2004). Intake can occur through incidental ingestion of soils, inhalation of dust of vapors, and to a lesser extent (for most contaminants) absorption through the skin. Assumptions are made about the fraction of the contaminant that is available for *uptake* in a persons blood stream via the stomach and small intestine. This is referred to as the *bioavailability* of the contaminant (NEPI 2000). The most widely accepted method to determine the bioavailability of a contaminant in soil is through *in vivo* studies where the soil is incorporated into a lab test animal’s diet. In the case of arsenic, the amount that is excreted in the animal’s urine is assumed to represent the fraction that entered the animal’s blood stream and was available for uptake.

In vivo bioavailability tests are time consuming and expensive, however, and not practical for routine site evaluations. As an alternative, faster and more cost-effective laboratory tests have been developed to estimate arsenic bioavailability in soil. These methods, referred to as *in vitro* bioaccessibility tests, utilize an acidic solution intended to mimic a child’s digestive tract (typically a glycine-buffered hydrochloric acid solution at pH 1.5; Ruby 1999; Gron and Andersen, 2003). Soil with a known concentration and mass of arsenic is placed in the solution and allowed to equilibrate for one hour. An extract of the solution is then collected and analyzed for arsenic. The concentration of arsenic in the solution is used to calculate the total mass of arsenic that was stripped from the soil particles. The ratio of the arsenic mass that went into solution to the original mass of arsenic in the soil is referred to as the *bioaccessible* fraction of arsenic.

The results of *in vitro* bioaccessibility tests for arsenic compare favorably with *in vivo* bioavailability studies (Ruby 1999; Gron and Andersen, 2003). This is supported by studies of arsenic-contaminated soils from the Kea‘au area of the Big Island of Hawai‘i. Samples of the soil were tested for bioavailable arsenic in an *in vivo* monkey study carried out by the University of Florida in 2005 and simultaneously tested for bioaccessible arsenic by *in vitro* methods (report pending publication). The concentration of total arsenic in the samples was approximately 700 mg/kg. The study concluded that the bioavailability of arsenic in the soil ranged from 3.2% to 8.9%. This correlated well with an *in vitro* test carried out on the same soil that yielded an arsenic bioaccessibility of 6.5%. The bioaccessibility of arsenic in soils from the same site was estimated to range from 16% to 20% in a separate study, suggesting that the *in vitro* test method may err on the conservative side in comparison to the more standard *in vivo* method (Cutler et al., 2006). This has been observed in other studies of bioavailability versus bioaccessibility. Bioaccessibility tests on soils from other areas around Kea‘au yielded similar results and again indicated that 80% to >90% of the arsenic in the soil is so tightly bound to soil particles that it is essentially “nontoxic.”

Bioaccessible arsenic was observed to increase with increasing total arsenic concentration (Cutler et al., 2006). This is probably because much of the arsenic in heavily contaminated soils is fixed to low-energy binding sites on soil particles and comparatively easy to remove. Continued stripping of remaining arsenic from progressively higher-energy binding sites requires greater effort (i.e., the arsenic becomes progressively less bioaccessible). Data from the study also indicate that arsenic bioaccessibility (and therefore toxicity) may increase with increasing phosphorous concentration in soil related to the use of fertilizers in gardens. This is because phosphorus is able to out compete arsenic for high-energy binding sites on soil particles. The relationship has not been fully demonstrated, however, and is still under investigation.

Based on a review of published literature and studies conducted to date in Hawai‘i, HDOH considers arsenic bioaccessibility tests to be sufficiently conservative and an important tool in the assessment of arsenic-contaminated properties. Bioaccessible arsenic analyses should always be conducted on the ≤250µm size fraction of the soil since this is the fraction that is most likely to be incidentally ingested. Most soils only contain a small percentage of particles 250µm in size or less. This typically requires the collection of very large samples (several kilograms) to obtain the mass needed for bioaccessibility tests. Appropriate sample handling, processing, and sub-sampling by the lab conducting bioaccessibility testing is essential. Guidance on suggested procedures and quality control for bioaccessibility lab tests will be forthcoming from HDOH. For more information on this subject contact John Peard of the HDOH HEER office (john.peard@doh.hawaii.gov).

Basis of Soil Action Levels

Arsenic action levels and correlative soil categories for residential and commercial/industrial properties are presented in Tables 1 and 2 and summarized in Figure 1. An action level of 20 mg/kg total arsenic in the ≤2mm size soil fraction is recommended to screen out sites where naturally occurring (“background”) concentrations of arsenic are not significantly exceeded (HDOH 2008a). Background total arsenic may approach 50 mg/kg in some areas but this is considered rare. Analysis of soil samples for bioaccessible arsenic is recommended at sites where total arsenic exceeds anticipated background concentrations.

Action levels for bioaccessible arsenic are presented in Table 1 (residential land use) and Table 2 (commercial/industrial land use). The action levels are based on direct-exposure models used by USEPA to develop soil *Regional Screening Levels* (RSLs) (replace 2004 Preliminary Remediation Goals; USEPA 2008). The USEPA RSLs for arsenic for residential and commercial/industrial land use are 0.39 mg/kg and 1.6 mg/kg, respectively, based on a target excess cancer risk of $1x10^{-6}$ (one-in-a-million). Risk-based action levels for arsenic of 0.42 mg/kg and 1.9 mg/kg are presented in the HDOH document *Evaluation of Environmental Hazards at Sites with Contaminated Soil and Groundwater*, based on a similar target risk but assuming a slightly lower, dermal absorption factor (HDOH 2008a). Both the USEPA RSLs and the HDOH Tier 1 action levels assume that 100% of the soil arsenic is bioavailable.

The USEPA RSLs and HDOH Tier 1 action levels for total arsenic are far below typical background concentrations of arsenic in soils from Hawai‘i, as well as most of the mainland US. To address this issue, action levels for Category 1 soils in Tables 1 and 2 are based on a target excess cancer risk of $1x10^{-5}$ (one-in-one-hundred-thousand) rather than $1x10^{-6}$. This generates residential and commercial/industrial action levels for bioaccessible arsenic of 4.2 mg/kg and 19 mg/kg, respectively. These action levels serve as useful starting points to help identify arsenic-contaminated sites that warrant further evaluation.

A second set of action levels is used to define soils that are most likely impacted above natural background levels but still may be acceptable for use in residential or commercial/industrial areas if adequate lawns and landscaping are maintained (Category 2 soils). An action level of 23 mg/kg bioaccessible arsenic was selected as an upper limit for soils in residential areas (Table 1). This reflects a noncancer Hazard Quotient of 1.0 and correlates to an excess cancer risk of approximately $5x10^{-5}$. Commercial/industrial action levels based on a similar excess cancer risk of $5x10^{-5}$ and a noncancer Hazard Quotient of 1.0 are 95 mg/kg and 310 mg/kg, respectively. Since the correlative action level for excess cancer risk is less than the action level for noncancer risk, the former (95 mg/kg) was chosen as an upper limit for soils in commercial/industrial areas (Table 2). These action levels are used to define the lower boundary of Category 3 soils.

At concentrations greater than 180 mg/kg, bioaccessible arsenic in soil begins to pose a potentially significant health risk to construction workers and utility workers (HDOH 2008a, refer to Table I-3 in Appendix 1, based on an excess cancer risk of $1x10^{-5}$). As discussed below, this is used as a “ceiling level” for soil that can be isolated under clean soil caps, buildings or paved areas.

The action levels for bioaccessible arsenic were used to group soils into three categories (see Tables 1 and 2). A discussion of potential remedial actions at each site that fall into these soil categories is provided in the following sections. The ultimate action taken at an individual site will be dependent on numerous site-specific factors, including current and planned land use, available options for onsite isolation or offsite disposal, and technical and economic constraints.

Soil Categories and Action Levels for use at Residential Sites

Category 1 Soils (R-1): Bioaccessible Arsenic ≤4.2 mg/kg, No Further Action

Long-term exposure to Category 1 (R-1) residential soils is not considered to pose a significant risk to residents. No further action is necessary at sites where the reported concentration of bioaccessible arsenic in soil is equal to or below 4.2 mg/kg.

Utility corridors should be backfilled with clean fill material (e.g., R-1 soils) or at a minimum R-2 soils in order to prevent excavation of contaminated soil and inappropriate reuse in other areas in the future. R-3 soils should not be placed in utility corridors.

Category 2 Soils (R-2): Bioaccessible Arsenic >4.2 mg/kg and ≤23 mg/kg, Consider Removal or Isolation of Localized Spill Areas

Long-term exposure to Category 2 (R-2) residential soils is not considered to pose a significant risk to residents. As a best management practice, however, HDOH recommends the removal or capping of Category 2 soils associated with easily identifiable, localized spill areas when feasible (e.g., past pesticide mixing or storage). HDOH does not consider capping or removal of Category 2 soils in large, former field areas to be necessary or practicable. These issues are discussed in more detail below.

At sites where R-2 soils are discovered in the vicinity of existing homes, residents should be encouraged to minimize exposure to the soil by taking the following precautions:

- Reduce areas of bare soil by planting and maintaining grass or other vegetative cover, or cover barren areas with gravel or pavement.
- Keep children from playing in bare dirt.
- Keep toys, pacifiers, and other items that go into childrens' mouths clean.
- Wash hands and face thoroughly after working or playing in the soil, especially before meals and snacks.
- Wash fruits and vegetables from home gardens before bringing them in the house. Wash again with a brush before eating or cooking to remove any remaining soil particles. Pare root and tuber vegetables before eating or cooking.
- Bring in clean sand for sandboxes and bring in clean soil for garden areas or raised beds.
- Avoid tracking soil into the house and keep the floors of the house clean. Remove work and play shoes before entering the house.

Testing of produce from gardens in the Keaʻau area by the Department of Health in 2005 did not identify levels of arsenic above U.S. norms. Uptake of the arsenic in edible produce or other plants does not appear to be a significant environmental health concern in former sugar cane operation areas. Produce should be thoroughly cleaned before cooking or eating, however, in order to avoid accidental ingestion of small amounts of soil.

Category 3 Soils (R-3): Bioaccessible Arsenic >23 mg/kg, Removal or Isolation Recommended

Long-term exposure of residents to Category 3 (R-3) residential soils is considered to pose potentially significant health risks. As discussed above, maximum-reported concentrations of bioaccessible arsenic in soil from former agricultural areas are far below levels that would cause immediate, acute health affects. Continued exposure to arsenic in R-3 soils over many years or decades could pose long-term, chronic health concerns, however.

Offsite disposal of R-3 soils in a permitted landfill facility is recommended when technically and economically feasible. Reuse of some or all of the soil as daily cover at a landfill may also be possible. This should be discussed with the landfill in question as well as with the HDOH Solid and Hazardous Waste Branch. Offsite disposal of soil with bioaccessible arsenic in excess of 180 mg/kg is especially recommended (action level for construction/trench work exposure).

Soils that fall into this category but cannot be disposed offsite due to technical and/or cost constraints should be placed in *soil isolation areas*. Optimally, a soil isolation area would be created under public buildings, private roadways, parking lots and other facilities/structures that constitute a permanent physical barrier that residents are unlikely to disturb in the future. Isolation of R-3 soils under public roadways should be done in coordination with the local transportation authority. Isolation of R-3 soils under permanent structures is preferable to isolation in open areas, due to the increased potential for open areas to be inadvertently disturbed during future gardening, landscaping or subsurface utility work. Soil that cannot be placed under a permanent structure or disposed of offsite should be isolated in well-controlled common areas, rather than on individual residential lots. Contaminated soil should be consolidated in as few isolation areas as possible. Areas where R-3 soils are placed and capped for permanent onsite management must be clearly identified on surveyed, post-redevelopment map(s) of the property. These maps should be included a risk management plan that is provided to HDOH for inclusion in the public file for the site (see "Identification of Soil Isolation Areas" below). Utility corridors should be backfilled with clean fill material (e.g., R-1 soils) when initially installed or following maintenance work in order to prevent excavation and inappropriate reuse of contaminated soil in the future.

Depending on site-specific conditions, permanent covers or caps for soil isolation areas may be constructed of paving materials such as asphalt and concrete ("hard cap") or earthen fill material ("soil cap") that meets R-1 (preferred) or R-2 action levels. A soil cap thickness of 24 inches is recommended for areas where landscaping activities may involve digging deeper than one foot or where gardens may be planted in the future (based on USEPA guidance for lead-contaminated soils, USEPA 2003). A cap of twelve inches may be acceptable in high-density residential redevelopments where gardens will not be allowed and use of the area will be strictly controlled. A clearly identifiable, marker barrier that cannot be easily penetrated with shovels or other handheld digging tools (e.g., orange construction fencing or geotextile webbing) should be placed between the contaminated soil and the overlying clean fill material. A similar marker barrier should be placed below or above gravel, concrete or other hard material placed on top of contaminated soil in order to avoid confusion with former building foundations or road beds.

Permeable marker barriers may be necessary in areas of high rainfall in order to prevent ponding of water during wet seasons. Leaching tests should be carried out on R-3 soils in order to evaluate potential impacts to groundwater (see discussion below).

When R-3 soils are identified at existing homes, removal or permanent capping of the soils should be strongly considered. In the interim, residents should follow the measures outlined for residential R-2 soils to minimize their daily exposure. Children should avoid areas of bare soil and regular work in garden areas.

Soil Categories and Action Levels for use at Commercial/Industrial Sites

Category 1 Soils (C-1): Bioaccessible Arsenic >4.2 mg/kg and ≤19 mg/kg, No Further Action

Long-term exposure to Category 1 (C-1) soils is not considered to pose a significant health risk to workers at commercial or industrial sites. Remediation of soil that exceeds action levels for residential, R-1 (preferred) or R-2 action levels, however, will minimize restrictions on future land use and should be considered when feasible. Note that this may require a more detailed sampling strategy than is typically needed for commercial/industrial properties (e.g., decision units 5,000 ft^2 in size or less). Long-term institutional controls to restrict use of property to commercial/industrial purposes may be required if the site will not be investigated to the level of detail required for future, unrestricted land use to ensure that action levels for Category 2 Residential soils are not exceeded

Category 2 Soils (C-2): Bioaccessible Arsenic >19 mg/kg and ≤95 mg/kg, Consider Removal or Isolation

Long-term exposure to Category 2 (C-2) soils is not considered to pose a significant risk to workers provided that lawns and landscaping are maintained to minimize exposure and control fugitive dust or if the soils. Remediation of commercial/industrial properties to action levels approaching those for C-1 soils or lower is recommended when technically and economically feasible, however, and should be discussed with the HEER office on a site-by-site basis. When selecting remedial options, long-term effectiveness should be given increasing weight as concentrations of bioaccessible arsenic approach the upper boundary for C-2 soils.

For new developments, isolation of C-2 soils under buildings, private roadways and other areas with a permanent cap that workers are unlikely to disturb in the future is recommended when feasible. Isolation of C-2 soils under public roadways should be done in coordination with the local transportation authority. Offsite reuse of C-2 soil as fill material should be avoided. Reuse of some or all of the soil as daily cover in a regulated landfill may be feasible, however. This should be discussed with the landfill in question as well as with the HDOH Solid and Hazardous Waste Branch. Areas of the property where capped or uncapped C-2 soil is located must be clearly identified on surveyed, post-redevelopment map(s) of the property and included in a risk management plan that is documented in the HDOH public file for the site (see "Identification of Soil Isolation Areas" below). Care must be taken to ensure that soil from these areas is not excavated and inadvertently reused in offsite areas where residents could be exposed on a regular basis. Utility corridors should be backfilled with clean fill material (e.g., R-1 soils) when initially installed or following maintenance work in order to prevent excavation and inappropriate reuse of contaminated soil in the future.

At existing facilities, areas of bare C-2 soils should be minimized by maintaining grass or other vegetative cover or by covering bare areas with gravel or pavement. Workers should be encouraged to maintain clean work areas and thoroughly wash hands before breaks and meals.

Category 3 Soils (C-3): Bioaccessible Arsenic >95 mg/kg, Removal or Isolation Recommended

Long-term exposure to Category 3 (C-3) soils is considered to pose potentially significant health risks to workers at commercial or industrial sites. Offsite disposal of C-3 soils is recommended when technically and economically feasible. Offsite disposal of soil with bioaccessible arsenic in excess of 180 mg/kg is especially recommended (action level for construction/trench work exposure). Soil that cannot be removed from the site should be placed in designated isolation areas under public buildings, private roadways, parking lots and other facilities/structures that constitute a permanent physical barrier that residents are unlikely to disturb in the future. Contaminated soil should be consolidated in as few isolation areas as possible. Areas of the property where C-3 soil is located must be clearly identified on surveyed, post-redevelopment map(s) of the property and included in a risk management plan that is documented in the HDOH public file for the site (see "Identification of Soil Isolation Areas" below). Care must be taken to ensure that soil from these areas is not excavated and inadvertently reused in offsite areas where residents could be exposed on a regular basis. Utility corridors should be backfilled with clean fill material (e.g., R-1 soils) in order to prevent inadvertent excavation and reuse of contaminated soil in other areas in the future.

As discussed for residential sites, isolation of contaminated soil under buildings or other permanent structures is preferred over isolation in open areas. If placement of the soil in an open area is necessary, use of areas that are unlikely to be disturbed in the future is preferred. A minimum cap thickness of twelve inches is generally acceptable for commercial/industrial sites where use of the area will be strictly controlled (USEPA 2003). A clearly identifiable marker barrier should be placed between the contaminated soil and the overlying clean fill material (e.g., orange construction fencing or geotextile webbing). Fencing, geotextile fabric or similar, easily identifiable markers should likewise be placed above any gravel, concrete or other hard material placed on top of contaminated soil in order to avoid confusion with former building foundations or road beds.

Use of Total Arsenic Data

Based on data collected to date, it is possible that a significant portion of former sugar cane land situated in areas of high rainfall (e.g., >100 inches per year) will fall into the R-2 or C-2 soil categories as described above and summarized in Tables 1 and 2. Some of these areas have already been redeveloped for residential houses. Determination of bioaccessible arsenic levels on individual lots with existing homes may not be economically feasible for some residents (current analytical costs $500 to $1000). If site-specific, bioaccessible arsenic data is not affordable for a private homeowner, HDOH recommends that the soil be tested for total arsenic (generally less than $100). The resulting data should then be adjusted using a default *bioavailability* value to estimate bioavailable arsenic concentrations. Based on data collected to date in the Kea‘au area, a 10% bioavailability factor (BF) is recommended for total arsenic values at or below 250 mg/kg. Measured concentrations of total arsenic should be multiplied by 0.1 and the adjusted concentration compared to the action levels in Table 1 or Table 2. For total arsenic above 250 mg/kg, a more conservative bioavailability factor of 20% (0.2) is recommended.

For residential sites, this approach corresponds to an upper limit of 42 mg/kg total arsenic for R-1 soils and 230 mg/kg total arsenic for R-2 soils (10% BF used). For commercial/industrial sites, this corresponds to an upper limit of 190 mg/kg total arsenic for C-1 soils (10% BF used) and 475 mg/kg total arsenic for C-2 soils (20% BF used). Soils that potentially fall into Category 3 for residential or commercial/industrial sites should be tested for bioaccessible arsenic if at all possible. In the absence of bioaccessibility data, it is recommended that children avoid playing or working in gardens or other areas where total arsenic action levels indicate the potential presence of R-3 soils. The default bioaccessibility factors presented were developed based on data from the Kea‘au region and are subject to revision as more data becomes available.

The total arsenic action levels proposed above should not be used for general screening purposes at sites where a formal environmental investigation is being carried out. As previously discussed and as noted in the summary tables, bioaccessible arsenic data should be collected at all sites where total arsenic concentrations exceed an assumed background concentration of 20 mg/kg unless otherwise approved by HDOH.

Soil Sampling Methods

The use of multi-increment field soil sampling and lab sub-sampling techniques is recommended over the use of discrete or traditional composite sampling techniques. This sampling approach allows for the determination of a statistically representative concentration of arsenic within a specific area of investigation or “decision unit.”, such as an individual yard, a park, a garden or a well-defined spill area. Additional guidance on the use of multi-increment and decision unit investigation strategies will be provided in the 2008 update to the HEER office *Technical Guidance Manual.*

Other Potential Environmental Concerns

A discussion of environmental hazards associated with contaminated soil is provided in the HDOH document *Evaluation of Environmental Hazards at Sites with Contaminated Soil and Groundwater* (HDOH 2008a). The arsenic action levels presented in this technical memorandum address human-health, direct-exposure hazards only. The action levels do not address potential leaching of arsenic from soil and subsequent impacts to underlying groundwater or potential toxicity to terrestrial flora and fauna. These issues should be evaluated on a site-specific basis as directed by HDOH. Arsenic is not considered to pose significant vapor intrusion or gross contamination hazards.

Based on data collected to date, leaching of arsenic from former sugar cane fields is not anticipated to pose a significant concern in Hawai‘i due to the apparent, relative immobility of the arsenic. Additional field data are needed to support this assumption, however, particularly for soils that exceed the upper action level for R-2 residential soils (i.e., >23 mg/kg bioaccessible arsenic). HDOH recommends that potential leaching of arsenic from soils that exceed 23 mg/kg bioaccessible arsenic be evaluated using the USEPA Synthetic Precipitation Leaching Procedure (SPLP) test or a comparable method. Refer to the HDOH technical memorandum *Use of Laboratory Batch Tests to Evaluate Potential Leaching of Contaminants from Soil* for additional guidance (HDOH 2007).

Assessment of additional pesticides and pesticide-related contaminants in agricultural areas should be carried out as needed based on the past use of the property. Refer to the 2008 update of the HEER office *Technical Guidance Manual* for additional information on target pesticides.

Environmental Hazard Evaluation Plans

Isolation areas where arsenic-contaminated soil is to be capped for permanent onsite management must be clearly identified on surveyed, post-redevelopment map(s) of the property. Areas of soil at commercial/industrial sites that exceed action levels for residential R-1, R-2 and R-3 soils should also be clearly surveyed and mapped. The maps identifying arsenic-impacted soils should be incorporated into an *Environmental Hazard Evaluation Plan* (EHMP, HDOH 2008a) that describes proper management, reuse and disposal of contaminated soil if disturbed during later redevelopment activities. A copy of the plan should be submitted to both HDOH and to the agency(s) that grants permits for construction, trenching, grading or any other activities that could involve future disturbance or excavation of the soil. The need to incorporate the risk management plan and specific land use restrictions in a formal covenant to the property deed should be discussed with HDOH on a site-by-site basis. Additional guidance on EHMPs will be provided in the 2008 update to the HEER office *Technical Guidance Manual*.

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Table 1. Soil categories and recommended actions for Residential Sites.

Total Arsenic (≤ 2 mm size fraction)	**Action**
≤20 mg/kg	Within range of natural background. No further action required and no restrictions on land use.
>20 mg/kg	Exceeds typical background. Re-evaluate local background data as available. Test soil for bioaccessible arsenic if background is potentially exceeded.

Bioaccessible Arsenic (≤250µm size fraction)	**Action**
R-1 Soils (≤4.2 mg/kg)	No further action required and no restrictions on land use.
R-2 Soils (>4.2 but ≤23 mg/kg)	Within USEPA range of acceptable health risk. Consider removal and offsite disposal of small, easily identifiable "hot spots" when possible in order to reduce potential exposure (not required for large, former field areas). Use of soil as daily cover at a regulated landfill may also be possible. For existing homes, consider measures to reduce daily exposure to soil (e.g., maintain lawn cover, ensure good hygiene, thoroughly wash homegrown produce, etc.). For new developments on large, former field areas, notify future homeowners of elevated levels of arsenic on the property (e.g., include in information provided to potential buyers during property transactions).
R-3 Soils (>23 mg/kg)	For existing homes, removal or onsite isolation of exposed soil is strongly recommended. Consider a minimum one-foot cover of clean fill material (two feet in potential garden areas) if soil cannot be removed. An easily identifiable marker barrier should be placed between the contaminated soil and the overlying fill (e.g., orange construction fencing or geotextile/geonet material). In the interim, take measures to reduce daily exposure to soil (e.g., maintain lawn cover, ensure good hygiene, thoroughly wash homegrown produce, etc.). Children should avoid areas of bare soil and regular work in gardens areas. For new residential developments, removal and offsite disposal of soil should be strongly considered. At a minimum, consider removal and offsite disposal of soil with concentrations of bioaccessible arsenic that approach or exceed 180 mg/kg (direct exposure action level for construction and trench workers). Use of soil as daily cover at a regulated landfill may be possible if concentrations of bioaccessible arsenic meet C-2 commercial/industrial soil criteria. If offsite disposal is not feasible but redevelopment of the property is still desired, consider use of soil as structural fill under public buildings, parking lots, private roads, or other paved and well-controlled structures. If capping in open areas is unavoidable, consider a one-foot minimum cap thickness with an easily definable marker barrier placed between the soil and the overlying clean fill (e.g., orange construction fencing or geotextile fabric). Capping of R-3 soils on newly developed, private lots is not recommended due to difficulties in ensuring long-term management of the soil. Backfill utility corridors with clean fill material (e.g., R-1 soils) to avoid excavation and inappropriate reuse of the soil in the future.

Table 1. Soil categories and recommended actions for Residential Sites (cont.).

R-3 Soils (cont.) (>23 mg/kg)	Require formal, long-term institutional controls to ensure appropriate management of soil in the future (e.g., Covenants, Conditions and Restrictions (CC&Rs), deed covenants, risk management plans, etc.). All areas of capped soil should be delineated on a surveyed map of the property to be subsequently included in the risk management plan.

The soil categories and arsenic action levels noted above are intended to be used as guidelines only and do not represent strict, regulatory cleanup requirements.

Table 2. Soil categories and recommended actions for Commercial/Industrial Sites.

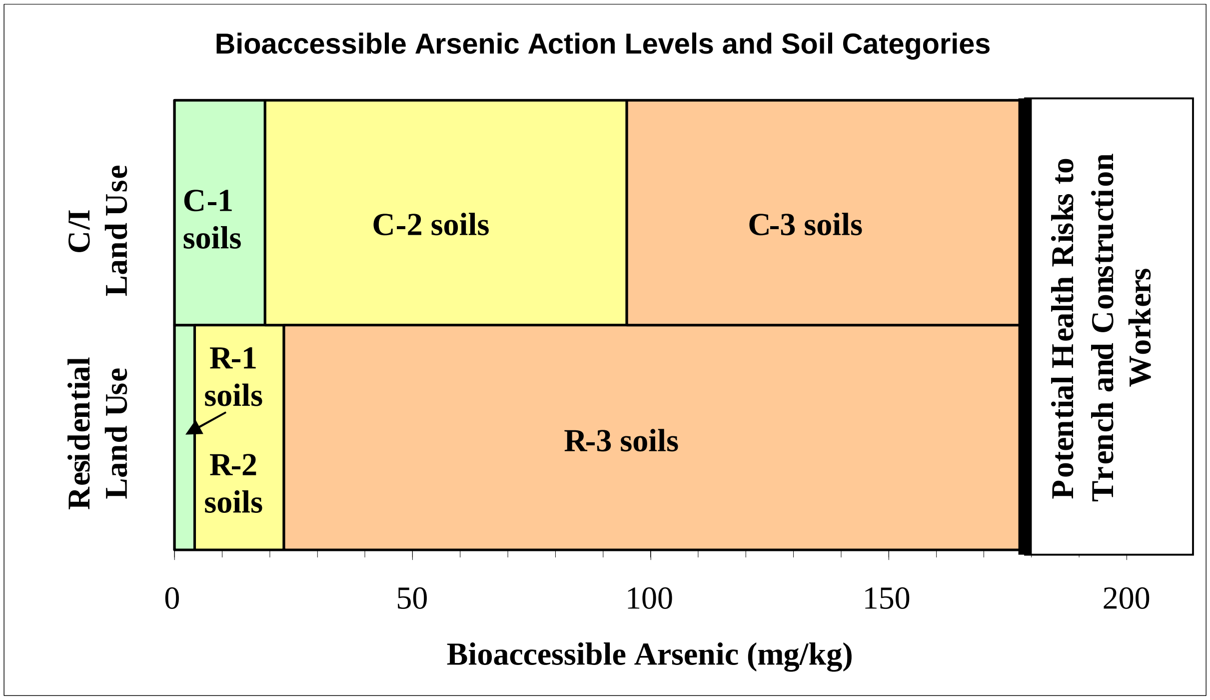
Total Arsenic (≤ 2 mm size fraction)	Action
≤20 mg/kg	Within range of natural background. No further action required and no restrictions on land use.
>20 mg/kg	Exceeds typical background. Re-evaluate local background data as available. Test soil for bioaccessible arsenic if background is potentially exceeded.

Bioaccessible Arsenic (≤250μm size fraction)	Action
C-1 Soils (>4.2 mg/kg but ≤19 mg/kg)	No remedial action required. However, consider remediation of commercial/industrial properties to meet Residential R-1 (preferred) or R-2 action levels when feasible in order to minimize restrictions on future land use. Note that this may require a more detailed sampling strategy than typically needed for commercial/industrial properties (e.g., smaller decision units). Require formal, long-term institutional controls to restrict use of property to commercial/industrial purposes if the site will not be investigated to the level of detail required for future, unrestricted land use (i.e., inform potential buyers, deed covenants, risk management plans, etc.).
C-2 Soils (>19 but ≤95 mg/kg)	Remedial actions vary depending on site-specific factors, including current and planned use, available options for onsite isolation or offsite disposal, and technical and economical constraints (see text). Potential actions include: Consider removal and offsite disposal of small, easily identifiable "hot spots" when possible in order to reduce the average concentration of bioaccessible arsenic on the property. Use of C-2 soils as daily cover at a regulated landfill may also be possible. For sites that have already been developed, consider a minimum one-foot cover of clean fill material if the soil cannot be removed. If capping of soil is not feasible, consider measures to reduce daily exposure to soil (e.g., maintain lawn cover, ensure good hygiene, etc.). For new developments, consider isolation of soil under buildings, private roads or other permanent structures if technically and economically feasible. If isolation under permanent structures is not feasible, consider a minimum one-foot cover of clean fill material. Maintain landscaping and lawns in open areas where soil will not be capped. Backfill utility corridors with clean fill material (e.g., R-1 soils) to avoid excavation and inappropriate reuse of contaminated soil in the future. Require formal, long-term institutional controls to restrict use of site to commercial/industrial purposes only and ensure appropriate management of soil if exposed in the future (e.g., inform potential buyers, deed covenants, risk management plans, etc.). All areas of capped soil should be delineated on a surveyed map of the property to be subsequently included in the risk management plan.

Table 2. Soil categories and recommended actions for Commercial/Industrial Sites (cont.).

C-3 Soils (>95 mg/kg)	Removal of soil at existing commercial/industrial sites strongly recommended. At a minimum, consider removal and offsite disposal of soil with concentrations of bioaccessible arsenic that approach or exceed 180 mg/kg (direct exposure action level for construction and trench workers). If C-3 soils cannot be removed for technical or economic reasons, consider a minimum one-foot cover of clean fill material (two feet in potential deep landscaping areas) and placement of an easily identifiable marker barrier between the clean fill and the underlying soil (e.g., orange construction fencing or geotextile/geonet material). For new developments, removal and offsite disposal of soil should be strongly considered. At a minimum, consider removal and offsite disposal of soil with concentrations of bioaccessible arsenic that approach or exceed 180 mg/kg (direct exposure action level for construction and trench workers). If offsite disposal is not feasible but redevelopment of the property is still desired, consider use of soil as structural fill under public buildings, private roads, or other paved and well-controlled structures. If capping in open areas is unavoidable, consider a one-foot minimum cap thickness with an easily definable marker barrier placed between the soil and the overlying clean fill (e.g., orange construction fencing or geotextile/geonet material). Backfill utility corridors with clean fill material (e.g., R-1 soils) to avoid excavation and inappropriate reuse of contaminated soil in the future. Require formal, long-term institutional controls to ensure appropriate management of soil in the future (e.g., inform potential buyers, deed covenants, risk management plans, etc.). All areas of capped soil should be delineated on a surveyed map of the property to be subsequently included in the risk management plan.

The soil categories and arsenic action levels noted above are intended to be used as guidelines only and do not represent strict, regulatory cleanup requirements.



Residential Land Use Soil Categories		Commercial/Industrial Land Use Soil Categories	
R-1	≤4.2 mg/kg	C-1	≤19 mg/kg
R-2	>4.2 mg/kg to ≤23 mg/kg	C-2	>19 mg/kg to ≤95 mg/kg
R-3	>23 mg/kg	C-3	>95 mg/kg
>180 mg/kg: Potential risk to trench & construction workers			

Figure 1. Summary of bioaccessible arsenic action levels and correlative soil categories for residential and commercial/industrial (C/I) land-use scenarios.

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In reply, please refer to:
File: EHA/HEER Office

TO: Interested Parties

FROM: Roger Brewer
Environmental Risk Assessment
HEER Office

THROUGH: Barbara Brooks
Toxicologist
HEER Office

DATE: June 13, 2008

SUBJECT: Tier 2 Action Levels for TEQ dioxins (update to March 23, 2006 memorandum)

This technical memorandum presents Tier 2 action levels and corresponding guidance for dioxin-contaminated soil. The guidance serves as an addendum to the Hazard Evaluation and Emergency Response (HEER) office document *Evaluation of Environmental Hazards at Sites with Contaminated Soil and Groundwater* (HDOH 2008a). The guidance updates and takes precedence over guidance published in March and September 2006 (HDOH 2006). The update primarily addresses recommendations for the management of Category 2 soils in former agricultural fields.

The guidance is especially intended for use during the redevelopment of former agricultural areas, although it is applicable to any site where releases of dioxins may have occurred. The action levels should be used to help determine the extent and magnitude of arsenic-contaminated soils and help guide the scope of remedial actions needed. The action levels are intended to serve as guidelines only, however, and do not represent strict, regulatory cleanup requirements. Alternative action levels may be proposed for any site in a site-specific, environmental risk assessment.

Overview

Three categories and associated actions for dioxin-contaminated soil are presented (based on reported concentrations of TEQ dioxins):

Category	*Residential Land Use	Commercial/Industrial Land Use
Category 1	<42 ng/kg	<170 ng/kg
Category 2	42 to <390 ng/kg	170 to <1,600 ng/kg
Category 3	>390 ng/kg	>1,600 ng/kg

*Includes schools, day centers, medical facilities and other related sensitive land uses.

No further action is necessary for Category 1 soils under the noted land use. Capping or removal of Category 3 soils is recommended.

HDOH considers soils that fall within Category 2 to be adequate for the noted land use without further action. For example, soils with ≤390 ng/kg TEQ dioxins are considered to be acceptable for unrestricted use in residential (i.e., unrestricted) settings. As a best management practice, however, HDOH recommends the removal or capping of Category 2 soils associated with easily identifiable, localized spill areas when feasible (e.g., past pesticide mixing or storage). DOH does not consider capping or removal of Category 2 soils in large, former field areas to be necessary or practicable. These issues are discussed in more detail below.

Update to 2006 Guidance

DOH has reviewed a significant amount of data for large, former field areas used to cultivate sugar cane since publication of our March 2006 guidance. Although a formal summary has not been prepared, anthropogenic "background" levels of TEQ dioxins in former sugar cane fields appear to be in the range of 50 ng/kg to 100 ng/kg (as measured by Method 8290). Concentrations of TEQ dioxins in undisturbed areas appear to be less than 50 ng/kg. To date, concentrations of TEQ dioxins above 390 ng/kg have not been reported for soils in former field areas. In contrast, concentrations of TEQ dioxins in former pesticide mixing areas have been reported at more than 1,000 times these levels, clearly demarking them from the former field areas.

Based on this additional information, most soils in former field areas are anticipated to fall into Category 2 for TEQ dioxins. DOH recognizes that management of these soils in large, redevelopment field areas is not practicable and, from a health risk standpoint, not strictly necessary. As a clarification to our March 2006 guidance, DOH now recommends that isolation or removal of Category 2 soils be considered only in cases where localized spill areas are identified (e.g., associated with former pesticide mixing or storage areas). While not required to meet target health risks or DOH cleanup requirements, management of small and easily identifiable "hot spots" when practicable will further reduce potential exposure of future residents and workers to dioxins.

For Category 2 soils in former field areas, DOH recommends that future land owners be notified of the past use of the land and the presence of elevated levels of dioxins as part of the due diligence process. As discussed in the March 2006 guidance, exposure to dioxins in the soil can be minimized by maintaining landscaping and avoiding areas of bare dirt. A similar update has been incorporated into DOH's Tier 2 action level guidance for arsenic-contaminated soils.

TCDD Toxicity Equivalent (TEQ) Concentration

The Minnesota Department of Health document referenced above provides a good summary of methods used to evaluate human health risks posed by dioxins (MDH 2003). The term "dioxins" is used to refer to a family of chlorinated compounds with similar chemical structures and mechanisms of toxicity, referred to as "congeners." The evaluation of risk to human health focuses on seventeen specific congeners - seven polychlorinated dibenzo-p-dioxins (PCDDs) and ten polychlorinated dibenzofurans (PCSFs). Individual congeners are not equally toxic. The toxicity of specific congeners is assigned a value relative to the toxicity of 2,3,7,8-TCDD, the most potent carcinogen of the 17 congeners studied. These values are referred to as "Toxicity Equivalence Factors" or "TEFs." The reported concentration of an individual congener is multiplied by its respective TEF to produce a Toxicity Equivalent (TEQ) concentration. The TEQ concentrations for individual congeners are then added together to calculate a total 2,3,7,8-TCDD TEQ concentration for the sample.

Recommended Action Levels for Dioxins

USEPA Region IX referred to a cancer slope factor of 1.5 E+05 $(\text{mg/kg-day})^{-1}$ to in their 2004 Preliminary Remediation Goals for dioxins, evaluated as 2,3,7,8 TCDD Toxic Equivalent Concentration (USEPA 2004, applied to 1,2,3,7,8 PeCDD in 2008 USEPA Regional Screening Levels). A toxicity review published by the Minnesota Department of Health presents an alternative cancer slope factor of 1.4E+06 $(\text{mg/kg-day})^{-1}$ for 2,3,7,8 TCDD, or approximately nine times more stringent that the slope factor currently used in the USEPA RSLs (MDH 2003). At a target 10^{-4} excess cancer risk, the USEPA and MDH cancer slope factors equate to residential soil screening levels of 42 ng/kg and 390 ng/kg, respectively (ng/kg = parts-per-trillion). There is a potential that USEPA will move toward the more stringent cancer slope factor in the near future. It is important, therefore, to take the soil action level based on this slope factor into account at dioxin-contaminated sites.

The ASTM document "Dioxin and Dioxin-Like Compounds in Soil" provides a useful approach to do this (ASTM 1997). The guidance uses lower and upper bound, dioxin action levels to recommend three potential options at dioxin-contaminated sites. A modification of this approach using the action levels noted above is summarized in the following table:

Dioxins (2,3,7,8 TCDD TEQ)	**Action**
Low Risk **≤42 ng/kg**	No further action required.
Intermediate Risk **>42 but ≤390 ng/kg**	Within USEPA range of acceptable health risk. Consider removal and offsite disposal of small, easily identifiable "hot spots" when possible in order to reduce potential exposure (not required for large, former field areas). Use of soil as daily cover at a regulated landfill may also be possible. For existing homes, consider measures to reduce daily exposure to soil (e.g., maintain lawn cover, ensure good hygiene, thoroughly wash homegrown produce, etc.). For new developments on large, former field areas, notify future homeowners of elevated levels of arsenic on the property (e.g., include in information provided to potential buyers during property transactions).
High Risk **>390 ng/kg**	Residential use not recommended in absence of remedial actions to reduce potential exposure.

For comparison purposes, correlative TEQ dioxin action levels for commercial/industrial land use based on the same target risk ranges are:

- Low Risk: <170 ng/kg;
- Intermediate Risk: >170 ng/kg but ≤1,600 ng/kg; and
- High Risk: >1,600 ng/kg.

The action levels noted above are intended to be used as guidelines only and do not represent strict, regulatory, cleanup standards. Additional guidance will be provided in the Summer 2008 update to the HEER office *Environmental Hazard Evaluation* guidance (HDOH 2008).

A minimum cap thickness of twenty-four inches is recommended for on-site isolation of Category 3 soils (e.g., refer to guidance for lead-contaminated sites in USEPA 2003). A clearly identifiable marker barrier should be placed between the contaminated soil and the overlying clean fill material (e.g., orange, plastic, construction fencing). Onsite isolation of soil with dioxin TEQ concentrations that could pose unacceptable health risks to future construction and utility trench workers is not recommended (e.g., >21,000 ng/kg, action level for construction worker exposure at target 10^{-4} excess cancer risk and MDH cancer slope factor; after HDOH 2005).

Doixin Test Methods

Use of bioassay methods (e.g., XDS-CALUX Bioassay tests) for total dioxins is acceptable for initial screening of soils, provided that adequate supporting documentation for the test has been submitted to HDOH for review. Reported levels of total dioxins based on bioassay tests should include a GCMS correction factor, as appropriate for the test method used. If the reported total dioxin concentration exceeds 42 ng/kg, then the concentration of individual congeners should be determined and the TCDD TEQ concentration for the sample calculated. The action levels noted above should then be used to determine appropriate actions. Confirmation analyses using GC/MS analysis should be provided for 10% of the samples tested or a minimum of two samples (e.g., USEPA Method 8290). Relatively inexpensive bioassay tests may also be useful for the investigation of large sites where a clear relationship between screening methods and GC/MS data has been established. Use of this approach should be discussed with HDOH on a site-by-site basis.

1998 USEPA OSWER Directive

A 1998 directive from USEPA recommends “preliminary remediation goals” for dioxins in soil of 1,000 ng/kg (1.0 ug/kg) for residential land use and 5,000 ng/kg (5 ug/kg) to 20,000 ng/kg (20 ug/kg) for commercial/industrial land use (USEPA 1998). These action levels reflect excess cancer risks of 2.5×10^{-4} and 1.3×10^{-4} to 5.2×10^{-4}, respectively, marginally over the maximum target cancer risk of 10^{-4} recommended in USEPA guidance for human health risk assessment (e.g., USEPA 1989).

The recommendation for action levels outside of the normal, acceptable risk range reflects a policy decision on the part of USEPA to strike a balance between the increased toxicity of dioxins identified in studies during the 1990s and exposures to dioxins in food and other sources. The action levels are used to help identify very-high-risk sites and focus initial State and Federal resources on these areas. ATSDR uses an action level of 1,000 ng/kg to identify “very-high-risk” sites where health studies of residents may be needed (ATSDR 1997). The USEPA directive notes that this does not necessarily exclude an evaluation of sites with dioxin levels below 1,000 ng/kg. Final cleanup standards for a given site could be lower and are dependent on site-specific considerations, including land use, anticipated exposure, the extent and magnitude of contamination and the feasibility of meeting more stringent cleanup standards.

The dioxin action levels are not recommended for use in Hawai’i. The number of sites in Hawai’i with significantly elevated levels of dioxins is expected to be relatively small in comparison to the mainland. Action levels presented in this memo are considered feasible and appropriate for identification of high-risk sites. Former pesticide mixing areas at agricultural sites have been identified as the primary areas of concern. Based on a review of data from these sites, the effort required to meet the action levels presented in this memo and further reduce health risks to future residents and workers is not likely to be significantly greater than the effort required to meet the action levels proposed in the USEPA directive.

Soil Sampling Methods

The use of multi-increment field soil sampling and lab sub-sampling techniques is recommended over the use of discrete or traditional composite sampling techniques. This sampling approach allows for the determination of a statistically representative concentration of arsenic within a specific area of investigation or "decision unit.", such as an individual yard, a park, a garden or a well-defined spill area. Additional guidance on the use of multi-increment and decision unit investigation strategies will be provided in the 2008 update to the HEER office *Technical Guidance Manual.*

Other Potential Environmental Hazards

A discussion of environmental hazards associated with contaminated soil is provided in the HDOH document *Evaluation of Environmental Hazards at Sites with Contaminated Soil and Groundwater* (HDOH 2008a). The dioxin action levels presented in this technical memorandum address human-health, direct-exposure hazards only. Risk to human health is anticipated to drive concerns for dioxin-contaminated soil, however. Dioxins (and furans) are not significantly mobile and are not anticipated to pose potential leaching hazards. Dioxins also do not pose significant vapor intrusion hazards or gross contamination hazards. Potential impacts on ecological habitats must be evaluated on a site-specific basis as needed.

Environmental Hazard Evaluation Plans

Isolation areas where dioxin-contaminated soil is to be capped for permanent onsite management must be clearly identified on surveyed, post-redevelopment map(s) of the property. Areas of soil at commercial/industrial sites that exceed action levels for residential R-1, R-2 and R-3 soils should also be clearly surveyed and mapped. The maps identifying arsenic-impacted soils should be incorporated into an *Environmental Hazard Evaluation Plan* (HDOH 2008a) that describes proper management, reuse and disposal of contaminated soil if disturbed during later redevelopment activities. A copy of the plan should be submitted to both HDOH and to the agency(s) that grants permits for construction, trenching, grading or any other activities that could involve future disturbance or excavation of the soil. The need to incorporate the risk management plan and specific land use restrictions in a formal covenant to the property deed should be discussed with HDOH on a site-by-site basis. Additional guidance on EHMPs will be provided in the 2008 update to the HEER office *Technical Guidance Manual*.

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TO: Interested Parties 2007-223-RB

FROM: Roger Brewer, Ph.D
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THROUGH: Barbara Brooks, Ph.D
Toxicologist
Hazard Evaluation and Emergency Response

DATE: April 12, 2007

SUBJECT: Use of laboratory batch tests to evaluate potential leaching of contaminants from soil (update to November 2006 technical memorandum)

Executive Summary

This technical memorandum presents the Batch Test Leaching Model (BTLM), a simple, Tier 3 approach for assessing the potential impact to groundwater posed by leaching of contaminants from vadose-zone soils. The BTLM uses site-specific soil data to evaluate contaminant mobility and estimate contaminant concentrations in soil leachate. If the contaminant is deemed sufficiently mobile, the model predicts future impacts to groundwater based on simple leachate dilution assumption. This can then be compared to target groundwater action levels appropriate for the site. An Excel spreadsheet is included to facilitate use of the model. Use of the spreadsheet model only requires input of the concentration of the contaminant in soil (in mg/kg) and the result of the batch test analysis (in µg/L). The BTLM can also be used to develop more realistic, site-specific soil action levels in lieu of the conservative, Tier 1 action levels for this concern published by HDOH. This guidance will be updated periodically as additional information and improved approaches are identified.

The guidance is most pertinent to vadose zone soils. Direct monitoring of groundwater should be carried out to evaluate leaching of contaminants in soils situated below the water table. Guidance presented in this memo does not apply to the evaluation of waste being placed in regulated landfills or to hazardous waste determinations. Evaluation of waste to be placed in landfills must be carried out under direction of the HDOH Solid and Hazardous Waste Branch.

Introduction

At a screening level, leaching of contaminants from soil is the primary environmental concern for the majority of the organic contaminants presented in the Hawai‘i Department of Health (HDOH) document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (i.e., Tier 1 soil action levels for leaching concerns are lower than action levels for direct exposure, vapor intrusion, ecotoxicity and gross contamination concerns, HDOH 2005). Site-specific evaluation is recommended when soil action levels for leaching concerns are exceeded. In addition, action levels for metals are not provided in the document and leaching concerns must again be evaluated on a site-by-site basis. However, easy-to-use and technically sound soil leaching models that can be applied to both organic and inorganic contaminants have been lacking. The guidance presented below is intended to help address this issue.

The guidance focuses on the use of laboratory batch tests to quantify the mobility of the contaminant in soil and estimate the initial concentration of the contaminant in soil leachate. Batch tests involve placing a small amount of the soil in buffered, de-ionized water, agitating the mixture for a set period of time and measuring the fraction of the contaminant that desorbs from the soil and goes into solution. The ratio of the mass of a contaminant that remains sorbed to the mass that goes into solution, adjusted to the test method, is referred to the contaminant’s “desorption coefficient” or “Kd” value.

A contaminant’s Kd value is a key parameter in soil leaching models. The lower the Kd value, the greater the mobility of the contaminant in soil and the greater the leaching threat. Contaminants with Kd values less than 1.0 are considered to be highly mobile and pose a significant threat to groundwater resources. Contaminants with Kd values greater than 20 are considered to be so tightly bound to the soil that they are essentially immobile and do not pose a significant leaching concern. The strength of binding can vary among different soil types, as well as contaminant concentration and the age of the release.

Batch test data can be input into an Excel spreadsheet model (“Batch Test Leaching Model (April 2007)) that accompanies this technical memorandum to calculate Kd values for target contaminants. Use of the model only requires input of the concentration of the contaminant in soil (in mg/kg) and the results of batch test analysis (in µg/L). Additional, default parameter values in the model can be adjusted if needed but this is generally not recommended. The concentration of the contaminant in leachate hypothetically derived from the soil tested is calculated based on the Kd value determined for the contaminant. The spreadsheet then estimates the ultimate concentration of the contaminant in groundwater based on a simple groundwater/leachate mixing model. The inclusion of a more refined approach for estimating contaminant concentrations in groundwater is anticipated for future updates to this guidance.

The remainder of this guidance provides a detailed discussion of contaminant partitioning in soil, key questions to be asked in site-specific leaching models, batch test methodologies for estimation of site-specific Kd values and calculation of contaminant concentrations in soil leachate and groundwater. Equations used in the Batch Test Leaching Model are presented in Appendix 1. The use of soil gas data to estimate concentrations of volatile contaminants in leachate is also briefly introduced. A detailed understanding of these topics is not necessarily needed to use the accompanying spreadsheets and carry out a simple, site-specific evaluation of potential soil leaching concerns using batch test data. A basic understanding of contaminant fate and transport in the subsurface is very useful, however, in determining how confident one can be in applying the results of the models to actual field conditions.

This memo updates a previous November 2006 version of the guidance and replaces text regarding use of the SPLP test presented in the May 2005 edition of the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater"* (Volume 1, Section 3.3.3; HDOH 2005). The approach described should be considered guidance only. Alternative approaches can be proposed for specific sites. This guidance will be updated as needed in the future. Comments and suggestions are welcome at any time and should be directed to Roger Brewer of HDOH at roger.brewer@doh.hawaii.gov.

Partitioning of Contaminants in Soil

Contaminants released into soil will partition into up to four different phases in the soil matrix (Figure 1). Some of the contaminant will dissolve into the soil moisture to form leachate. Another portion will chemically bind ("sorb") to soil particles, primarily organic carbon and clay particles. If the contaminant is volatile, a portion will also partition into air-filled pore space as a vapor phase. If the total mass of the contaminant is great enough, the soil particles, soil moisture and soil vapor will become saturated and free-phase product will also be present.

In theory, the various phases of a contaminant will eventually come into equilibrium with each other. The nature of this equilibrium is controlled by the chemical properties of the contaminant, the chemistry and physical properties of the soil and the presence of other contaminants. Contaminants that readily bind to soil particles will be present primarily in the sorbed phase (e.g., PAHs, PCBs, etc.). Contaminants that are not very sorptive will accumulate in the soil moisture or soil vapor (e.g., perchlorate, chlorinated herbicides, BTEX, MTBE, solvents, etc.). Contaminants that are by nature gases will persist mainly as vapors in the air-filled pore space, especially if the soil is very dry (e.g., vinyl chloride).

In the absence of free product, the relationship between sorbed, dissolved and vapor phases of a contaminant in soil is relatively straightforward and can be described by simple partition coefficients (USEPA 2001). A contaminant's "Henry's Law Constant" is the ratio of the vapor-phase concentration of a contaminant to the dissolved-phase concentration, at equilibrium. The Henry's Law Constant is relatively constant between sites, although it may vary slightly due to differences in soil temperature and the presence of other contaminants.

A contaminants sorption coefficient, or "Kd" value, is the ratio of the sorbed-phase concentration to the dissolved-phase concentration, at equilibrium (see Figure 1). For initial screening purposes and calculation of Tier 1 soil Action Levels, Kd values for organic chemicals are estimated using published *sorption* coefficients ("koc" values) and assumptions about the organic carbon content of the soil (Kd = published koc value x assumed fraction organic carbon in soil, typically 0.1%). Generic Kd values have also been published for a limited number of metals and other inorganic contaminants, although they are considered to much less reliable than for organic compounds. In the field, however, contaminant sorption (or more specifically "desorption") coefficients can vary significantly between sites, due to differences in soil properties, the mixture of contaminants present and even the age of the release. The variability of contaminant Kd values in the field implies that this parameter should be included in site-specific evaluations of potential leaching concerns. In practice, this is rarely done.

A contaminants Henry's Law Constant and assumed (or site-specific) Kd value can be used in conjunction with assumed or know soil properties to determine how the contaminant is actually distributed in the soil. Table 1 summarizes the distribution of several common contaminants in soil as assumed in the leaching models used to generate Tier 1 action levels published but HDOH (HDOH 2005). The percent mass in each phase is calculated based rearrangement of a simple equilibrium partitioning equation presented in USEPA's *Soil Screening Guidance* (USEPA 2001, refer also to Appendix 1). Similar assumptions about contaminant partitioning in soil are made in the models used to generate the USEPA Preliminary Remediation Goals or Preliminary Remediation Goals, although this cannot be readily discerned from the equations presented in the accompanying guidance document (USEPA 2004).

As expected, contaminants such as benzo(a)pyrene and PCBs are almost entirely absorbed to soil particles (refer to Table 1). Perhaps surprising, however, is the tendency for the main mass of moderately volatile contaminants such as benzene, PCE and MTBE to be sorbed to soil particles or dissolved in soil moisture, versus being present as vapors in the soil air space. Confusion about this issue has led to over estimation (and probably over concern) of contaminant loss during sampling of soil for this group of chemicals. Compare this to contaminants that are gases and truly volatile by nature, such as vinyl chloride (see Table 1). Testing soil samples for the presence of vinyl chloride and estimating leaching concerns is probably not a worthwhile effort. The use of soil gas samples to estimate concentrations of highly volatile contaminants in soil leachate and even monitor the downward migrating vapor plumes is much more preferable. A brief introduction to this approach is provided later in this guidance and also included in the BTLM spreadsheet.

Site-Specific Evaluation of Soil Leaching Concerns

Four basic questions need to be posed when evaluating the potential for contaminants to leach from soil and impact groundwater (Figure 2):

1. "Is the contaminant potentially mobile?"
2. "What is the concentration of the contaminant in leachate in the primary source area?"
3. "What is the concentration of the contaminant in leachate at the point that the leachate reaches the top of the water table?" and
4. "What is the concentration of the contaminant in groundwater after the leachate has impacted the groundwater?"

Each of these relatively common sense and straight forward questions should be answered in a site-specific evaluation of potential soil leaching concerns. In practice, they rarely are, due in part to the "black box" nature of most soil leaching models. The guidance presented in this technical memorandum focuses on the first two of these questions, contaminant mobility and the initial concentration of the contaminant in leachate.

Mobility in Soil

Contaminant mobility in soil is evaluated in terms of how tightly bound the contaminant is to soil particles. From a modeling perspective, this is again described in terms of the contaminant's desorption coefficient or Kd value. Increasing Kd values reflect decreasing mobility in soil.

Figure 3 presents default, Tier 1 Kd values for several common contaminants and subdivides them in terms of relative mobility or leachability in soil (after Fetter 1993). Contaminants with a generic Kd value of less than 1.0 are considered to be highly mobile in soil, a fact that correlates well with field data and a list of common groundwater contaminants. Contaminants with a Kd value of greater than 20 in soil are considered to be essentially immobile. Not surprisingly, contaminants such as MTBE, PCE, BTEX, perchlorate and chlorinated pesticides like atrazine are predicted to be highly mobile in soil, at least at a screening level, whereas PAHs, PCBs and similar contaminants are considered to be essentially immobile. (Note that trace levels of strongly sorptive contaminants like chlordane in groundwater indicate that these contaminants can be mobile under some circumstances, especially if the leachate is migrating through unweathered bed rock.)

The ability of a contaminant to bind to soil is very much tied to the nature and concentration of the contaminant, the presence of other contaminants that may compete for prime sorption spots, the soil mineralogy and chemistry (including organic carbon and clay content) and the time elapsed since the release of the contaminant. Use of generic Kd values could in theory *under* predict how strongly bound a contaminant is to soil, especially in the presence of other contaminants or in soils with extreme pH, redox or other soil conditions. Based on (admittedly limited) data collected to date, however, generic Kd values typically used for organic contaminants tend to significantly *over* predict the potential mobility of contaminants in soils. This is especially true for organic contaminants. This makes the use of laboratory batch tests very important when Tier 1 action levels or screening levels for potential leaching concerns (based on generic Kd values) suggest that leaching concerns need to be further evaluated.

Initial Concentration in Leachate

A contaminant's Kd value is used in conjunction with it's Henry's Law Constant and assumptions about soil properties to estimate the initial concentration of a contaminant in leachate. The relatively simple equation used to perform this calculation is presented in Appendix 1 and incorporated into the accompanying spreadsheet. The proportion of the contaminant that will move into soil leachate is again mainly controlled or reflected by the contaminant's Kd value. A Kd value less than 1.0 indicates that most of the contaminant will move into soil leachate in comparison to the fraction of the contaminant that will remain sorbed to soil particles.

Concentration in Leachate at Groundwater Interface

As the leachate migrates downward, contaminant concentrations can be progressively reduced due to resorption of the contaminant to soil particles, chemical or biological degradation or volatilization into the soil air space. Estimates of contaminant concentrations in leachate at the point that the leachate reaches the groundwater interface can be made using a vadose-zone fate and transport model. This important step is not included into the BTLM at this time. The BTLM model instead very conservatively assumes that the concentration of the contaminant in leachate at the groundwater interface is equal to that in the initial source area. A more detailed evaluation of contaminant fate and transport in soil leachate (e.g., using SESOIL, VLEACH or other vadose-zone leaching models) may be particularly useful at sites where the depth to groundwater from the base of the contaminated soil is greater than approximately ten meters and target contaminants that have default koc values greater than 1,000 cm^3/g (e.g., naphthalene), are highly degradable (e.g., TPH and BTEX), and/or are moderately or highly volatile (e.g., PCE and vinyl chloride).

Concentration in Groundwater

The concentration of a contaminant in groundwater after mixing of the leachate with the groundwater can be estimated by either dividing the concentration of the contaminant in leachate by simple dilution factor or again by use of a more rigorous fate and transport model (refer to equations in Appendix 1). The BTLM model presented relies on the former, although a more refined approach may be added in the future.

The HDOH Environmental Action Levels document (or EAL Surfer) should be referred to for target groundwater goals (HDOH 2005). Target groundwater goals will in general be the lowest of the drinking water goal (i.e., lowest of Primary and Secondary MCLs or equivalents), surface water goal (assuming potential discharge to a body of surface water, acute or chronic aquatic toxicity goal based on site location) and any other applicable goals (vapor intrusion, gross contamination, etc.).

Use of Batch Test Data To Estimate Contaminant Kd Values

Relatively simple batch test methods have been in use for decades to evaluate leaching of metals from mine tailings and estimate the mobility of pesticides sprayed on agricultural lands (USEPA 1992, 1999). The tests collectively account for a host of factors that may control binding to (sorption) and leaching of (desorption) contaminants from soil. The tests do not identify exactly how the contaminant is bound to the soil, although a review of soil properties and chemistry can shed light on this issue if needed. The most commonly used batch test method to evaluate potential leaching of contaminants from soil is the *Synthetic Precipitation Leaching Procedu*re or "SPLP" test (USEPA 1994, similar to the California "WET" test). The SPLP test is carried out as follows:

Step 1. Analyze soil sample for concentrations of target contaminants (e.g., in mg/kg)

Step 2. Run SPLP test on split sample:

- Place 100 grams soil in two liters of a de-ionized water solution (pH 5.5, 25° C),
- Remove airspace (especially for VOCs),
- Agitate 18 hours.

Step 3. Analyze extract for contaminants of concern.

Step 4. Estimate Kd by comparison of the mass of contaminant that remained sorbed to the soil to the mass of the contaminant that went into solution.

The equations used to calculate a contaminant's Kd value in soil based on batch test data are provided in Appendix 1 and incorporated into the accompanying BTLM spreadsheet. The calculated Kd value is then used to evaluate the potential mobility of the contaminant in the soil and estimate the initial concentration of the contaminant in soil leachate and groundwater, as described in the previous section.

For batch test results that are below standard, commercial lab Method reporting Limits (MRL), Kd can be estimated using 1/2 the MRL. If the estimated Kd is less than 20, a worst-case concentration of the contaminant in groundwater can calculated as described above.

Contaminant Kd values estimated through use of batch tests apply only to the soil tested and only for the reported concentration of the contaminant in the soil. Kd values could vary with respect to contaminant concentration in the same soil type. This may need to be evaluated on a site-specific basis in cases where soil contamination is widespread and very heterogeneous.

For large areas where contaminant concentrations vary significantly and individual spill areas cannot be easily identified, it may be useful to conduct a series of batch tests and evaluate the variation in Kd with respect to contaminant concentrations in soil (keeping in mind the need to separate different soil types). Soil cleanup levels can then be developed by plotting contaminant concentration in soil versus estimated concentration in leachate, generating a regression line through the data (USEPA 1992, 1999). Soil cleanup levels can be calculated or read directly off of the graph by setting a target concentration of the contaminant in the leachate (e.g., target groundwater concentration times assumed groundwater/leachate dilution factor). An example of this approach based on perchlorate soil and SPLP data collected at a site in California is given in Figure 4. (Note that final cleanup standards varied slightly from that noted in the figure due to assumptions about representative contaminant distribution and Kd values in soil across the site.) In Hawai‘i, this approach may be especially useful in the evaluation of large, pesticide mixing areas associated with former agricultural lands.

It is important to understand that batch tests were not designed to directly estimate the concentration of a contaminant in soil leachate. Batch tests were instead designed to calculate Kd sorption or desorption coefficients, which can then be used to estimate contaminant concentrations in leachate if desired. The volume of solution used in batch test can be used to illustrate this point. A solution volume of two liters was selected primarily to help ensure that laboratory detection limits could be met, not to mimic the supposed concentration of the contaminant in actual soil leachate – as is commonly misinterpreted (USEPA 1992). If the same mass of soil (generally 100 grams) were placed in a swimming pool-size volume of solution then the resulting concentrations of target contaminants in the batch test would of course be very different. Assuming that the contaminant is not completely stripped from the soil, however, the ratio of the mass that remains sorbed to the mass that moves into solution (i.e., the Kd value) should be constant. For highly sorptive contaminants (e.g., PCBs and PAHs) and for many metals, the difference between batch test results and calculated concentration of the contaminant in leachate may indeed be very small. For less sorptive contaminants like BTEX, MTBE, perchlorate and moderately mobile pesticides, however, estimated concentrations in leachate may be an order of magnitude or more greater than the concentration reported in the batch test data. This is especially true for contaminants with Kd values less than 20 in the soil tested, where a significant fraction of the contaminant partitions into the batch test solute (e.g., >25%).

Soil Sampling Strategies

A minimum of three soil samples is generally needed to validate batch test data for each area investigated. Recording the soil type and testing for the total organic carbon content and percent clay content of the soil is also recommended. Although not directly incorporated into the BTLM, this information may prove useful in understanding the nature of contaminant binding in the soil and help direct soil cleanup actions, if needed.

For large sites with varying soil types, contaminant mixtures or release histories, it may be necessary to define multiple “decision units” and evaluate each area separately. For example, the binding capacity of sandy soils is likely to be much lower than clayey or organic-rich soils. If both soil types are present at a contaminated site, it would be prudent to treat each soil type area as a separate decision unit.

The collection and analysis of multi-increment samples (essentially very good “composite” samples) is preferred for easily identifiable spill areas or “hot spots,” especially where the primary contaminants are non-volatile. Collection and field-based extraction of multi-increment samples for volatile contaminants may also feasible, although this subject is beyond the current scope of this memo. Guidance on the collection and evaluation of multi-increment samples is currently being prepared by HDOH. In the interim, and especially for cases under the formal oversight of HDOH, it is recommended that potential users of the BTLM guidance review sampling plans with the HDOH project manager prior to collection and submittal of the samples for analysis.

Use of Soil Gas Data to Evaluate Groundwater Protection Concerns

Batch tests can be used to evaluate both nonvolatile and volatile contaminants, although special care must be taken during sampling and testing of the latter (refer to USEPA 1994 SPLP method guidance). The concurrent use of soil gas data to estimate the concentration of volatile contaminants in soil leachate may also be prudent. Reasonably accurate estimations of the contaminant concentrations in soil moisture or leachate can be made by dividing the concentration of the contaminant in soil gas (converted to ug/L) by the chemical’s dimensionless Henry’s Law Constant (see equation in Appendix 1). A simple model based on this approach and incorporating a groundwater:leachate dilution factor is presented in Appendix 1 and included in the BTLM spreadsheet.

Cases where soil gas data may prove beneficial for evaluation of potential impacts to groundwater include: 1) sites with releases of relatively persistent, volatile chemicals that remain very dry throughout much of the year (i.e., non-irrigated areas with very low precipitation, or paved areas that overlie shallow groundwater), 2) sites known to be impacted by volatile contaminants but where specific source areas have not been identified, 3) sites where the threat to groundwater is primarily posed by downward releases of vapors from underground tanks, pipelines, etc., and 4) sites where the vulnerability and sensitivity of the first-encountered groundwater resource is very high (e.g., unconfined aquifer that is currently used as a source of drinking water). In very wet or heavily irrigated areas (e.g., groundwater recharge greater than ten inches or 25cm per year), mass loading of the contaminant to groundwater via vapor-phase plumes is likely to be insignificant in comparison to contaminant migration via leachate. In very dry areas, however, the amount of moisture in the soils may not be sufficient to initiate the downward migration of leachate by the force of gravity. If this is the case then the model discussed above will overstate the potential threat to groundwater posed by dissolved-phase contaminants in the soil moisture.

A focus on the potential for vapor plumes to impact groundwater will be more appropriate for dry areas. Easy-to-use models that specifically evaluate the downward migration of vapor plumes to groundwater are not currently available. An evaluation of potential groundwater impact concerns may instead have to rely on long-term monitoring of soil gas in the vadose zone. Soil gas "action levels" for protection of groundwater can be developed by rearranging the Herny's Law Constant equation to solve for the concentration of the contaminant in soil vapor and setting the dissolved-phase concentration of the contaminant equal to a target groundwater or leachate goal (refer to equations in Appendix 1).

Soil gas data will be less useful for estimation of semi-volatile contaminant concentrations in leachate. This is due to the very low Henry's Law Constants for these contaminants and associated limitations on soil gas method reporting limits. As noted in Table 1 for PAHs, the overwhelming majority of the contaminant mass will also be sorbed to the soil, rather than in the soil vapor. Batch tests on representative soil samples therefore offer a better approach for the evaluation of leaching concerns related to these contaminants.

Leaching of Heavily Contaminated Soils

Soils that contain significant amounts of pure-phase or "free" product" may not be amenable to use of the Batch Test Leaching Model as described above (i.e., contaminant that is not sorbed to the soil, dissolved into the soil moisture or present as vapors in air-filled pore space). This is particularly true for soils that are heavily contaminated with petroleum. Contaminant Kd values can only be calculated if any free product present completely dissolves into the batch test solution. If free product forms in the batch test solution then analysis of solution for dissolved-phase constituents will not accurately reflect the total mass of contaminants that were stripped from the soil during the test. This will cause the model to over predict the mass of the contaminant that remained sorbed to the soil and in turn over predict the contaminants Kd value.

If the reported concentration of a contaminant in a batch test analysis exceeds 75% of the assumed solubility then it should be assumed that pure-phase contaminant product may be present in the batch test solution. In such cases, the spreadsheet model will generate a caution message and a Kd value will not be calculated. The potential mobility of the contaminant with respect to it's Kd value therefore cannot be accurately evaluated. In the spreadsheet model, the estimated concentration of contaminant in soil leachate is set to the highest of the contaminant's solubility and the reported concentration of the contaminant in the batch test analysis. Potential impacts to groundwater are estimated by dividing the assumed concentration of the contaminant in leachate by the input groundwater:leachate dilution factor. The potential downward mobility of liquid-phase free product in the soil should also be further evaluated.

Special Considerations For Petroleum-Contaminated Soils

Soils impacted by petroleum should be tested for both Total Petroleum Hydrocarbons (TPH) and target indicator compounds, including BTEX, MTBE and related fuel oxygenates and the PAHs naphthalene and methylnaphthalene (refer to Volume 1, Section 2.2.2 in HDOH EAL document, HDOH 2005). Testing for other PAHs is not necessary, due to their relative immobility in soil and low concentration in most petroleum products.

Problems related to the presence of free product in the batch test solution as discussed above could be especially pronounced for soils heavily impacted with middle distillates (diesel, jet fuel, etc.) and heavier residual fuels (waste oil, hydraulic fluid, etc.). The low solubility of these fuels in comparison to gasoline can lead to the presence of droplets of free product in soil at concentrations above only a few hundred parts-per-million (mg/kg) TPH. At high enough concentrations, this could lead to the presence of free product in the batch test solution. This will negate use of the BTLM model to calculate a Kd value for the sample tested and evaluate the potential mobility of the contaminant, as discussed in the previous section.

If the batch test results for Total Petroleum Hydrocarbons (TPH) suggest the potential presence of free product in the solution then the concentration of TPH in soil leachate should be assumed to be equal to the higher of the reported result and the assumed solubility of the targeted petroleum product. In the absence of a more site-specific review, the potential concentration of the contaminant in groundwater should be estimated by dividing the concentration in leachate but the groundwater:leachate dilution factor selected for the site. This is automatically carried out in the accompanying BTLM spreadsheet.

The presence of potentially mobile free product in the soil should also be evaluated. This can be done by comparison of TPH data for vadose-zone soil to HDOH action levels for gross contamination concerns in subsurface soils (HDOH 2005, Appendix 1). An action level of 2,000 mg/kg for gasoline contaminated soils. A somewhat higher action level 5,000 mg/kg is used for soils contaminated with either middle range petroleum distillates (e.g., diesel fuel and jet fuel) or residual fuels (motor oil, waste oil, etc.). These action levels are intended to minimize the presence of mobile free product in soil and are based on field observations and published studies (e.g, API 2000). Minimum conditions for use of the action levels in other areas include: 1) the source of the release has been eliminated, 2) grossly contaminated soil has been removed to the extent practicable (e.g., within 15 feet of the ground surface and/or to the top of bedrock) and 3) remaining contamination does not threaten nearby water supply wells or aquatic habitat (refer also to Volume 1, Section 2.2 of the HDOH 2005 EAL document).

Residual petroleum contamination in soil can be expected to naturally degrade over time. Note that impacted soil that is disturbed during future subsurface activities must also be properly managed. Continued groundwater monitoring may also be required for highly sensitive sites. Additional guidance for the long-term management of petroleum-contaminated soil (and groundwater) is currently being prepared by HDOH.

Other Limitations

Evaluation of Past Impacts to Groundwater

The approach described in this technical memorandum can only be used to predict *future* leaching of contaminants from soil and subsequent impacts to groundwater. Batch tests on residual contaminants in soil cannot necessarily be used to predict if *past* impacts to groundwater may have occurred. In part this is because the contaminants may be much more strongly bound to soil particles under current conditions than during the initial release. The possibility of past impacts to groundwater must be evaluated on a site-by-site basis, based on the nature of the contaminant released, the subsurface geology and the depth to groundwater among other factors.

Placement of Soil Below Water Table

The batch test method may not accurately mimic the placement of contaminated soil or other media below the water table for long periods of time and should not be used to predict these conditions. Long-term immersion could significantly enhance desorption of contaminants, especially if rate-limited processes such as desorption, organic carbon decay or mineral dissolution affect contaminant partitioning. Long-term immersion of the soil could increase impacts to groundwater that significantly exceed levels predicted by short-term batch tests. In the absence of a more detailed groundwater impact study, placement of contaminated soil below the water table or at a depth that is subject to future inundation by a rise in groundwater should be avoided (e.g., areas where the water table has dropped significantly due a prolonged dry period but is expected to rise again in the future). If this cannot be avoided and nearby water supply wells or aquatic habitats could be threatened, then long-term monitoring of the groundwater to verify that the contaminants are not significantly mobile is probably warranted.

Long-Term Groundwater Monitoring

Although the batch test method is believed to be very accurate, long-term groundwater monitoring may be prudent in some cases to verify the results of the evaluation. Monitoring may be especially warranted at sites where batch test data suggest that relatively high concentrations of chlorinated solvents, pesticides or other persistent contaminants can be left in place (e.g., in comparison to Tier 1 action levels for leaching concerns) but important drinking water resources are potentially threatened. Monitoring may also be needed at site where subsurface conditions could change over time and allow for increased leaching of contaminants (e.g., rising water table).

Use of Kd Values in Fate & Transport Models

Contaminant Kd values derived from batch tests cannot necessarily be incorporated into vadose-zone fate and transport models for deeper soils, even if the soil types are very similar. This is because the Kd value most likely reflects an increased difficulty in desorbing or leaching of *aged* contaminants from the tested soil. Use of the Kd value to evaluate migration of the contaminant in leachate through deeper soils not yet impacted by the initial release could over predict *resorption* to soil particles thus *under* predict potential impacts to groundwater. The use of batch tests to estimate site-specific *sorption* coefficients for contaminants in deeper soils may be practical but is beyond the current scope of this technical memorandum.

Evaluation of Solid or Hazardous Waste

Guidance presented in this memo does not apply to the evaluation of waste being placed in regulated landfills or to hazardous waste determinations. Evaluation of waste to be placed in landfills must be carried out under direction of the HDOH Solid and Hazardous Waste Branch.

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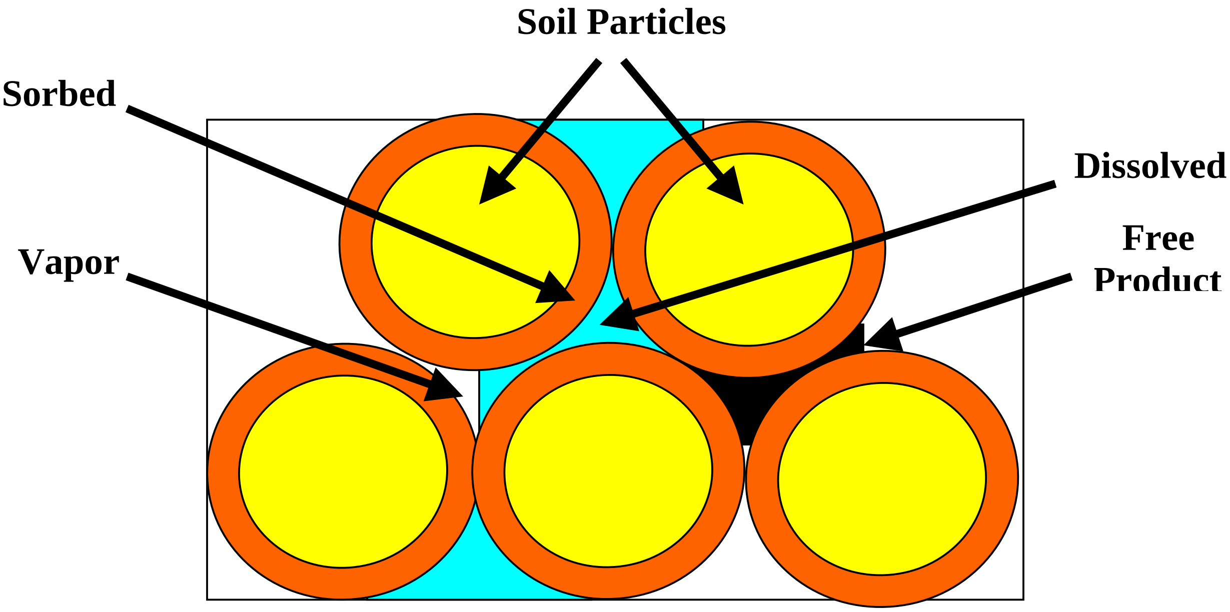
Table 1. Distribution of contaminants in soil based on contaminant properties and soil characteristics assumed in Tier 1 leaching models. Note how the fraction of the contaminant in the dissolved-phase is strongly tied to the assumed sorption coefficient or “Kd” value.

Chemical	**Default Sorption Coefficient (Kd)**	***Contaminant Phase Versus Percent Total Mass in Soil**		
		Sorbed	**Dissolved**	**Vapor**
Arsenic	29	99.9+%	0.0004%	0%
Benzo(a)pyrene	5,500	99.9+%	0.002%	0%
PCBs	33	99.7%	0.3%	0.01%
TPH	5.0	98%	1.9%	0.1%
Atrazine	0.23	70%	30%	0%
PCE	0.16	39%	25%	35%
Benzene	0.059	29%	50%	21%
MTBE	0.006	5%	91%	4%
Vinyl Chloride	0.0	5%	31%	64%

*Based on soil equilibrium partitioning equation presented in USEPA *Soil Screening Guidance* (USEPA 2001). Leachate is represented by the dissolved-phase mass of the contaminant. For organic contaminants, Tier 1 Kd value = published sorption coefficient (koc) x assumed total organic carbon content in soil of 0.1% (refer to HDOH 2005, Appendix 1, Table H). Assumes and soil moisture content of 0.10. Arsenic default Kd from USEPA *Soil Screening Guidance*.



Partition Coefficients

Kd = Sorbed Concentration/Dissolved Concentration

Henry's Law constant = Vapor Concentration/Dissolved Concentration

Figure 1. Partitioning of contaminants in soil between sorbed, dissolved and vapor phases.

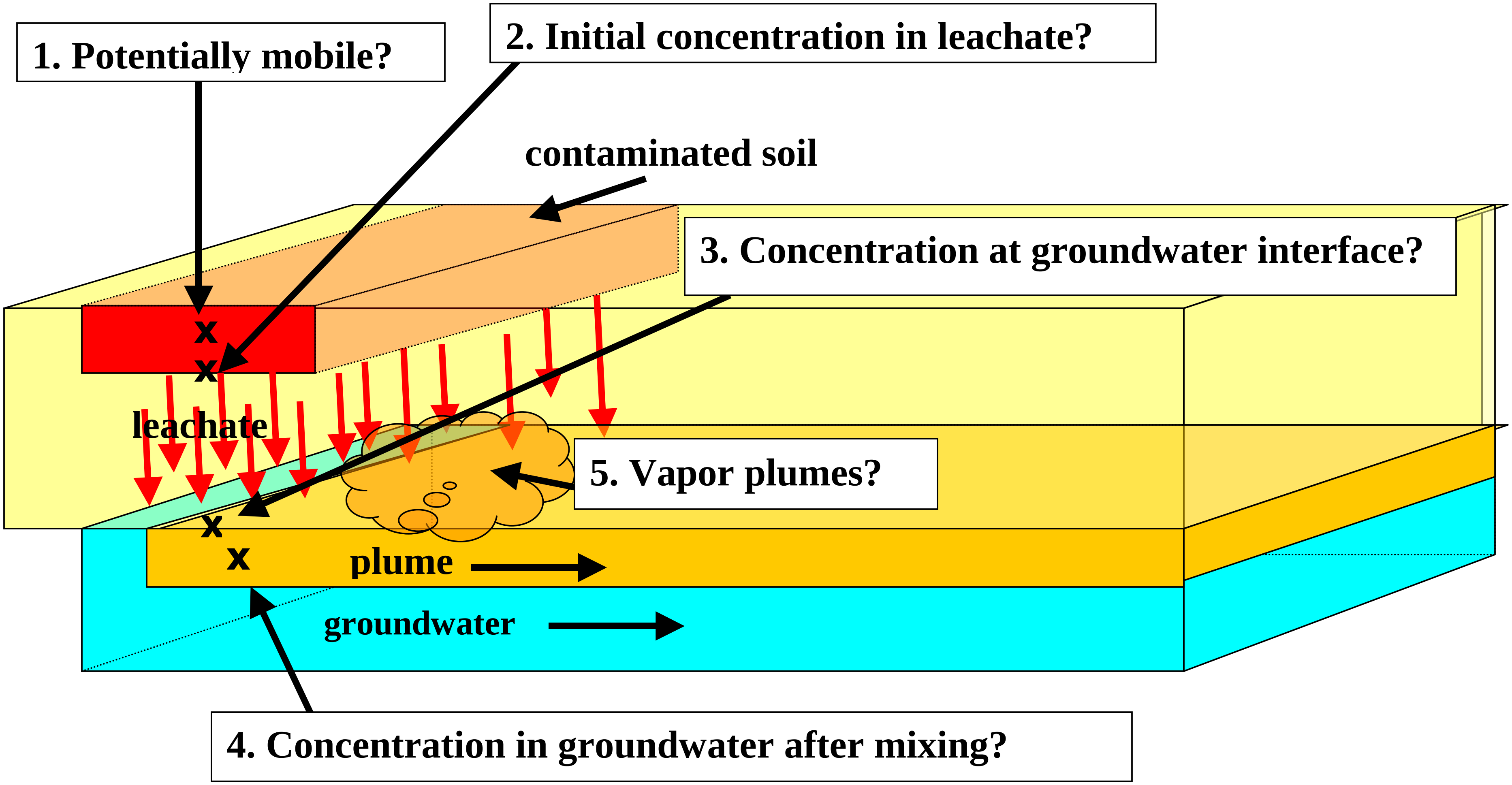


Figure 2. Basic questions that should be answered in all site-specific evaluations of soil leaching concerns. The guidance focuses on site-specific approaches to answering Questions 1 and 2, although approaches for answering the remaining questions are also provided.

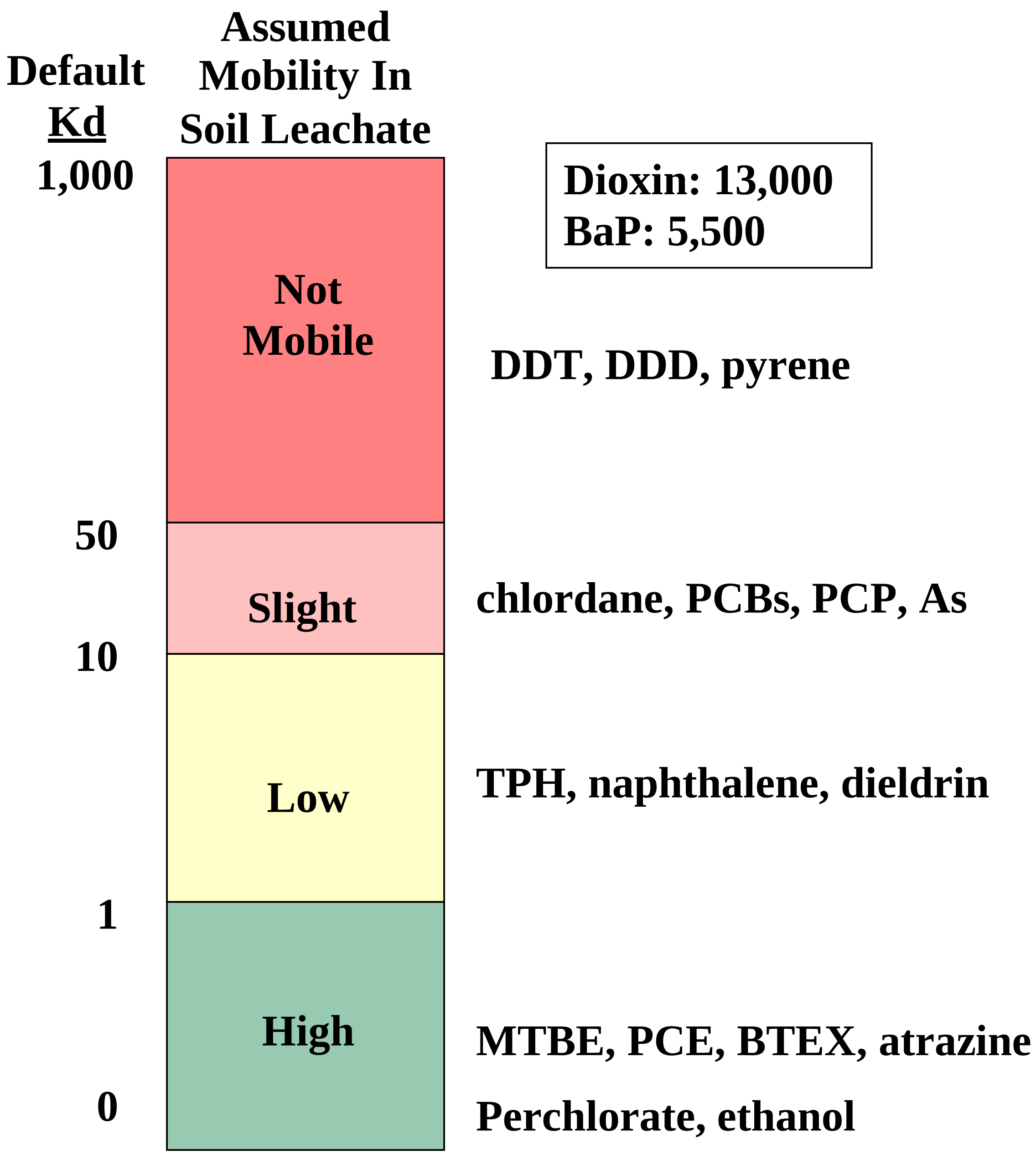


Figure 3. Assumed mobility of contaminants in soil leachate with respect to default Kd values used to develop HDOH Tier 1 soil action levels for leaching concerns. For organic contaminants, Kd values based on published koc sorption coefficients and total organic carbon content in soil of 0.1% (refer to Appendix 1 in HDOH EAL document, HDOH 2005). For arsenic, default Kd value of 29 from USEPA *Soil Screening Guidance* (USEPA 2001).

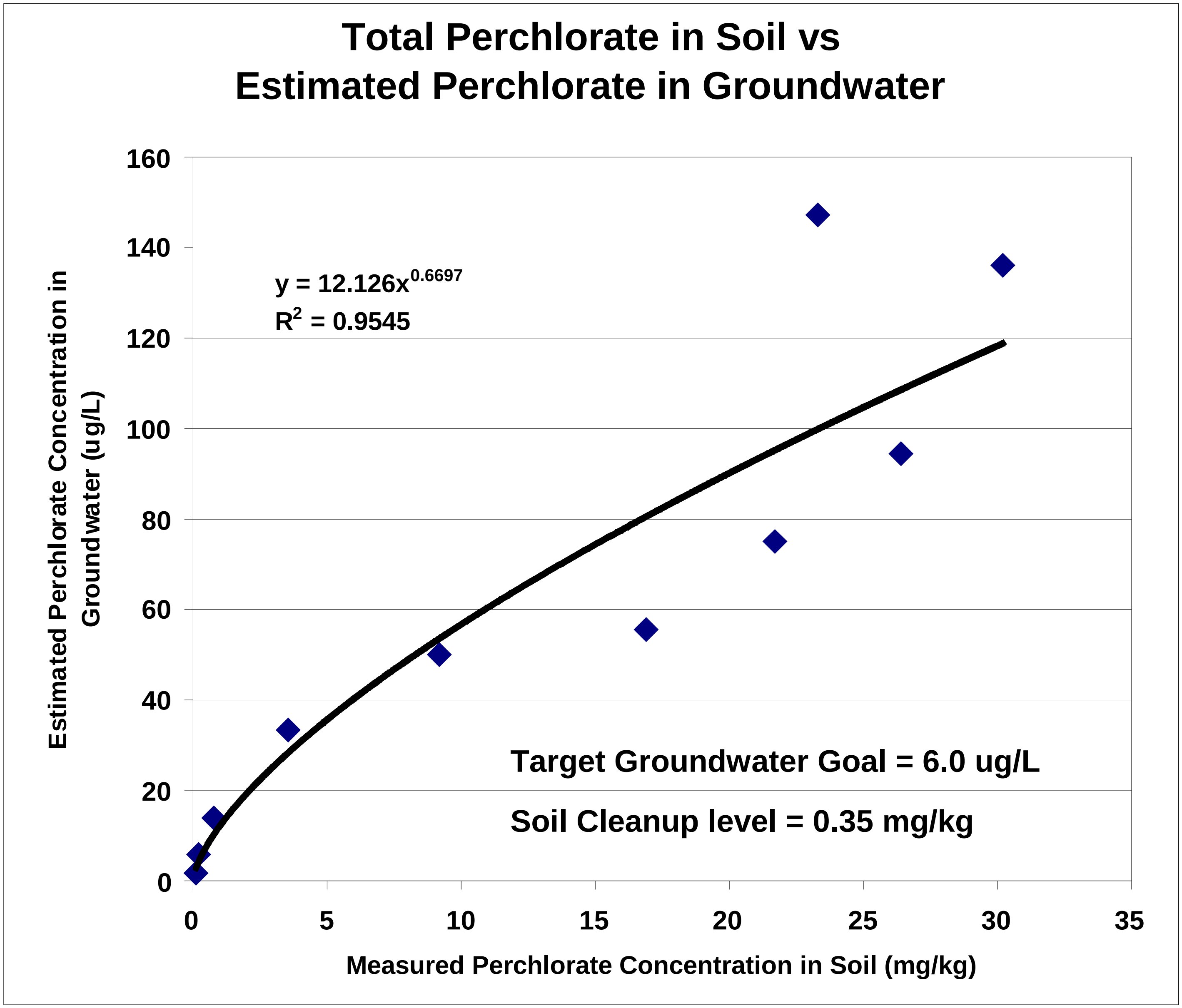
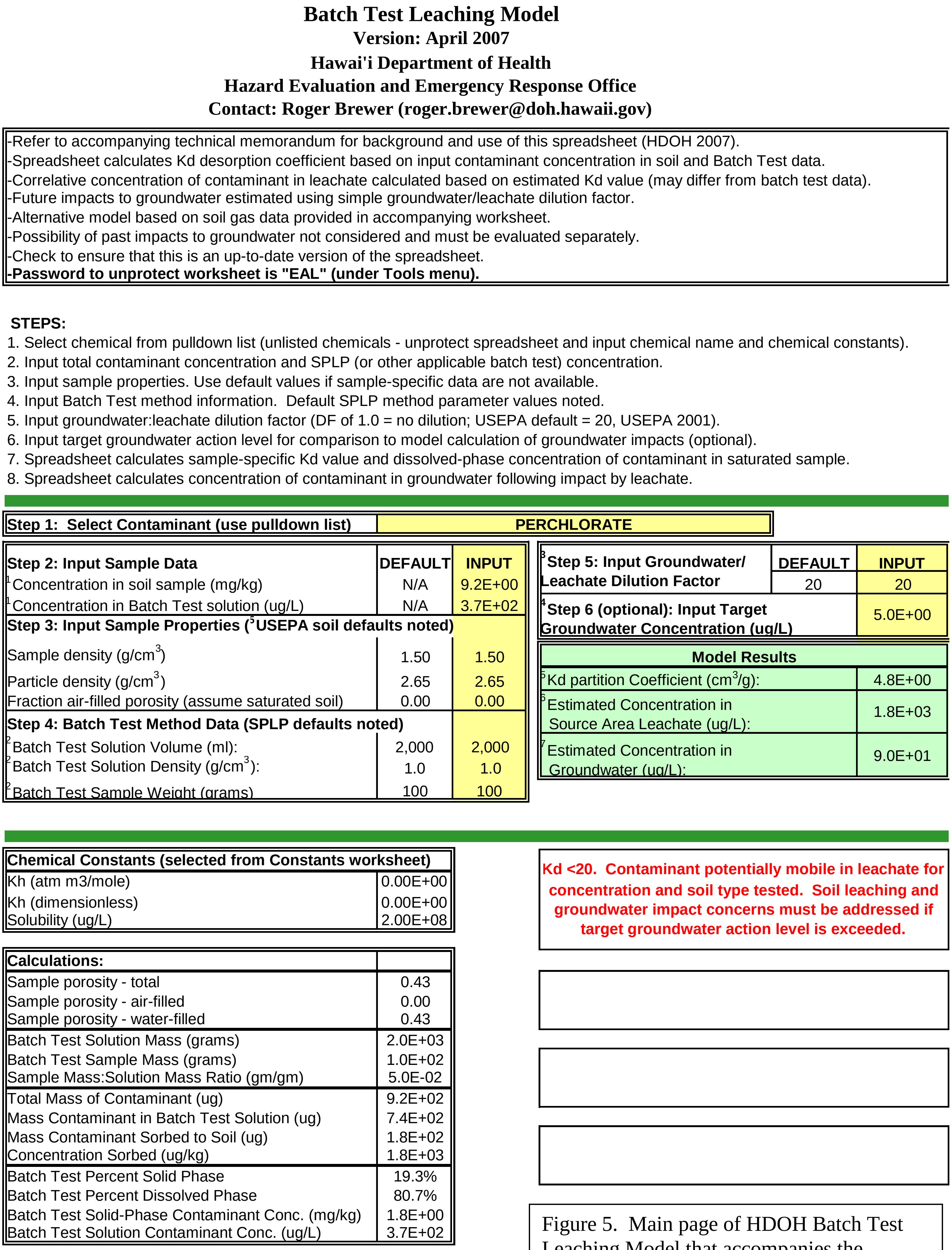


Figure 4. Example graphical calculation of soil cleanup levels based on use of multiple batch tests to estimated perchlorate desorption coefficients and correlative concentrations of perchlorate in soil leachate and groundwater at varying soil concentrations of perchlorate in soil. (For example only.)



Batch Test Leaching Model

Version: April 2007

Hawai'i Department of Health

Hazard Evaluation and Emergency Response Office

Contact: Roger Brewer (roger.brewer@doh.hawaii.gov)

-Refer to accompanying technical memorandum for background and use of this spreadsheet (HDOH 2007).
-Spreadsheet calculates Kd desorption coefficient based on input contaminant concentration in soil and Batch Test data.
-Correlative concentration of contaminant in leachate calculated based on estimated Kd value (may differ from batch test data).
-Future impacts to groundwater estimated using simple groundwater/leachate dilution factor.
-Alternative model based on soil gas data provided in accompanying worksheet.
-Possibility of past impacts to groundwater not considered and must be evaluated separately.
-Check to ensure that this is an up-to-date version of the spreadsheet.
-Password to unprotect worksheet is "EAL" (under Tools menu).

STEPS:

1. Select chemical from pulldown list (unlisted chemicals - unprotect spreadsheet and input chemical name and chemical constants).
2. Input total contaminant concentration and SPLP (or other applicable batch test) concentration.
3. Input sample properties. Use default values if sample-specific data are not available.
4. Input Batch Test method information. Default SPLP method parameter values noted.
5. Input groundwater:leachate dilution factor (DF of 1.0 = no dilution; USEPA default = 20, USEPA 2001).
6. Input target groundwater action level for comparison to model calculation of groundwater impacts (optional).
7. Spreadsheet calculates sample-specific Kd value and dissolved-phase concentration of contaminant in saturated sample.
8. Spreadsheet calculates concentration of contaminant in groundwater following impact by leachate.

Step 1: Select Contaminant (use pulldown list)	**PERCHLORATE**

Step 2: Input Sample Data	**DEFAULT**	**INPUT**
[1] Concentration in soil sample (mg/kg)	N/A	9.2E+00
[1] Concentration in Batch Test solution (ug/L)	N/A	3.7E+02
Step 3: Input Sample Properties ([5]USEPA soil defaults noted)		
Sample density (g/cm^3)	1.50	1.50
Particle density (g/cm^3)	2.65	2.65
Fraction air-filled porosity (assume saturated soil)	0.00	0.00
Step 4: Batch Test Method Data (SPLP defaults noted)		
[2] Batch Test Solution Volume (ml):	2,000	2,000
[2] Batch Test Solution Density (g/cm^3):	1.0	1.0
[2] Batch Test Sample Weight (grams)	100	100

[3] **Step 5: Input Groundwater/ Leachate Dilution Factor**	**DEFAULT**	**INPUT**
	20	20
[4] **Step 6 (optional): Input Target Groundwater Concentration (ug/L)**		5.0E+00

Model Results	
[5] Kd partition Coefficient (cm^3/g):	4.8E+00
[6] Estimated Concentration in Source Area Leachate (ug/L):	1.8E+03
[7] Estimated Concentration in Groundwater (ug/L):	9.0E+01

Chemical Constants (selected from Constants worksheet)	
Kh (atm m3/mole)	0.00E+00
Kh (dimensionless)	0.00E+00
Solubility (ug/L)	2.00E+08

Kd <20. Contaminant potentially mobile in leachate for concentration and soil type tested. Soil leaching and groundwater impact concerns must be addressed if target groundwater action level is exceeded.

Calculations:	
Sample porosity - total	0.43
Sample porosity - air-filled	0.00
Sample porosity - water-filled	0.43
Batch Test Solution Mass (grams)	2.0E+03
Batch Test Sample Mass (grams)	1.0E+02
Sample Mass:Solution Mass Ratio (gm/gm)	5.0E-02
Total Mass of Contaminant (ug)	9.2E+02
Mass Contaminant in Batch Test Solution (ug)	7.4E+02
Mass Contaminant Sorbed to Soil (ug)	1.8E+02
Concentration Sorbed (ug/kg)	1.8E+03
Batch Test Percent Solid Phase	19.3%
Batch Test Percent Dissolved Phase	80.7%
Batch Test Solid-Phase Contaminant Conc. (mg/kg)	1.8E+00
Batch Test Solution Contaminant Conc. (ug/L)	3.7E+02

Figure 5. Main page of HDOH Batch Test Leaching Model that accompanies the technical memorandum (as of April 2007).

Appendix 1
Batch Test and Soil Gas Leaching Model Equations

Batch Test Leaching Model Equations
The equations discussed below are incorporated into the Excel-based Batch Test Leaching Model that accompanies this technical memorandum. Figure 5 in the main text depicts the first page of the model (April 2007 version). The model will be updated as needed in the future.

Step 1. Calculate a partition coefficient for each chemical of potential concern.
The results of the SPLP test can be used to develop a sample-specific partition coefficient (Kd) for each chemical of potential of concern. The partition coefficient is calculated as follows (after Roy et. al, 1992; see also McClean and Bledsoe, 1992, and USEPA 1999):

$$Kd\ (L/kg) = \frac{Concentration_{sorbed}\ (\mu g/Kg)}{Concentration_{solution}\ (\mu g/L)} \qquad (1)$$

where Concentration$_{sorbed}$ is the concentration of the contaminant that remained sorbed to the soil following the batch test and Concentration$_{solution}$ is the resulting concentration of the contaminant in the batch test solution. The term Kd is commonly reported in equivalent units of (ug/g)/(ug/cm^3) or cm^3/g, based on an assumed batch test solution density of 1.0 g/cm^3.

The sorbed concentration of the contaminant is calculated as follows:

$$Concentration_{sorbed}(ug/kg) = \frac{Mass_{sorbed}\ (\mu g)}{Sample\ Mass\ (kg)}. \qquad (2)$$

where Mass$_{sorbed}$ is the mass of the contaminant still sorbed to the soil following the batch test. The mass of the sample called for in the SPLP batch test is 100 grams or 0.1 Kg (USEPA 1994).

The mass of the contaminant sorbed to the soil is calculated by subtracting the mass of the contaminant that went into the batch test solution from the initial, total mass of the contaminant in the soil sample:

$$Mass_{sorbed}\ (\mu g) = Mass_{total}(\mu g) - Mass_{solution}\ (\mu g) \qquad (3)$$

where Mass$_{total}$ is original, total mass of the contaminant in the soil sample and Mass$_{solution}$ is the mass of the contaminant in the batch test solution. The total mass of the contaminant in the soil sample is calculated as:

$$Mass_{total}(\mu g) = Concentration_{total}\ (mg/kg) \times \left(\frac{1{,}000\,\mu g}{1mg}\right) \times Sample\ Mass(kg) \qquad (4)$$

where Concentration$_{total}$ is the reported total concentration of the contaminant in the soil sample that used in the batch test (tested on a split sample). The mass of the contaminant in the batch test solution is calculated as:

$$Mass_{solution}(\mu g) = Concentration_{solution}(\mu g/L) \times Solution\,Volume(L)\,. \qquad (5)$$

The default volume of solution used in SPLP batch tests is two liters (USEPA 1994).

Note that use of the batch test method to estimate Kd values is not longer valid if the solubility limit of the contaminant is exceeded in the batch test solution (refer to section on Leaching of Heavily Contaminated Soils in the main text). Exceeding the contaminants solubility suggests that free product is present in the soil (either liquid or dry). As a precautionary measure, a cutoff of 75% the assumed contaminant solubility is used in the Batch Test Leaching Model spreadsheet to identify if free product may be present in the batch test solution. The free product acts as a second reservoir of contaminant mass that will bias the true equilibrium concentration of the contaminant in the dissolved and sorbed phases. To accurately calculate desorption coefficients, batch test analyses must be run samples with lower concentrations of the contaminant in soil.

Step 2. Estimate the concentration of the contaminant in source-area leachate.
Once the soil-specific Kd value for a target contaminant has been determined, it is relatively simple to estimate the concentration of the contaminant in the soil moisture or "leachate" within the main body of contaminated soil or the leachate "source area"). This is done by incorporating the calculated Kd into a simple equilibrium partitioning equation and assuming default (or site-specific) soil properties (after USEPA 2001):

$$C_{total} = C_{leachate} \times \left(Kd + \left(\frac{\theta_w + (\theta_a \times H')}{\rho b} \right) \right) \times \left(\frac{1mg}{1000\mu g} \right) \qquad (6)$$

where: C_{total} = Total concentration of chemical in sample (mg/kg);

$C_{leachate}$ = Dissolved-phase concentration of chemical (µg/L);

Kd = Estimated or measured partition coefficient L/kg;

$Theta_w$ = water-filled porosity (L_{water}/L_{soil});

$Theta_a$ = air-filled porosity (L_{air}/L_{soil});

H' = Henry's Law Constant at 25°C ((µg/L-vapor)/(µg/L-water)); and

p_b = Soil bulk density (Kg/L).

Table H in Appendix 1 of the HDOH EAL document provides a summary of "dimensionless" Henry's Law Constants (H') for common volatile contaminants (HDOH 2005). For the purpose of calculating Tier 1 action levels, Kd is calculated as the chemical's published organic carbon partition coefficient (koc) times the fraction organic carbon in the soil (foc). This is discussed in Appendix 1 of the HDOH Environmental Action Levels document (HDOH 2005). Note that in this equation Kd and p_b are expressed in units of L/Kg and Kg/L, respectively, rather than in equivalent units of cm^3/g and g/cm^3. A default soil density of 1.5 Kg/L and soil porosity of 43% (0.43) are typically used in Tier 1 risk assessment models (e.g., USEPA 2001, 2004).

Equation 6 can be rearranged to solve for $C_{leachate}$ as follows:

$$C_{leachate} = C_{total} \div \left(\left(Kd + \left(\frac{\theta_w + (\theta_a \times H')}{\rho b} \right) \right) \times \left(\frac{1mg}{1000\mu g} \right) \right). \qquad (7)$$

This equation is incorporated into the "Batch Test Leaching Model" worksheet of the Excel file that accompanies this technical memo. The sorption coefficient should be used to estimate the dissolved-phase concentration of the contaminant in a hypothetical, saturated sample of soil at equilibrium and at the same contaminant concentration as the SPLP test. Since the soil is assumed to be fully saturated with water, the vapor-phase term of the equation "θ_a x H'" goes to zero.

Step 3. Tier 3 calculation of ultimate contaminant concentration in groundwater.

A conservative estimate of the contaminant concentration in groundwater that cuold be impacted by the leachate is made by dividing the calculated concentration of the contaminant in leachate by an assumed groundwater:leachate dilution factor (DF):

$$C_{groundwaater} = \frac{C_{leachate}}{DF} \qquad (8)$$

$$DF = \frac{\text{Volume Impacted Groundwater}}{\text{Volume Leachate}}. \qquad (9)$$

where: $C_{groundwater}$ = Concentration of chemical in groundwater (µg/L);
$C_{leachate}$ = Concentration of chemical in leachate (µg/L); and
DF = Groundwater/Leachate dilution factor (m^3/m^3).

This equation is incorporated into the Batch Test Leaching Model spreadsheet that accompanies this technical memo. A default DF of 20 is considered appropriate for sites less than or equal to 0.5 acres in size (USEPA 2001). A more site-specific DF factor can be calculated if needed, based on the following equation (USEPA 2001):

$$\text{Dilution Factor} = 1 + \left(\frac{K \times i \times d}{I \times L} \right) \qquad (10)$$

where "K" is the aquifer hydraulic conductivity (m/year), "i" is the regional hydraulic gradient, "d" is the assuming mixing zone depth (default is two meters), "I" is the surface water infiltration rate (m/year" and "L" is the length of the contamianted soil area that is parallel to groundwater flow (m).

Note that this equation does not consider an expected reduction in contaminant concentrations as the leachat migrates downward. This component of the evalaution can be included in more site-specific evaluations as needed.

Soil Gas Leaching Model

For volatile contaminants, soil gas data offer an alternative approach for estimation of contaminant concentrations in leachate as well as a method to evaluate the threat posed to groundwater by downward migrating vapor plumes. The relationship between vapor-phase and dissolved-phase volatile chemicals under equilibrium conditions is relatively straightforward:

$$H' = \frac{Cvapor\ (ug/L)}{Cleachate\ (ug/L)}\ . \tag{11}$$

where: H'=Henry's Law Constant at 25°C;

C_{vapor}= Vapor-phase concentration in soil gas;

$C_{leachate}$= Dissolved-phase concentration in soil pore waters.

Table H in Appendix 1 of the HDOH EAL document provides a summary of "dimensionless" Henry's Law Constants (H') for common volatile contaminants (HDOH 2005). To calculate the concentration of the contaminant in the soil moisture the equation is rearranged to solve for "$C_{leachate}$." The C_{vapor} term is also adjusted to units of ug/m3 to correspond with the units typically reported in site data:

$$Cleachate\ (ug/L) = \frac{Cvapor\ (ug/m3) \times \frac{1\ m3}{1{,}000\ L}}{H'}\ . \tag{12}$$

Equation 8 above can be used to estimate potential impacts to groundwater with respect to soil gas-based estimates of contaminant concentrations of the in leachate.

Soil gas "action levels" for protection of groundwater can be developed by rearranging the equation to solve for C_{vapor} and setting $C_{leachate}$ equal to a target leachate goal (e.g., groundwater action level times appropriate groundwater:leachate dilution factor):

$$\mathrm{Cvapor\ (ug/m3) = Cleachate\ (ug/L) \times H' \times \frac{1{,}000\ L}{1\ m3} \times AF} \tag{13}$$

The term "AF" is an attenuation factor that describes the anticipated decrease in contaminant concentrations over time as the vapor migrates to and eventually impacts groundwater (e.g., via natural degradation, resorption to soil particles or migration into soil moisture). Approaches for calculation of site-specific, vapor attenuation factors are not well established and beyond the scope of this technical memorandum.

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In reply, please refer to:
File: EHA/HEER Office
07-251 RB

May 11, 2007

TO: Interested Parties

FROM: Keith E. Kawaoka, D.Env., Program Manager
Hazard Evaluation and Emergency Response Office

SUBJECT: **Pesticides in Former Agricultural Lands and Related Areas – Updates on Investigation and Assessment (arsenic, technical chlordane, and dioxin test methodologies and action levels and field sampling strategies)**

Attached for you information is a technical report that presents guidance on the assessment of pesticides in former agricultural lands and related areas. This report serves as an addendum to the Hazard Evaluation and Emergency Response (HEER) Office document, *Screening for Environmental Concerns at Sites With Contaminated Soil and Groundwater* (May 2005).

If you have any question, place call Dr. Roger Brewer of my office at 1-808-586-4238, or contact him by email at roger.brewer@doh.hawaii.gov.

Attachment

Pesticides in Former Agricultural Lands and Related Areas
Updates on Investigation and Assessment

This technical report presents updated guidance on the investigation and assessment of residual pesticides in soils. The guidance focuses on the redevelopment of former agricultural land but is also applicable to golf courses, nurseries, military housing complexes and similar, large-scale projects involving soils that may have been treated with pesticides. Updates are provided for arsenic, chlordane and dioxin test methodologies and action levels. A basic review of multi-increment sampling strategies is also presented.

This technical report serves as an addendum to the Hawaiʻi Department of Health (HDOH), Hazard Evaluation and Emergency Response (HEER) document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (May 2005 and updates) and other related technical reports noted below. Information presented in these technical memoranda will be incorporated into the upcoming revision of the HEER office *Technical Guidance Manual.* Comment and suggestions are welcome. Please contact Dr. Roger Brewer of HDOH at 1-808-586-4328 or roger.brewer@doh.hawaii.gov for further information.

Pesticides of Potential Concern

"Pesticides" is a general term that includes any type of chemical mixture specifically formulated to kill "pests." Pesticides commonly used in Hawaiʻi include herbicides, fungicides and insecticides, the latter including termiticides and nematocides. HDOH recommends that sites where pesticides may have been regularly applied in the past be tested for residual contamination prior to redevelopment. The guidance is especially pertinent to large tracts of former agricultural land, golf courses, nurseries and military housing complexes that are being demolished and redeveloped with new homes.

In the case of former agricultural lands, contamination is likely to be heaviest in former pesticide mixing and staging areas, seed dipping areas and storage areas, although heavy contamination could occur in association with bagasse piles, settling ponds, former plantation camp areas, etc. Residual contamination in former fields has not been well documented, although HDOH is continuing to collect data for these areas. Conditions can vary dramatically from site to site.

Types of pesticides commonly used in Hawai'i include:

Pesticide Group & Related Contaminants	**Standard USEPA Laboratory Method**
Organochlorine pesticides	8081A
Organophosphorus pesticides	8041A
Chlorinated herbicides	8151A
Carbamates	8321A
Pentachlorophenol	8270
Fumigants	8260
Dioxins/furans	8280/8290
Heavy metals (primarily arsenic, lead & mercury)	various

The above list is not intended to be comprehensive, nor is it intended to represent a required list of target analytes that must be tested for in areas where pesticides were used in the past. Specific pesticides of concern should be based on a review of the historical use of the site with a focus on pesticides that may be persistent in soil above HDOH Environmental Action Levels (EALs, HDOH 2005 and updates). Soil and groundwater action levels for the majority of commonly used pesticides in Hawai‘i are included in this document. Contact the HEER office for pesticides not listed in the EAL document.

Fumigants are not likely to be persistent in shallow soils more than one year after use due to a propensity to volatilize into the atmosphere and degrade or be carried downward in leachate. Organochlorine pesticides are known to be very persistent in soils in Hawai‘i, as are arsenic and lead. Organophosphorus pesticides, chlorinated herbicides, carbamates and pentachlorophenol are more susceptible to biological and chemical breakdown over time and are more likely to be persistent in heavily contaminated, pesticide mixing areas than in fields. As of the date of the technical report, however, HDOH has not compiled adequate data to rule out the potential presence of these pesticides in former field areas above levels of concern. As discussed below, significant levels of dioxins and furans may also remain in soils even though the parent pesticide has degraded below levels of concern.

Summaries of historical pesticide use on agricultural lands are available from the Hawai‘i Department of Agriculture and other sources (e.g., Hanson 1959, 1962; HDOA 1969, 1977, 1989). The Clean Water Branch of HDOH provides a brief summary of pesticides in their NPDES guidance (HDOH 2004). A selection of pesticide-related documents can be downloaded from the HDOH EAL web page (refer to HDOH 2005).

A detailed review of pesticide use in Hawai‘i and a compilation of persistent contaminants that could accumulate in soil above levels of concern will be included in the upcoming revision to the HEER office Technical Guidance Manual (anticipated Fall 2007). Additional pesticides will be added to the current list of chemicals in the EAL lookup tables as needed.

Arsenic

HDOH recommends that the name of the soil series and a summary of the soil type be noted for samples tested for bioaccessible arsenic, including mention of the total iron and aluminum oxide content (NCRS 2007). HDOH also recommends that the fine-grained (<250µm) fraction of the soil sample that is to be tested for bioaccessible arsenic also be tested for total arsenic.

Guidance on the collection and interpretation of bioaccessible arsenic data is presented in the HDOH 2006 technical report *Soil Action Levels and Categories for Bioaccessible Arsenic* (HDOH 2006a). HDOH recommends that bioaccessible arsenic test be carried out when the total arsenic concentration in the soil exceeds 20 mg/kg (assumed upper limit for background arsenic in soil). Bioaccessible arsenic tests are used to estimate the fraction of total arsenic that could be stripped or “desorbed” from the soil following ingestion and thus made available for uptake. Arsenic that remains sorbed to the soil sample is considered to be unavailable for uptake and essentially “non-toxic.” The concentration of bioaccessible arsenic in a soil sample is calculated by dividing the mass of arsenic that moves into the batch test solution by the mass of the sample. Although not required as part of the bioaccessibility test, HDOH recommends that the concentration of total arsenic also be determined for the sample. This will help confirm the results of the test and provide insight on the range of arsenic bioaccessibility in the fine-grained fraction of contaminated soil.

The HEER Office has not developed generic bioaccessible factors for arsenic in soils in Hawaiʻi and currently recommends testing on a site-by-site basis. The use of bioaccessible arsenic tests has not been formally adopted by USEPA as a substitute for bioavailable arsenic testing (i.e. in-vivo or animal testing). In lieu of formal guidance, USEPA has recommended that HDOH provide additional information to demonstrate a preponderance of evidence that the arsenic is indeed tightly bound to the soil and has very limited availability for uptake in humans. These lines of evidence include:

- *In vivo* studies that indicate very low arsenic bioavailability in soils from heavily impacted areas in Keaʻau (Exponent 2005, Roberts et al., 2006);
- The correlation of *in vivo* study results with bioaccessible arsenic data collected at the same site (e.g., Cutler 2006);
- Correlation of decreasing arsenic bioavailability with increasing iron oxide concentration (Roberts et al., 2006);
- Average iron oxide concentration in soils used for agriculture in Hawaiʻi of 10-30%, well above typical soils on the US mainland (NRCS 2007);
- A lack of arsenic in groundwater underlying current and former sugar cane areas, indicating strong binding to soil and minimal leaching potential (HDOH 2006b);
- Laboratory testing at UH Manoa that demonstrated tropical soils (Andisols and Oxisols) with high levels of oxide and hydroxide mineral species have a natural ability to sequester arsenic, even over a wide pH range, making the arsenic less available to the soil solution - and therefore also estimated to be less bioaccessible through human ingestion and digestion (Cutler et al., 2006);
- Soil uptake factors for vegetables and fruits grown in arsenic-contaminated soils in the Keaʻau area are >2 orders of magnitude less than uptake factors published in scientific literature, supporting a conclusion that the arsenic is much more tightly bound to the soils than might otherwise be expected (HDOH, internal data);
- Laboratory batch test data that indicate arsenic sorption coefficients in soil greater than 500 (HDOH, internal data); and
- Use of a conservative, maximum-acceptable target risk to establish upper-bound action levels for bioaccessible arsenic in soil (HDOH 2006a).

HDOH recommends that a brief summary of the soil series associated with the subject site and sample point locations be provided with bioaccessible arsenic data (NRCVS 2007). The relationship between soil mineral characteristics and bioaccessibility is very complex and dependent on more than the metal oxide content of the soil. For example, the arsenic binding capacity of soils developed on coralline, coastal sediments is significantly less than soils developed over basalt, although these soils are rarely used for agriculture. Additional research is currently under way by the University of Hawaiʻi as well as other groups.

Technical Chlordane and Other Organochlorine Pesticides

HDOH recommends that soils potentially treated with termiticides be tested for *technical chlordane* rather than individual chlordane isomers and related compounds generally found in technical chlordane. The concentration of chlordane isomers, heptachlor and heptachlor epoxide do not need to be reported. Laboratories should be directed to test for technical chlordane using USEPA Method 8081A or an equivalent method (USEPA 1996). This must be specifically requested prior to submittal of the samples and noted on the Chain of Custody form. Laboratories should also be instructed to report any additional organochlorine pesticides that are not typically found in technical chlordane (e.g., DDT, dieldrin, endrin, etc.).

Technical chlordane is a mixture of chlordane (50-75%) and over 100 related compounds, including heptachlor and heptachlor epoxide (ATSDR 1994). Toxicity factors published by the USEPA are based on studies of technical chlordane, not individual chlordane isomers (USEPA 1997). These toxicity factors collectively take into account the full suite of compounds present in technical chlordane and are used to generate the USEPA Region IX Preliminary Remediation Goals (USEPA 2004) and HDOH Environmental Action Levels (HDOH 2005) for direct-exposure concerns. Since the quantification of technical chlordane includes chlordane, heptachlor and heptachlor epoxide, these individual compounds do not need to be reported in the analysis or evaluated separately in an Environmental Hazard ("risk") Assessment unless otherwise directed by HDOH. Doing so will cause the health risk posed by these compounds to be double counted, since it will already be included in the assessment of technical chlordane.

Tier 1 Environmental Action Levels (EALs) for technical chlordane are presented in the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (HDOH 2005). Tier 1, direct-exposure action levels technical chlordane were generated using a target excess cancer risk of 10^{-6} and a noncancer hazard quotient of 1.0 (refer to Appendix 1, Tables I-1 through I-3). However, use of a target, cumulative risk of 10^{-5} is generally acceptable for evaluation of multiple contaminants under a Tier 2 or Tier 3 assessment. Since technical chlordane is actually a mixture of numerous chemicals, it is more appropriate to screen site data using Tier 2 direct-exposure action levels based on a cumulative target cancer risk of 10^{-5}. Correlative action levels for residential and commercial/industrial exposure are 16 gm/kg and 65 mg/kg, respectively. After taking into account action levels for leaching concerns, the following action levels are generated:

Tier 2 Action Levels for soil with technical chlordane only

Exposure Scenario	**Direct Exposure (mg/kg)**	**[1]Leaching (mg/kg)**	**[2]Final Tier 2 Action Level (mg/kg)**
Residential	16	15	15
Commercial/Industrial	65	15	15

1. HDOH EAL guidance document, Appendix 1, Table E-1.
2. Lowest of direct-exposure and leaching soil action level

These action levels will replace the Tier 1 action levels for technical chlordane currently presented in the HDOH EAL document (HDOH 2005). On a site-specific basis, HDOH may require calculation of cumulative cancer and noncancer health risks if contaminants not related to technical chlordane are identified in the soil above HDOH Tier 1 action levels for direct-exposure concerns. This may be necessary to assure that a cumulative cancer risk of 10^{-5} and a noncancer Hazard Index of 1.0 are not significantly exceeded. Leaching concerns posed by the additional contaminants must also be evaluated.

Refer to the HDOH technical report *Use of laboratory batch tests to evaluate potential leaching of contaminants from soil* for guidance on the site-specific evaluation of potential leaching concerns and the development of alternative action levels (HDOH 2007). Technical chlordane has a very low mobility in soil and the soil leaching action level is considered to be highly conservative. If the batch tests indicate that the technical chlordane does not pose a threat to groundwater then the direct-exposure action levels (or estimated cumulative health risks) can be used to guide final remedial actions.

Soil that meets the Tier 2, commercial/industrial direct-exposure action level for technical chlordane (i.e., up to 65 mg/kg) can be used as interim (daily) cover in landfills, provided that the soil passes a TCLP leaching test and given the concurrence of the landfill operator. A maximum concentration of 65 mg/kg technical chlordane is recommended, unless otherwise approved by HDOH. Soil used for longer-term, intermediate cover must meet more stringent action levels (e.g., residential). Contact the HDOH Solid and Hazardous Waste Branch for additional information regarding the use or disposal of soil at landfills.

Dioxin

HDOH concurs with the use of bioassay kits to help reduce the time and expense related to investigation of dioxin concentrations in soil. Dioxins are included in Table 1 as potential contaminants of concern due to their presence in pesticides (NTP 2005), especially pentachlorophenol (PCP), 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) and 2,4,5-trichlorophenoxypropionic acid (2,4,5-TP or Silvex). These chemicals were used as herbicides on agricultural lands in Hawaiʻi. Dioxins can also be created when organic material is burned in the presence of chlorine, including the burning of sugar cane fields where organochlorine pesticides and other chlorine containing media are present.

Quantification of dioxins in soil is for use in human health risk assessments is carried out using GC/MS laboratory methods (USEPA Methods 8280 and 8290). Risk to human health is estimated in terms of toxicity equivalents of individual dioxin and furan congeners or “TEQ dioxins” (WHO 2005). Soil action levels for TEQ dioxins are discussed in the HDOH technical report *Proposed dioxin action levels for East Kapolei Brownfield Site* (HDOH 2006c).

Laboratory GC/MS tests can be expensive and time consuming, with analytical costs typically ranging between $750 and $1,000 per sample. Bioassay methods offer a cheaper and faster approach to screen for dioxins in soils. Bioassay methods currently available include CALUX (Dennison et al. 1999, USEPA 2005a) and Cape Technology’s DF1 kit (USEPA 2005b). Bioassay data are reported directly in terms of TEQ units. In order to evaluate the accuracy and precision of bioassay kits for soils in Hawaiʻi, HDOH collected 25 soil samples from a former sugar cane field in west Oʻahu and tested the samples for TEQ dioxins using both High Resolution GC/MS and CALUX. A summary of the results of the study is presented in Figure 1. As can be noted in the figure, CALUX consistently over predicted TEQ dioxin concentrations in the soil in comparison to the GC/MS analysis. While the correlation of the CALUX test with the GC/MS data is somewhat low, the conservative nature of the CALUX test supports its use as screening tool to estimate maximum levels of TEQ dioxins in soil.

For sites where a bioassay method is used for dioxin analysis, HDOH recommends that dioxin levels be confirmed on 10% of the samples using GC/MS (or two samples, whichever is greater). The GC/MS analyses should be conducted on samples with the highest-reported, bioassay TEQ dioxins results. Additional analysis of samples using GC/MS methods may be necessary for sites where CALUX tests indicate TEQ dioxins in soil over the HDOH upper action level of 390 ng/kg.

Refer to the HDOH technical report *Proposed dioxin action levels for East Kapolei Brownfield Site* for additional guidance on soil action levels (HDOH 2006c).

Multi-Increment and Decision Unit Investigation Strategies

HDOH strongly encourages the use of *multi-increment* and *decision unit* strategies (Ramsey and Hewitt 2005) to enhance sample representativeness in the investigation of contaminated soil. Multi-increment samples significantly increase the accuracy of representative contaminant concentrations, in comparison to traditional, discrete samples (Jenkins et al. 2005). Establishing decision units early in the investigation helps integrate the field investigation with an assessment of potential environmental concerns, referred to as an "Environmental Hazard ("risk") Assessment" (HDOH 2005).

Detailed guidance on multi-increment and decision-unit investigation strategies will be included in the upcoming revision to the HEER Office Technical Guidance Manual (anticipated late 2007). In the interim, a brief summary of these approaches is provided below. Example work plans and site investigation reports can be reviewed at the HEER office and will be posted to the HDOH EAL web page (refer to HDOH 2005). Reviewers of these reports should be aware that the projects were carried out during ongoing refinement of approaches for the investigation of large areas and the sampling strategies presented may not be directly transferable to new sites without modification and consultation with HDOH.

Multi-Increment Samples

Multi-increment samples improve the reliability of sample data by reducing the variability of the data as compared to conventional discrete sampling strategies. Thirty to fifty small *increments* of soil (typically 10 to 50 grams per increment) are collected from each specific *decision unit* of interest (see below). The increments are collected in a stratified-random manner (e.g., by walking up and down adjacent rows) and physically combined into one sample. The combined sample is analyzed to obtain a representative contaminant concentration for the entire decision unit. Multi-increment sampling data typically have low variability and high reproducibility, which results in a high level of confidence for decision-making. Three multi-increment samples, referred to as field replicate samples or *triplicates*, should be collected in 10% of the decision units being tested (minimum one set of triplicate samples per site). Data for the samples can be statistically compared in order to evaluate the precision of the field sampling methodology.

Multi-increment samples generally weigh between 500 and 2,000 grams. The laboratory dries the sample, sieves it to <2mm particle size (can also be done in the field) and collects a subsample for analysis. To obtain a representative sub-sample, the field sample must be processed so that the entire "population" of soil particles is accessible for collection. Sub-sampling can be accomplished with a sectoral splitter or by collecting a multi-increment sample using the same approach as used to collect the field sample but with smaller tools and increment masses (USEPA 2003). A larger mass than typically called for in the published USEPA laboratory method is recommended for in order to reduce lab fundamental error due to the range of particle sizes being tested (e.g. 10 gram versus 1 gram sample for total arsenic analyses, based on a maximum particle size of 2 mm). [Note that a mass of 1 gram is considered acceptable for samples that have been sieved to <250µm, as is required for bioaccessible arsenic analysis.]

Multi-increment samples can be collected for both nonvolatile and volatile contaminant analyses. Sample collection for volatile contaminants requires that increments be placed in an extraction solution in the field (ADEC 2007). Issues related to field extraction solutions, methanol transportation in the field, appropriate sample containers, elevated laboratory method reporting limits, etc., still need to be worked out, however, and this approach has not yet been widely used in Hawai‘i. Additional guidance will be provided in the upcoming revision of the HEER office *Technical Guidance Manual* (anticipated late 2007). Consultants who would like to use the approach in the meantime should provide sampling and analysis work plans to the HEER office for review and ensure close coordination with the receiving laboratory.

Decision Units

Multi-increment samples should be collected in carefully selected *decision units*. A decision unit is an area where a decision is to be made regarding the extent and magnitude of contaminants with respect to the environmental concerns posed by the contaminants. (Strictly speaking, a decision unit is really a volume rather than area of soil, since the thickness of the decision unit is often a key factor.) These concerns include direct exposure to the soil, intrusion of vapors into overlying buildings, leaching and contamination of groundwater, toxicity to terrestrial flora and fauna and gross contamination (odors, explosive hazards, etc.; HDOH 2005). A decision unit can be an identified spill area or “hot spot,” a residential yard, a playground or schoolyard, a garden, a commercial/industrial property or other specific area of interest. The size and shape of a decision unit is primarily controlled by the environmental concerns posed by the contaminants present and the intended use of the site.

An investigation of individual spill areas is generally necessary to assess leaching, vapor intrusion and gross contamination concerns at sites contaminated with highly mobile or volatile contaminants. This can include releases from pipelines or tanks or heavily contaminated portions of pesticide mixing areas in former agricultural lands. Each spill area represents a single decision unit. Discrete samples, or more preferably multi-increment samples collected over small areas, can be useful for delineation of spill area boundaries. The spill areas themselves should be sampled using multi-increment samples when feasible, however. Non-volatile contaminants in spill areas can be readily sampled using multi-increment sampling methods. Volatile contaminants could also be investigated with multi-increment sampling in these areas, although guidance on field methods has yet to be worked out in detail (see above).

Decision units that encompass an entire residential or commercial lot are appropriate for assessment of direct-exposure concerns. This is typically the driving environmental concern for the investigation of former agricultural field areas. Each residential lot represents a separate decision unit. Testing every lot may not be feasible or necessary for projects over 10 to 25 acres in size, depending on the size of the individual lots (default is 5,000 ft^2). For moderate-size sites, it may be feasible to combine multiple lots into larger “composite” decision units (typically up to five lots) and collect a single multi-increment sample from within each unit. The maximum concentration of a contaminant in any given lot is equal to the concentration reported for the composited decision unit times the number of lots included (i.e., assumes all of the contamination is on one lot). The variance of contaminant concentrations between composited decision units may also be useful to estimate worst-case contaminant concentrations on individual lots.

For very large redevelopment projects (e.g., >100 acres), testing each individual lot and even combining lots into larger decision units may not be practical. As an alternative, HDOH recommends that multi-increment samples be collected from a statistically defendable number of 5,000ft^2 decision units randomly located across the site. Each decision unit represents a hypothetical, residential lot. The data from these decision units can be statistically evaluated to predict maximum contaminant concentrations on any given lot within the site. Although not every lots is tested, this approach ensures that data are at least available for nearby, presumably comparable lots.

A minimum of 59 decision unit is required to obtain the HDOH-desired, 95% confidence level that residual levels of pesticides on untested lots do not exceed the maximum concentration identified on the lots tested (USEPA 1989). Past crop types, topography, soil type, planned future use and related factors should be considered in the selection of decision unit locations in order to ensure that a representative sampling of the site is carried out. Areas suspected of potentially higher levels of contamination should be investigated separately and not included in the 59 decision units selected to characterize the primary field area (e.g., former pesticide mixing areas, storage areas, plantation camps, rail lines, etc.) This approach has been used at several large-scale redevelopment sites in Hawaiʻi and will be discussed in the upcoming revision of the HEER office Technical Guidance Manual.

Initial Screening of Agricultural Lands

It is often desirable to carry out a screening level investigation of former agricultural land prior to committing funds for a full-scale, detailed investigation, as described above. Although not adequate for HDOH to make final regulatory determinations, this step provides important information that can be used to prepare a more detailed work plan. Defensible methods to screen large areas of land are still being developed. A combined multi-increment/decision unit approach is preferred over the collection of a limited number of discrete or composite samples based on the total acreage of the site. Two example approaches are described below.

A relatively quick and sensible approach is to divide the site into neighborhood-size decision units rather decision units based on the size of hypothetical, individual lots. An area of ten acres is a reasonable starting point for a “neighborhood.” A minimum of 15 decision units per site is preferable. This helps to ensure coverage of large-scale heterogeneities across the site and, if needed, is usually adequate for use in basic statistical analyses. The size and shape of individual decision units can vary and should be determined with respect to soil type, topography, past crop use, proposed redevelopment, etc., as discussed above. A multi-increment sample should be collected from each decision unit, with triplicates collected in ten-percent of the decision units (minimum two). Each sample should be tested for the full suite of pesticides that may have been used at the site in the past, including related contaminants like arsenic and dioxins. Again, areas suspected of higher levels of contamination should be investigated separately.

An alternative approach for sites where access is an issue is to collect multi-increment samples in 18 (vs 59), 5,000ft^2 decision units randomly located across the site, each representing a hypothetical, residential lot. This allows an estimation of maximum contaminant levels on any given lot to a 60% confidence level (USEPA 1989). The samples should be tested as described above. The collection of multi-increment samples in specified decision units is preferred to the collection of randomly located, discrete samples in large field areas.

As is often the case, developing the most appropriate investigation for a given site involves a balance of short-term time versus long-term uncertainty and liability. A neighborhood-based, screening level investigation is recommended where feasible. Testing entire neighborhoods will provide some level of comfort to future residents whose lots were not tested during the full-scale investigation. Perhaps most importantly, however, this approach requires a thorough walkthrough of the entire site. This will assist in the identification of areas suspected of elevated contamination, including previously unknown dumping sites, waste pits, former plantation camp areas, storage areas, etc. When walking and testing the entire site is not feasible, testing a limited number of lot-size decision units is recommended. One advantage of this approach is that the decision unit data can potentially be included in the full-scale investigation of the property (e.g., 18 of the 59 total decision units), saving on follow up investigation time costs.

Sample data from the screening level investigation should be used to initially assess residual pesticide levels in the fields and to prepare a more focused list of target pesticides of concern for the detailed investigation. Pesticides that are not detected during the initial screening investigation can generally be eliminated, although this should be discussed with HDOH. Eliminating specific pesticides from the list of target contaminants will require approval if the site is being formally overseen by HDOH.

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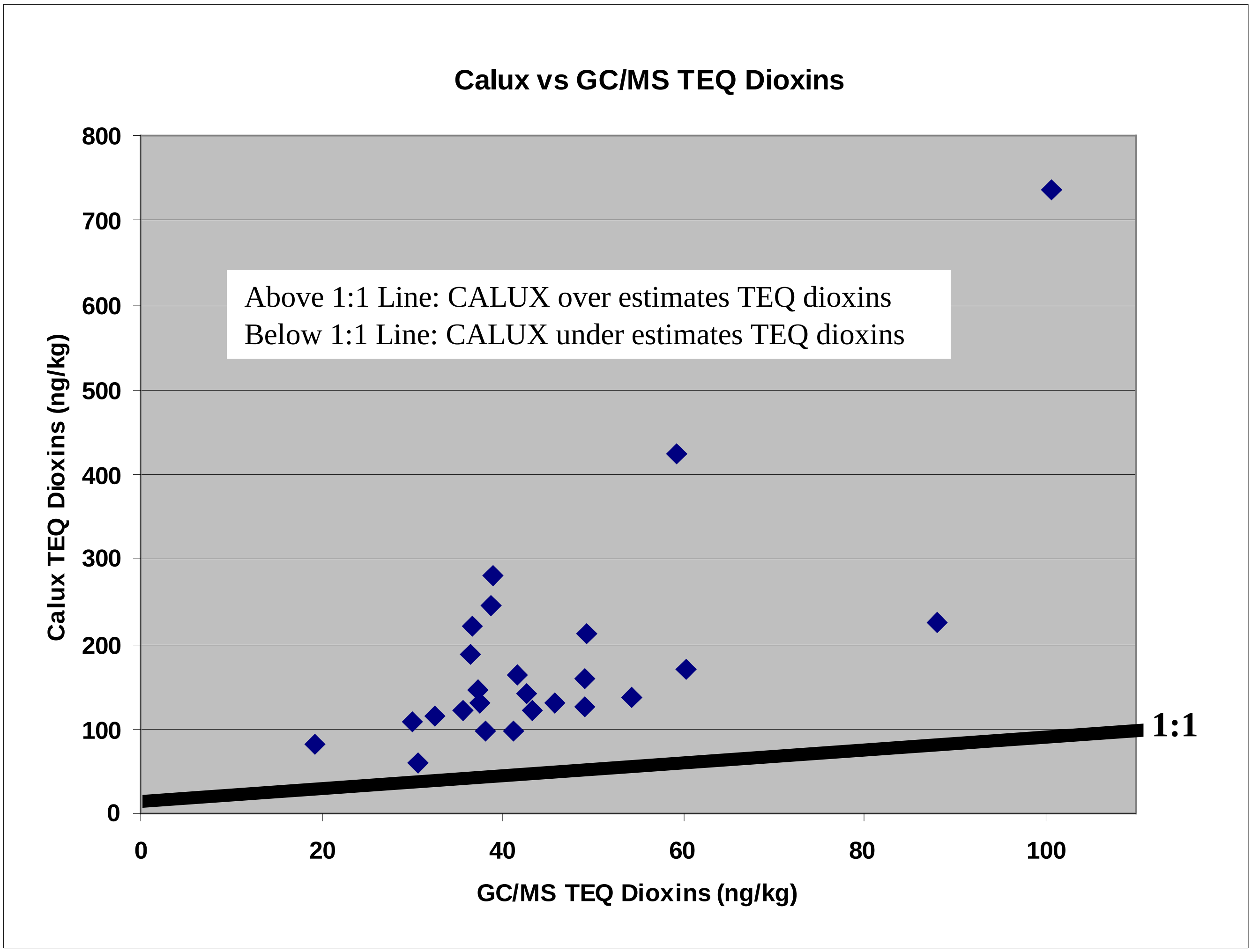

Figure 1. Results of East Kapolei study conducted on 25 samples of soil from a former sugar cane field. CALUX consistently over estimated TEQ dioxins in comparison to High Resolution GC/MS data for split samples.

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In reply, please refer to:
File: EHA/HEER Office
2007-314-RB

June 27, 2007

TO: Interested Parties

FROM: Keith E. Kawaoka, D.Env., Program Manager
Hazard Evaluation and Emergency Response Office

Steven Chang, Chief
Solid & Hazardous Waste Branch

SUBJECT: Long-Term Management of Petroleum-Contaminated Soil and Groundwater

Attached for your information is a technical report that presents guidance on the long-term management of petroleum-contaminated soil and groundwater. This report serves as an addendum to the Hazard Evaluation and Emergency Response (HEER) Office document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (May 2005 and updates).

If you any questions, please contact Dr. Roger Brewer of the HEER Office at 1-808-586-4238 or contact him by email at roger.brewer@doh.hawaii.gov.

Attachment

Long-Term Management of Petroleum-Contaminated Soil and Groundwater

This technical memorandum outlines procedures for long-term management of residual petroleum contamination in soil and groundwater at sites where full cleanup is not practicable. Topics discussed include:

- Revisions to *Target Contaminants of Concern* for petroleum-contaminated media;
    - Addition of naphthalene for gasoline releases;
    - Reduction of target PAHs for diesel-only releases to naphthalene and methylnaphthalenes;
    - Inclusion of methane in soil gas samples;
- Identification of specific environmental concerns in an *Environmental Hazard Assessment* (formerly referred to as an Environmental *Risk* Assessment);
- Identification of long-term management needs and preparation of an *Environmental Hazard Management Plan*;
- Need for continued Hawaii Department of Health (HDOH) oversight*:*
    - Remaining contamination does not exceed action levels: *No Further Action* and case closure with no long-term monitoring or management requirements;
    - Remaining contamination exceeds action levels but very limited threat to human health and the environment: *No Further Action* and case closure with no requirement for continued monitoring; management of remaining contamination in accordance with the *Environmental Hazard Management Plan* required; or
    - Remaining contamination exceeds action levels and potentially significant threat to human health and the environment: Case remains open under continued HDOH oversight but responsible party may request concurrence that further active remediation is not practicable.

An important goal of the guidance is to allow closure of "low-risk" and low-priority cases. These are cases where remaining contamination is minimal and does not pose a significant risk to human health and the environment, even though a limited area of soil or groundwater is contaminated above HDOH environmental action levels. The remaining contamination must be properly managed in accordance with the *Environmental Hazard Management Plan* prepared for the site. No further reporting requirements will be imposed, although HDOH reserves the right to reopen the case if remaining contamination is not properly managed in the future. This allows HDOH to focus its resources on high-risk and high-priority sites. Formally closing low-risk sites also assists the owner in property transactions and redevelopment (which in some cases could assist in further cleanup). Clearly documenting post-remediation site conditions and remaining environmental concerns also reduces the chance that the owner could be inappropriately included as a "responsible party" for future, unrelated releases after the property has been sold.

The guidance draws from and adds to information presented in the Hazard Evaluation and Emergency Response (HEER) and Solid & Hazardous Waste Branch (SHWB) office *Technical Guidance Manual* documents (HDOH 1997, 2000). Guidance documents prepared by the USEPA and other state agencies are also referred to. In particular, this document incorporates guidance published by the State of California in 1996 to address what they termed "low-risk" petroleum-release sites (CalEPA 1996a). California's guidance is based on the premise that petroleum contamination does not pose a significant threat to human health and the environment once the source of the release is stopped and gross contamination is removed from the immediate release area (irregardless of contaminant concentrations). While very practical, the discovery of extensive plumes of MTBE-contaminated groundwater from gas stations and leaking pipelines soon afterwards and the growing importance of vapor intrusion concerns reduced the usefulness of California's guidance. The guidance presented below helps address these gaps by requiring a full evaluation of potential environmental concerns and closer HDOH oversight of cases where soil and/or groundwater are contaminated with persistent and highly mobile chemicals like MTBE.

The guidance also serves as an update and addendum to the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (HDOH 2005a). The guidance applies to both petroleum releases overseen by the HEER Office and releases overseen by the SHWB. Responsible parties with cases being overseen by the Underground Storage Tank section of the SHWB may continue to refer to action levels presented in 1995 HDOH Risk-Based Corrective Action guidance if they choose until such time that SHWB regulations pertaining to releases from underground storage tanks are updated (HDOH 2005b, regulations currently under review).

This guidance is intended to provide a starting point for discussion of possible case closure and removal from HDOH oversight. The guidance is *not* intended to represent strict requirements for closure and issuance of *No Further Action* letters to responsible parties. The information provided in this guidance will be updated as appropriate and will be included in future revisions of the HEER and SHWB *Technical Guidance Manual* documents (currently underway). Comments and suggestions are welcome and should be addressed to Roger Brewer of HDOH at roger.brewer@doh.hawaii.gov.

Overview

Responsible parties for sites where full cleanup of contaminated soil and groundwater has occurred and representative concentrations of contaminants in soil, soil gas and groundwater are below HDOH Tier 1 Environmental Action Levels (EALs) can petition HDOH for a *No Further Action* letter and case closure. Site conditions often limit the extent to which contaminated soil and groundwater can be aggressively remediated, however. This situation is especially common in heavily developed, urban areas. Excavation and removal of heavily contaminated soil and free product in the immediate area of the release is generally achievable. Concerns about building foundations, subsurface utilities and roadways coupled with high costs, however, often limit the feasibility of complete cleanup.

This guidance describes conditions where continued HDOH oversight of the site will be required (refer to Figures 1, 2 and 3). The guidance also presents conditions where a responsible party can petition for case closure under a *No Further Action* letter when contaminant concentrations exceeds Tier 1 EALs (or approved, alternative action levels) but the remaining threat to human health and the environment is minimal. When the remaining threat is still significant but further attempts to actively reduce contaminant levels via excavation, soil vapor extraction, direct groundwater treatment, etc., is not practicable, the responsible party can petition HDOH to concur that no further active remediation is required at the site. This allows current and future owners (as well as financial institutions) to better assess the monetary, environmental liability tied to the property and reduce financial uncertainty in property transfer or redevelopment plans.

Costs associated with long-term monitoring or engineered controls (caps, etc., if applicable) are, in contrast, relatively easy to project.

Continued HDOH oversight will likely be required at sites where Tier 1 EALs (or approved, alternative action levels) are exceeded *and* one or more of the following conditions exist (refer also to Figures 2 and 3):

- Sites where active remediation is still technically and economically practicable;
- A plume of contaminated groundwater is present that could threaten existing or future water supply wells;
- A plume of contaminated groundwater is present that could be acutely toxic to aquatic organisms if it discharges into a surface water body;
- Persistent chemicals such as lead, PCBs, chlorinated solvents, etc., are present above action levels for unrestricted/residential land use and no land use covenant/deed restriction in place;
- Remaining contamination poses direct-exposure and/or vapor-intrusion concerns for current and anticipated future land use in the absence of engineered controls;
- Greater than ten cubic meters of grossly contaminated soil are present within three meters of the ground surface (or above groundwater, if less than three meters deep).

Sites where each of the following conditions are met can petition for a *No Further Action* letter and case closure, provided that the remaining contamination is properly managed in accordance with the *Environmental Hazard Management Plan* prepared for the site (refer to Figures 2 and 3):

<u>General:</u>

- The release has been stopped and ongoing sources, including free product, have been removed or remediated to the extent practicable;
- Remaining contamination documented in an updated site assessment report, including maps that clearly define the extent and magnitude of remaining contamination above HDOH EALs (or other approved screening levels);
- Remaining environmental concerns are documented in an *Environmental Hazard Assessment* report;
- Requirements for long-term management of remaining contamination are presented in an *Environmental Hazard Management Plan;*

<u>For soil:</u>

- Representative concentrations of persistent chemicals do not exceed action levels (e.g., lead, PCBs, PAHs, etc.; multi-increment data preferred for surface and near surface samples, when practicable);
- Engineered controls (pavement, etc.) in place to prevent direct-exposure, vapor-intrusion or leaching concerns;
- Volume of contaminated soil within three meters (ten feet) of surface $\leq 10\text{m}^3$ (approximately 15 cubic yards);

For groundwater:

- Body of groundwater that exceeds action levels is not expanding and/or or migrating (i.e., the plume is "stable" or shrinking);
- For impacted drinking water resources:
    - Plume is not within 300m (approximately1,000 ft) of an active water supply well and within the producing aquifer or within 150m of a surface water body that is a potential source of drinking water;
    - Persistent chemicals not present above drinking water goals (MTBE, chlorinated solvents, etc.);
    - Non-persistent, petroleum-related contaminants do not exceed drinking water goals by more than one order of magnitude;
- For plumes within 150m of an aquatic habitat (including drainage ways that lead to a surface water body):
    - Contaminant concentrations do not exceed action levels for chronic aquatic toxicity concerns for undeveloped waterfronts; or
    - Contaminant concentrations do not exceed action levels for acute aquatic toxicity concerns for developed waterfronts;
- For plumes not within 150m of an aquatic habitat:
    - Contaminant concentrations do not exceed action levels for acute aquatic toxicity concerns; and
- No vapor intrusion or methane buildup concerns in the absence of engineered controls.

The distance of 300m from a producing well to highlight "high-risk" plumes is subjective and is not necessarily reflective of groundwater flow rates in well capture zones. The two-year capture zone for municipal water wells installed in the basal, basalt aquifer can extend outward from the well head 3,000 meters or more (personal communication, HDOH Safe Drinking Water Branch). The upper few meters of the aquifer (where petroleum-contaminated groundwater is usually restricted), however, may not be included in the primary capture zone for wells that are screened well below the top of the water table. Unfortunately, detailed information on the design and construction of municipal water supply wells is not available to the general public. A more detailed evaluation will be required if HDOH determines that a water supply well is potentially at risk of being contaminated.

Sites where the above conditions are met can petition HDOH for case closure under a *No Further Action* letter. The burden and responsibility for long-term management of remaining contamination, as described in an *Environmental Hazard Management Plan*, is placed on the property owner (or other responsible party). HDOH reserves the right to reopen a case if it is determined that residual contamination is not being adequately managed.

Sites that do not meet these conditions will remain under the long-term oversight of HDOH, unless otherwise determined on a case-by-case basis. Responsible parties can, however, petition HDOH for a letter concurring that *No Further Active Remediation* is required. This lessens uncertainty regarding the financial "environmental liability" associated with the property and can assist in future property transfers and redevelopment.

Determining Need for Continued HDOH Oversight

A stepwise approach to determine the need for continued HDOH oversight of petroleum-contaminated sites is discussed below and summarized in Figures 1 through 3. Target contaminants of concern should be identified based on a comparison to HDOH Tier 1 EALs or approved, alternative action levels. The extent and magnitude of remaining petroleum contamination above action levels must be clearly documented in an updated site assessment report that summarizes post-remediation site conditions.

Potential environmental concerns posed by the contamination must be identified and discussed in an *Environmental Hazard Assessment* report. In most cases, this will involve a comparison of site data to HDOH EALs for specific environmental concerns or acceptable, alternative criteria (HDOH 2005a). A more detailed assessment of environmental concerns can be carried out on a site-by-site basis as needed.

This information should be used to develop an *Environmental Hazard Management Plan* that describes long-term monitoring and management of remaining contaminated soil and groundwater at the site. The report must discuss any engineered or institutional controls necessary to keep the contamination from spreading as well as to prevent adverse exposure of residents or workers and ensure proper reuse or disposal of soil and groundwater that is disturbed during future subsurface activities. Both the *Environmental Hazard Assessment* and *Environmental Hazard Management Plan* can be presented as part of the updated, site assessment report.

Step 1: Identify Target Contaminants of Concern

Table 1 provides an updated summary of contaminants of potential concern that must be included in environmental investigations at petroleum release sites. Petroleum contamination must be evaluated in terms of both Total Petroleum Hydrocarbon (TPH) and target "indicator chemicals" for the specific type of petroleum product released (e.g., benzene, toluene, ethylbenzene and xylenes or "BTEX", methyl tertiary butyl ether [MTBE], polynuclear aromatic hydrocarbons [PAHs], etc.). Soil, groundwater and soil gas samples must always be tested for TPH in addition to the target indicator chemicals noted in Table 1 and discussed below.

Petroleum is a complex mixture of hundreds of different compounds composed of hydrogen and carbon (i.e., "hydrocarbon" compounds). The bulk of these compounds are evaluated under the all-inclusive category of "TPH." Gasoline-range TPH is a petroleum mixture characterized by a predominance of branched alkanes and aromatic hydrocarbons with carbon ranges of C6 to C12 and lesser amounts of straight-chain alkanes, alkenes and cycloalkanes of the same carbon range (API 1994). Total Petroleum Hydrocarbon associated with middle distillates (e.g., kerosene, diesel fuel, home heating fuel, jet fuel, etc.) is characterized by a wider variety of straight, branched and cyclic alkanes, PAHs (especially naphthalenes and methyl naphthalenes) and heterocyclic compounds with carbon ranges of approximately C9 to C25. Residual fuels (e.g., Fuel Oil Nos. 4, 5, and 6, lubricating oils, mineral oil, used oils, asphalts, etc.) are characterized complex, polar PAHs, naphthenoaromatics, asphaltenes and other, high-molecular-weight, saturated hydrocarbon compounds with carbon ranges that in general fall between C24 and C40.

Laboratory analysis for TPH as gasolines and middle distillates is generally carried out using gas chromatography, modified for "gasoline-range" organics ("Volatile Fuel Hydrocarbons") and "diesel-range" organics ("Extractable Fuel Hydrocarbons"), respectively (e.g., EPA Method

8015). Analysis for TPH as residual fuels up to the C40 carbon range can be carried out by gas chromatography, infrared or gravimetric methods. The latter methods are rarely used, however, due to an inability to discriminate the type of the petroleum present and interference with organic material in the soil.

Environmental action levels for TPH are developed by assigning representative fate and transport properties and toxicity factors to each TPH category and applying the same models and approaches as used for the target, indicator compounds (HDOH 2005a). A more in-depth analysis of the specific components of the TPH can be carried out in a site-specific environmental hazard assessment as needed (e.g., TPHWG 1998, MAEDP 2002).

Target indicator chemicals typically make up only a small fraction of the total petroleum present but are important players in the assessment of environmental hazards posed to human and the environment. A brief discussion of target indicator chemicals for petroleum products is included in Chapter 2 of the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (HDOH 2005a). The 2005 HDOH guidance recommends that the following PAHs be included as target indicator chemicals for soil and groundwater contaminated with middle distillates and residual fuels:

- acenaphthene
- acenaphthylene
- anthracene
- benzo(a)anthracene
- benzo(b)fluoranthene
- benzo(g,h,i)perylene
- benzo(a)pyrene
- benzo(k)fluoranthene
- chrysene
- dibenzo(a,h)anthracene
- fluoranthene
- fluorene
- indeno(1,2,3)pyrene,
- methylnaphthalenes (1- and 2-)
- naphthalene
- phenanthrene
- pyrene

Environmental Action Levels for these chemicals are included in the HDOH EAL lookup tables (HDOH 2005a). The list of target PAHs was taken from guidance prepared by the USEPA and various state agencies in the 1990s (e.g., CalEPA 1996b, USEPA 2004).

This technical memorandum reduces the PAHs that must be included as target indicator compounds for releases of middle distillate fuels to naphthalene and methylnaphthalene (Table 1, after MADEP 2002). A review of field data and discussions suggests that the majority of the PAHs are not present in middle distillate fuels at concentrations that would drive environmental concerns and cleanup actions. From an environmental hazard standpoint, cleanup of releases of middle distillate fuels is almost always driven by Total Petroleum Hydrocarbons (TPH) contamination, not PAHs. Naphthalene and methylnaphthalenes are two potential exceptions, since they can be present in middle distillate fuels at relatively high concentrations and are moderately volatile and mobile. Naphthalene is also an upcoming contaminant in vapor intrusion studies, although it is unlikely to be present in middle distillate fuels at levels that would pose vapor intrusion concerns when TPH itself does not exceed HDOH action levels.

Soil and groundwater contaminated with middle distillate fuels must also be tested for BTEX (Table 1). Although BTEX rarely drives cleanup for releases middle distillate fuels, their presence or absence is a useful indicator of past gasoline releases at the site or the migration of gasoline-contaminated groundwater onto the property from offsite sources. Testing for naphthalene at gasoline release sites is also recommended (refer to Table 1).

Soil and/or groundwater contaminated with used oils, coal tar, asphalt and other heavy petroleum mixtures must be tested for the full suite of PAHs noted above. Releases of unused lube oil, transformer oils, mineral oils, virgin hydraulic oils, Fuel Oil #6 and similar products do not require testing for PAHs and other chemicals if it can be demonstrated that product released was never heated to high temperatures (potentially producing PAHs). Testing must also be carried out for volatile organic compounds (VOCs, including chlorinated solvents), PCBs and heavy metals unless otherwise justified.

Step 2: Prepare Updated Site Assessment Report

Site conditions following active remediation of contaminated soil and groundwater to the extent practicable must be clearly documented in an updated site assessment report. Information that should be provided in the report includes:

- Summary of Past, Current and Anticipated Future Site Activities and Uses:
    - Describe past and current site uses and activities;
    - Describe foreseeable future site uses and activities;
- Summary of Pre- and Post-Remediation Site Conditions:
    - Identify all types of impacted media;
    - Identify all sources of chemical releases;
    - Identify all chemicals of concern;
    - Delineate on to-scale maps the magnitude and extent of contamination above EALs (or other approved action levels) to extent practicable and applicable;
    - Identify nearby groundwater extraction wells, bodies of surface water and other potentially sensitive ecological habitats;
    - Ensure data are representative of site conditions.

Surveyed, to-scale maps of the site that clearly indicate the location of remaining contaminated soil and groundwater must be included in the report. This information will be necessary for both the assessment of potential environmental concerns or *hazards* posed by the contamination as well as the preparation of an *Environmental Hazard Management Report*, discussed in the following steps.

Step 3: Prepare Environmental Hazard Assessment

An *Environmental Hazard Assessment* is an evaluation of potential environmental concerns at sites where releases of petroleum or other hazardous chemicals have occurred (HDOH 2005a). Common environmental concerns that must be assessed at sites where petroleum-contaminated soil and/or groundwater are identified include:

Soil:

- Direct exposure to contaminants in soil (ingestion, dermal absorption, inhalation of vapors and dust in outdoor air);

- Emission of vapors to building interiors;
- Impacts to terrestrial ecological habitats;
- Leaching and impacts to groundwater resources; and
- General gross contamination and resource degradation (including generation of vapors and explosive hazards, potentially mobile free product, odors, general resource degradation, etc.);

Groundwater:

- Impacts to drinking water resources;
- Emission of vapors to building interiors;
- Impacts to aquatic habitats (discharges of contaminated groundwater to surface water); and
- Other gross contamination and resource degradation concerns (including intrusion of vapors into utility conduits, potentially mobile free product, sheens, etc.).

A more detailed discussion of common environmental concerns posed by contaminated soil and groundwater is provided in the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (HDOH 2005a).

The presence or absence of potential environmental concerns is first evaluated in a brief, *Environmental Hazard Assessment.* This can be done by comparison of site data to the summary, Tier 1 EALs presented in Volume 1 of the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (HDOH 2005a). The presence of chemicals at concentrations above an action level *does not* necessarily indicate that hazardous conditions exist at the site. It *does*, however, indicate that additional evaluation of identified, potential concerns is warranted.

When a Tier 1 EAL (or approved, alternative action level) is exceeded, specific environmental concerns can be identified by comparison of representative contaminant concentrations to detailed action levels presented in Appendix 1 of the HDOH EAL document. The Excel-based, EAL "Surfer" or electronic lookup tables can be used to expedite this process (available for download from the HDOH EAL webpage, see URL address in HDOH 2005a reference). The Surfer allows direct input of representative contaminant concentrations. Specific environmental concerns are identified if input contaminant concentrations in soil or groundwater exceed the primary Tier 1 EAL. The Surfer then generates a "Summary Report" that can be printed and included as supporting documentation for a basic *Environmental Hazard Assessment* report. Note that decision unit and multi-increment investigation strategies are preferred over the use of discrete sample data, when feasible (refer to HDOH 2007b).

An *Environmental Hazard Assessment* report must be prepared to document potential environmental concerns associated with remaining contamination at the site. This document should include the following information:

- Site Background;
- Summary of investigations (including to-scale maps with a north arrow);
- Applicability of HDOH EALs or alternative action levels;
- Selection of soil and groundwater categories;

- Selection of EALs & comparison to site data;
- Identification of specific environmental concerns if final Tier 1 EALs exceeded; and
- Recommendations for followup actions, including preparation of an *Environmental Hazard Management Plan* or, if needed, a more detailed assessment of identified environmental concerns.

A more detailed discussion of the preparation of *Environmental Hazard Assessment Reports* is provided in Volume 1 of the HDOH EAL document (HDOH 2005a). For relatively simple sites, the assessment can be included as a separate chapter in the post-remediation report, with EAL Surfer printouts, etc., included in the appendices. Maps that depict specific environmental concerns posed by contamination in various areas of the site can also be very useful, and in some cases required, for inclusion in the site *Environmental Hazard Management Report*, as discussed below (e.g., areas that pose direct-exposure, leaching or vapor intrusion concerns; areas of free product, grossly contaminated soil or methane buildup, etc.).

Conditions that pose immediate or short-term environmental concerns should be addressed as quickly as possible. This includes exposure of residents or workers to potentially harmful levels of contaminants in soil ("direct exposure"), impacts to water supply wells, intrusion of vapors or methane into overlying structures (including explosive hazards) and discharges of free product to surface water.

Note that the approach described above is referred to as *Environmental "Risk" Assessment* in the 2005 HDOH EAL document. The term "risk" is replaced with the term "hazard" in this guidance document. This was done to emphasize the fact that some environmental concerns are not necessarily toxicological in nature, as the term "risk" is often interpreted to indicate. Examples include explosive hazards, leaching of contaminants from soil and even general gross contamination concerns. Human health and ecological risk are of course an important component of an *Environmental Hazard Assessment*, but they cannot be used as stand-alone tools to assess the need for potential cleanup actions at sites where petroleum-contaminated soil and groundwater are identified. This change in terminology will be noted in upcoming revisions of HDOH environmental guidance documents.

Step 4: Prepare Environmental Hazard Management Plan

The purpose of an *Environmental Hazard Management Plan* (EHMP) is threefold: 1) document the extent and magnitude of contaminated soil and groundwater left in place at a site, 2) summarize identified environmental concerns posed by the contamination and 3) provide a framework for long-term management of the contamination. An EHMP must be prepared for all petroleum-release sites where residual soil and groundwater contamination is left in place above levels that could pose potential environmental concerns. A copy of the plan must be submitted to HDOH for inclusion in the public file.

An *Environmental Hazard Management Plan* is similar in intent to what are commonly referred to as *Risk Management Plans* or *Soil and Groundwater Management Plans*, as described in the current editions of the HEER Office and SHWB *Technical Guidance Manuals* (HDOH 1997, 2000; USEPA 2003). A *Risk Management Plan* or *Exposure Prevention Management Plan* typically focuses on the reduction or elimination of risks to human health posed by direct exposure to contamination in soil or groundwater or by the emission of vapors into buildings.

While important, other potential concerns such as leaching, explosive hazards and the simple need to properly manage grossly contaminated soil or groundwater are often ignored. A *Soil and Groundwater Management Plan* describes measures for handling, reusing and/or disposing of contaminated soil and groundwater that is encountered during future subsurface activities, including the repair of underground utilities or redevelopment of the property. Again, this information is important but these plans often fail to identify the specific environmental concerns posed by the contamination.

An *Environmental Hazard Management Plan* combines all necessary information into a single, stand-alone document that identifies the nature of the contamination present, the potential environmental concerns posed by the contamination, and appropriate measures to ensure that these concerns are adequately addressed. An *Environmental Hazard Management Plan* should include the following information, at a minimum:

- Brief summary of the site background and history of contaminant releases;
- Identification of specific contaminants of concern, including TPH, "Target Indicator Compounds" and any other contaminants associated with the release (refer to Step 1);
- Clear depiction of the extent and magnitude of remaining contamination in soil, groundwater and/or soil gas, presented on easily readable, to-scale maps with a north arrow (refer to Step 2);
- Identification and discussion of all potential environmental concerns (refer to Step 3);
- Requirements for long-term monitoring of contaminants in soil, groundwater, and/or soil gas;
- Discussion of engineered and/or institutional controls needed to address identified environmental concerns, including caps, barriers, etc., needed to eliminate exposure pathways;
- Guidance on the proper handling, reuse and disposal of contaminated soil and/or groundwater that is encountered during future site activities;
- Measures for repair or replacement of engineered controls that are disturbed or breached during future site activities; and
- Any other information required to adequately mitigate and manage remaining environmental concerns at the site.

A brief Fact Sheet that summarizes key elements of the *Environmental Hazard Management Plan* in simple, non-technical terms will be required for large, complex sites where significant public review is anticipated.

Long-term environmental concerns must be clearly assessed and documented to ensure that in-place management of the remaining petroleum contamination is viable and carried out properly. Examples of potential, long-term management actions include: 1) capping of grossly contaminated soil under paved areas or buildings, 2) installation of vapor barriers beneath buildings, 3) lining of utility corridors to prevent the migration of contaminated groundwater or vapors into storm drains, utility trenches or other subsurface conduits, 4) restrictions on subsurface activity in some areas without pre-approved work plans, 5) procedures for proper disposal or reuse of contaminated soil and groundwater disturbed during subsurface activities, 6) long-term monitoring of on-site groundwater and soil gas and, 7) installation of offsite "sentinel wells" to monitor potential long-term impacts to more distant water supply wells or surface water bodies.

Additional guidance on engineered and institutional controls and the preparation of *Environmental Hazard Management Plans* will be provided in the upcoming revision of the HEER Office *Technical Guidance Manual* (anticipated late 2007, refer also to USEPA 2003). The complexity of the *Environmental Hazard Management Plan* for a given site will depend on the extent and nature of the specific contaminants released (mobility, toxicity, explosive hazard, etc.), the specific environmental concerns posed by the contamination and the current and future site use. For relatively simple sites, the *Environmental Hazard Management Plan* can be included as an appendix in the final site closure report.

Step 5: Determine Need for Continued HDOH Oversight

Figures 2 and Figure 3 provide flow charts to assist in determining an appropriate course of action for long-term oversight of petroleum-contaminated soil and groundwater, respectively. The flow charts, and related discussion below, should be considered general guidance only and not strict requirements that must be met before the status of a site can be updated to "closed" under a *No Further Action Letter*. As in any subject where the distinct lines between "yes" and "no" are difficult to draw, the use of sound, professional judgment is very important.

Cases where remaining contamination is minimal in extent and/or magnitude and not likely to pose significant environmental concerns under worst-case conditions can generally be closed under a *No Further Action* letter from HDOH. No further monitoring or reporting requirements will be imposed on these sites. Long-term management of remaining contamination must be carried out in accordance with the *Environmental Hazard Management Plan* prepared for the site. HDOH retains the right to reopen the case and impose enforcement actions if contaminated soil or groundwater is not properly managed.

Continued HDOH oversight will be necessary at sites where remaining contamination could pose significant environmental concerns if not appropriately managed. Sites where potentially significant, environmental concerns remain but active remediation (excavation, soil vapor extraction, etc.) is no longer practical can, and should, request a letter from HDOH clarifying that no *further active remediation* is required. The need for ongoing groundwater or in some cases soil gas monitoring should also be evaluated. The letter is intended to clarify that all major cleanup actions have been completed at the site and that the site has moved into a status of long-term monitoring and management. These letters help property owners, financial institutions and potential purchasers establish the "environmental liability" associated with the remaining environmental contamination and can greatly assist in future property transactions and redevelopment. The *Environmental Hazard Management Plan* should include a description of conditions that will need to be met before the case can be formally closed and a no further action letter issued.

Long-Term Oversight of Petroleum-Contaminated Soil

Continued HDOH oversight of cases with residual petroleum contamination in soil will be required if one of more of the following conditions exists and sufficient justification to close the case is not otherwise provided (see Figure 2):

- Additional remediation technically and economically practicable;
- Anticipated residential redevelopment in near future and representative contaminant concentrations exceed action levels for unrestricted land use;
- Persistent contaminants present above direct-exposure or vapor intrusion action levels for unrestricted land use and no deed restriction recorded (PAHs, MTBE, heavy metals, PCBs, chlorinated solvents, etc.);
- Direct exposure, vapor intrusion and/or leaching concerns under current or anticipated land use but engineered controls not in place prevent exposure or contaminant migration; and/or
- Nonpersistent contaminants only (e.g., TPH, BTEX, etc.) but volume of soil contaminated above action levels exceeds 10 cubic meters (approximately 15 cubic yards).

HDOH Tier 1 EALs are pre-approved for use at all sites and should be referred to in the absence of acceptable, site-specific, Tier 2 or Tier 3 action levels (refer to HDOH EAL document, HDOH 2005a).

For the purposes of this guidance, the term “soil” refers to any unconsolidated soil, sediment or fill material. HDOH Environmental action levels for soil are primarily intended for comparison with sample data collected above the water table. This is because residents, as well as commercial and industrial workers, are unlikely to come into regular contact with soil below the water table. The EALs also include consideration of vapor intrusion concerns and leaching concerns, both of which should not be applied to soils situated in groundwater. Direct collection of groundwater data is instead more pertinent to evaluate these concerns. The collection of soil sample data below the water table can sometimes assist in developing long-term management strategies for sites where residual contamination is to be left in place, however. Procedures for management of contaminated soil situated at or below the water table that is disturbed during future subsurface activities should also be included in the site *Environmental Hazard Management Plan.* Formal covenants that restrict land use and implement engineered controls to prevent exposure or leaching are required for sites where representative concentrations of persistent chemicals exceed action levels for unrestricted, residential land use.

Multi-increment sample data are preferred to establish representative contaminant concentrations within designated decision units over discrete sample data, although in practice this approach is most applicable for surface samples to be tested for non-volatile contaminants. The State of Alaska recently published guidance on the collection of multi-increment samples that area to be tested for volatile chemicals (ADEC 2007). The approach calls for the placement of soil increments in methanol in the field. Restrictions on airline transportation of methanol may limit the use of this approach in Hawaiʻi, however. Additional guidance on this subject to be presented in the upcoming update of the HEER Office *Technical Guidance Manual* (anticipated Fall 2007).

Soil gas data are preferred over soil data for evaluation of potential vapor intrusion concerns. Leaching concerns should be evaluated based on comparison to HDOH action levels, the results of laboratory batch test (HDOH 2007a) and/or groundwater monitoring data for sites where the contaminated soil is not capped or in direct contact with groundwater. Closure of a case under a *No Further Action* letter with deeper, grossly contaminated soil that exceeds ten cubic meters in volume is acceptable provided that the soil does not pose significant leaching and groundwater contamination concerns. This should be discussed on a case-by-case basis with HDOH.

Gross contamination action levels for soil address odor and aesthetic concerns and resource degradation in general (refer to Volume 1 of the HDOH EAL document). The action levels also help identify soil with mobile free product or explosive levels of vapors. Remaining gross contamination concerns at sites where active soil cleanup is no longer practicable should be evaluated by an inspection of soils that exceed action levels for TPH. Gross contamination action levels for soils contaminated with gasoline and middle distillate fuels (diesel, jet fuel, etc.) are based to a large degree on field experience. Action levels for shallow soils (≤3m) are considered to be relatively accurate for odor concerns in a residential land use scenario (100 mg/kg and 500 mg/kg for gasoline and middle distillate fuels, respectively, refer to Appendix 1 of the HDOH EAL document for commercial/industrial action levels). Action levels for deeper soils are useful to identify the presence of potentially mobile, free product or the production of potentially explosive petroleum or methane vapors (2,000 mg/kg and 5,000 mg/kg, respectively).

Gross contamination action levels for the broad category of TPH “residual fuels” (motor oil, mineral oil, grease, etc.) are significantly more flexible. Used oil could in some cases pose nuisance concerns at concentrations as low as the default residential action level of 500 mg/kg for residual fuels but higher levels are acceptable on a case-by-case basis if it can be adequately demonstrated that the contamination does not pose adverse nuisance conditions. An in-house study using spiked soil samples indicated action levels of 5,000 mg/kg (shallow soils) and 25,000 mg/kg (deep soils) are appropriate for mineral oil (commonly used in electrical transformers), provided that the oil has not been heated to high temperatures, subjected to fire or contaminated with other chemicals. Similar gross contamination action levels may be appropriate for heavy greases.

Long-Term Oversight of Petroleum-Contaminated Groundwater

Continued HDOH oversight of cases with residual petroleum contamination in groundwater will be required if one of more of the following conditions exists and sufficient justification to close the case is not otherwise provided (see Figure 3):

- The area of the plume that exceeds action levels is still expanding and/or or migrating away from the original release area;
- The plume is within the capture zone of an active water supply well or within 150m of a potable surface water body and contaminant levels exceed drinking water action levels;
- The plume is not within the capture zone of an active supply well but within a potential drinking water aquifer and concentrations of TPH, BTEX and related petroleum compounds exceed action levels by an order of magnitude or more;
- The plume is not within the capture zone of an active supply well but within a potential drinking water aquifer and concentrations of MTBE, chlorinated solvents or other persistent compounds exceed action levels;
- The plume is within the capture zone of a nondrinking water, industrial or irrigation supply well and contaminant levels exceed action levels for impacts to surface water bodies or other environmental concerns;
- The plume is within 150m of an undeveloped water front or sensitive aquatic habitat and contaminants exceed action levels for chronic toxicity to aquatic organisms;

- The plume is within 150m of a highly developed waterfront area (e.g., wharf area) and contaminants exceed action levels for acute toxicity to aquatic organisms or potentially mobile free product is present;
- Storm sewers, abandoned pipelines or other subsurface utilities are located adjacent to or within plume and could serve as potential conduits for migration of free product or other contaminants to surface water bodies above the levels of concern noted above; and
- Free product on groundwater could pose a risk to on-site workers involved in excavation or dewatering activities, and/or long-term methane generation or vapor intrusion concerns.

A more detailed discussion of groundwater utility (e.g., drinking water supply, irrigation supply, etc.) is provided in Volume 1 of the HDOH document *Screening For Environmental Concerns at Sites With Contaminated Soil and Groundwater* (HDOH 2005a). The status of an aquifer as a potential source of drinking water is determined in part on the location of the groundwater with respect to the Underground Injection Control (UIC) Line and the state *Aquifer Identification and Classification* technical reports prepared by the University of Hawai'i. Groundwater in a viable aquifer that is situated inland ("mauka") of the UIC line or in the basal aquifer under coastal caprock sediments is generally considered by HDOH to be a potential water supply resource.

Once the source of a release has been removed (including vadose-zone soil that could act as a secondary leaching source), a minimum of two years of quarterly monitoring is generally required to establish that a plume is not expanding or migrating above levels of potential concern. This assumes that groundwater is not contaminated with MTBE and other persistent chemicals above levels of concern, in which case a plume may never become truly "stable" and long-term monitoring will be required. Long-term monitoring data can also be used to develop degradation trends for contaminants of concern (e.g., API 2007). If a convincing case can be made that contaminant levels will reach target goals within five years and currently used water supply wells are not threatened then closure of the case under a *No Further Action* letter will be considered.

If the source(s) of groundwater contamination has been gone for five or more years earlier, less data, in some cases even a single monitoring event, will be adequate to establish that a plume has reached it's greatest extent and is unlikely to spread further. Natural degradation and sorption of remaining contamination to soil particles quickly halt the spread and migration of petroleum-contaminated groundwater once the source has been removed. Plumes rarely extend more than 150 meters from the original release area in the absence of MTBE or other persistent and highly mobile chemicals. However, storm sewers, abandoned pipelines, other subsurface utilities or shallow irrigation wells could act as conduits for contaminated groundwater to reach more distant surface water bodies. Potential dewatering at construction sites must also be considered in areas of shallow groundwater, as should the potential for contaminated groundwater to enter an irrigation or industrial water supply well and ultimately be discharged into an irrigation canal, storm water drain or other direct conduit to a surface water body. These situations will require that the groundwater be screened against chronic rather than acute aquatic toxicity goals and must be evaluated on a site-by-site basis. HDOH NPDES requirements may also apply for surface discharges of contaminated groundwater.

Dilution of contaminated groundwater upon discharge to a surface water body is not taken into consideration for initial screening of potential impacts to aquatic habitats. This is because organisms living in the sediment that organisms living in the water column rely on as a food source could be exposed directly to the groundwater prior to discharge. Benthic habitats located along natural stream or channel banks or shoreline areas are particularly at risk. Groundwater in these areas should be screened against the more stringent, chronic, aquatic toxicity action levels included in Tier 1 EALs for areas within 150m of a surface water body (refer to Appendix 1 of the HDOH EAL document). Screening of groundwater data against acute aquatic toxicity action levels is considered adequate in highly developed waterfront areas (wharfs, seawalls, etc.) where significant benthic communities are generally absent in the area where contaminated groundwater may discharge and the primary risk is to aquatic organisms living in the water column. Impacts that result in a sheen on a surface water body must be avoided in all cases.

Other factors that can be considered in evaluating the need for continued HDOH oversight include the aerial extent of impacted groundwater and impacts to deep, non-potable groundwater. In commercial/industrial areas, petroleum-contaminated groundwater generally does not pose a significant threat to human health and the environment regardless of the actual concentrations of TPH or petroleum-related target indicator chemicals if the following conditions are met: 1) plume is not expanding or migrating away from the release area above final, target action levels, 2) area of remaining free product is less than approximately 100 square meters (assumed size of an existing or future building, minimal vapor intrusion and methane buildup concerns,) and 3) depth to groundwater is greater than five meters (unlikely to be encountered during future construction activity). This assumes the absence of conduits for offsite migration (storm sewers, etc.). Closure of such cases under a *No Further Action* letter with management of remaining contamination under an *Environmental Hazard Management Plan* should be considered. The primary concerns for deep (e.g., >5m), non-potable groundwater impacted with petroleum are offsite migration, the generation of methane and vapor intrusion into existing or future buildings. Closure of the case under *No Further Action* letter should be considered regardless of contaminant concentrations in groundwater if long-term groundwater monitoring data indicate that the plume is not migrating away from the release area above levels of concern and soil gas data rule out the potential for significant methane buildup or vapor intrusion concerns.

Wells that will no longer be used to monitor groundwater must be properly abandoned. Documentation on well abandonment must be submitted to HDOH for inclusion in the public file.

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Table 1. Recommended Target Analyte List For Petroleum Products

Petroleum Product	**Media**	**Recommended Target Analytes**
Gasolines	Soil	TPH, benzene, toluene, ethylbenzene, xylenes (BTEX), naphthalene, MTBE and appropriate additives and breakdown products (e.g., DBA, TBA, lead, etc.)
	Soil Gas	Same as soil plus methane
	Groundwater	Same as soil
Middle Distillates (diesel, kerosene, stoddard solvent, heating fuels, jet fuel, etc.)	Soil	TPH, BTEX, naphthalene, methylnaphthalenes (total 1- and 2-)
	Soil Gas	Same as soil plus methane
	Groundwater	Same as soil
Residual Fuels (lube oils, hydraulic oils, mineral oils, transformer oils, Fuel Oil #6/Bunker C, waste oil, etc.)	Soil	TPH, *VOCs, naphthalene, methylnaphthalenes plus remaining 15 priority pollutant PAHs, plus PCBs and heavy metals unless otherwise justified
	Soil Gas	TPH, VOCs, naphthalene, methylnaphthalenes, methane
	Groundwater	same as soil

*VOC: Volatile Organic Compounds, including BTEX and chlorinated solvent compounds

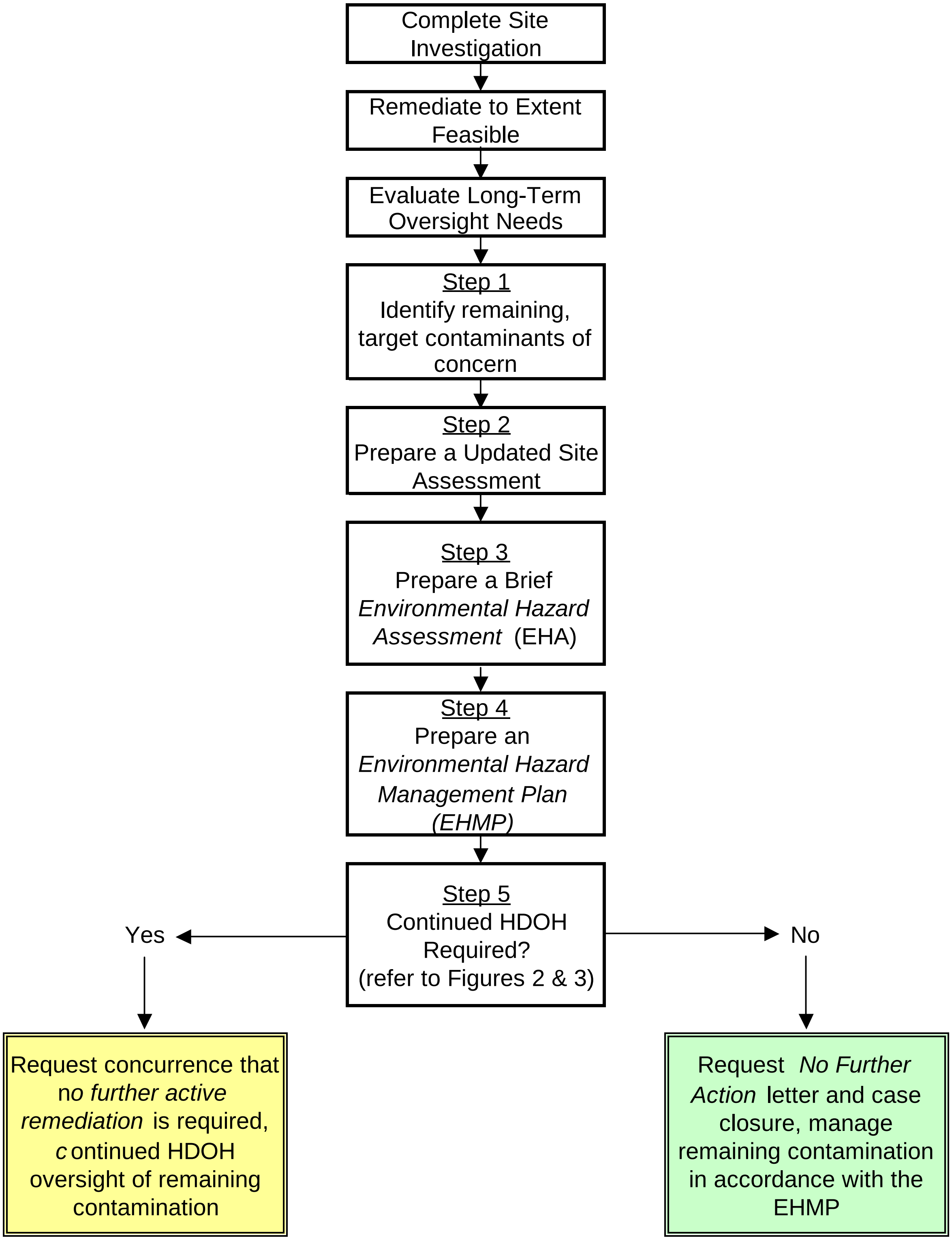

Figure 1. Overview of procedure to determine need for continued, HDOH oversight at sites with remaining petroleum contamination in soil or groundwater above HDOH EALs (or other approved action levels).

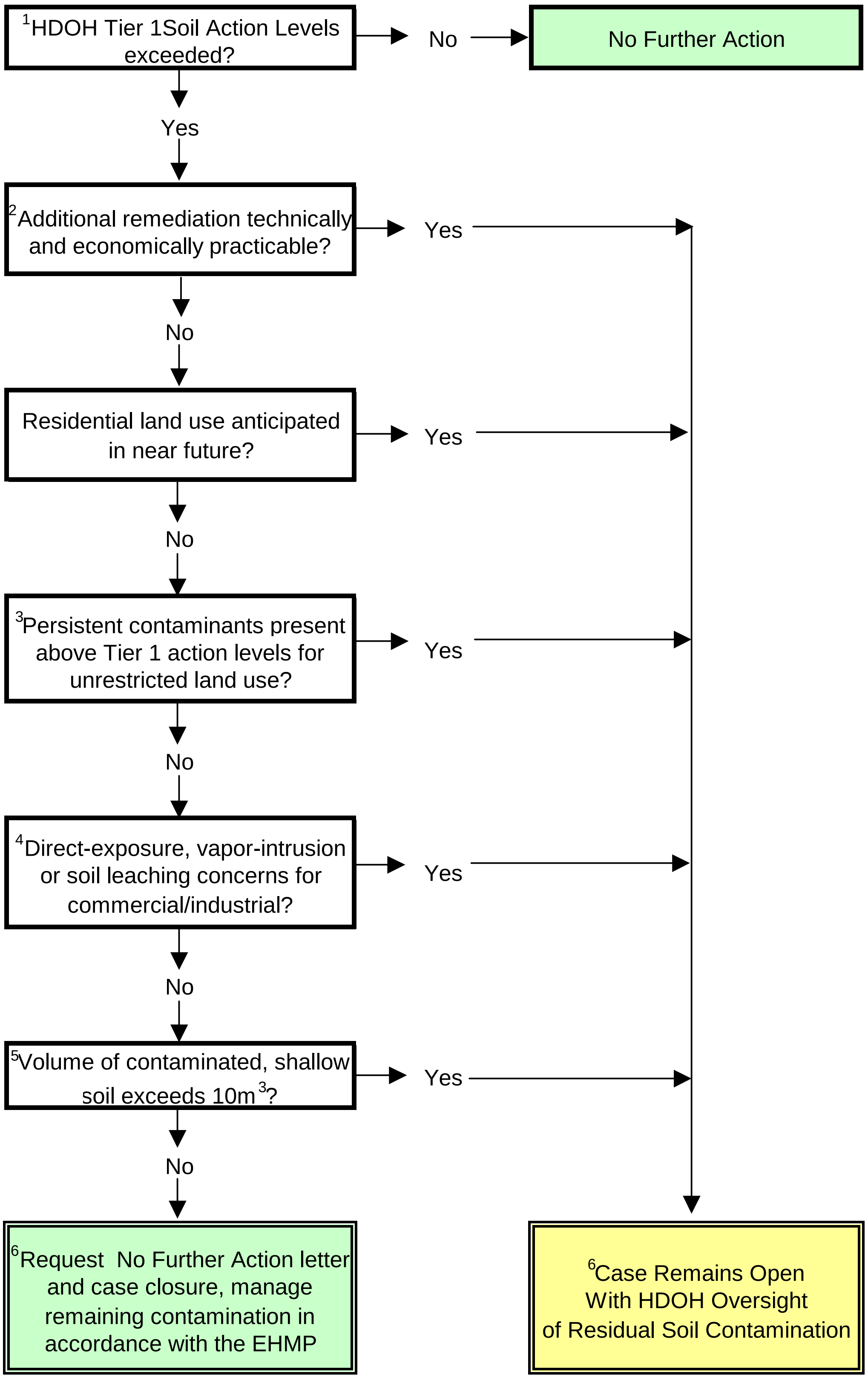

Figure 2. Decision path for long-term oversight of petroleum-contaminated soil following active remediation to extent practicable.

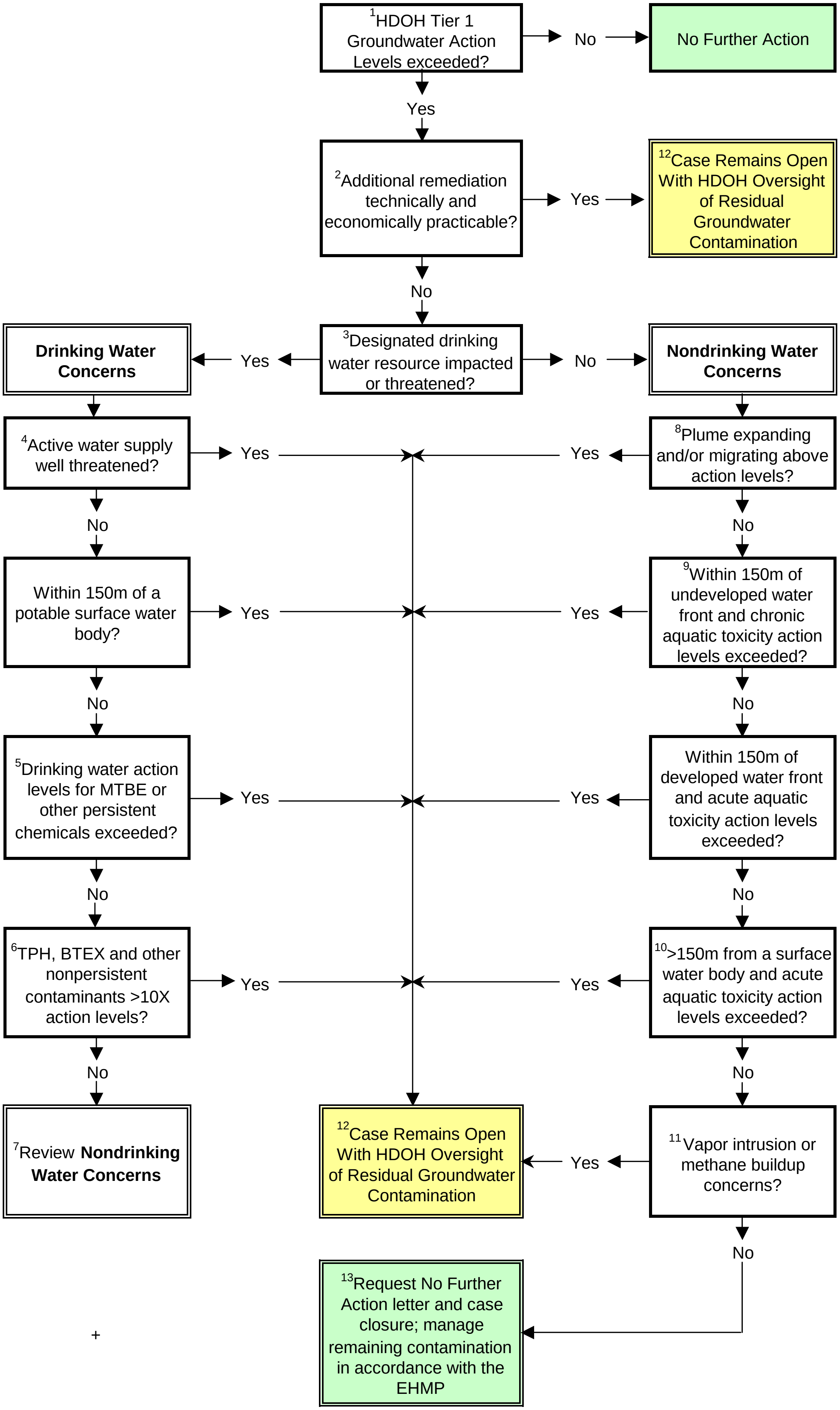

Figure 3. Decision path for long-term oversight of petroleum-contaminated groundwater following active remediation to extent practicable.

Figure footnotes

Figure 2 – Residual soil contamination:

1. Based on comparison of representative contaminant concentrations to HDOH Tier 1 EALs or approved, alternative action levels. "Soil" refers to any unconsolidated media situated above groundwater and does not include soil in the capillary fringe zone or in a smear zone associated with a fluxuating water table. Use groundwater data to evaluate potential concerns posed by soils situated below water table or within capillary fringe zone or groundwater smear zone.
2. Technical and economic practicability of additional cleanup should be discussed with HODH on a case-by-case basis.
3. MTBE, heavy metals, PCBs, chlorinated solvents, etc.
4. Commercial/industrial HDOH EALs for direct-exposure, vapor-intrusion exceeded and/or action levels for leaching concerns exceeded (or approved, alternative action levels) and engineered controls (pavement, etc.) not adequate to prevent exposure or leaching.
5. Shallow soils defined as soils within three meters (approximately ten feet) of the ground surface (HDOH 2005a). Closure of cases with greater volumes of contaminated soil left in place possible is based on a case-by-case review with HDOH.
6. No Further Action. Submittal of updated site assessment, *Environmental Hazard Assessment* and *Environmental Hazard Management Plan* required. Manage remaining contamination in accordance with the *EHMP*.
7. Case remains open under HDOH oversight. Submittal of updated site assessment, *Environmental Hazard Assessment* and *Environmental Hazard Management Plan* required. Option to petition HDOH for *No Further Remedial Action Required* letter.

Figure 3 – Residual groundwater contamination:

1. Based on comparison of representative contaminant concentrations to HDOH Tier 1 EALs or approved, alternative action levels.
2. Technical and economic practicability of additional cleanup should be discussed with HODH on a case-by-case basis.
3. Inland of UIC line or based on published groundwater resource reports.
4. Plume is within 1,000 feet in the upgradient direction of an active, producing water supply well and within producing aquifer (closer review of the potential threat to water supply wells may be required on a case-by-case basis).
5. Contaminants such as MTBE and chlorinated solvents that are known to degrade very slowly in the environment under natural conditions. Contaminant level as exhibited by current monitoring data or projected five-year degradation curve.
6. Contaminants such as TPH and BTEX that are known to rapidly degrade in the environment under natural conditions.
7. Refer to decision pathway for potential environmental concerns not directly related to drinking water.
8. Plume expanding and/or migrating above action levels, includes potential offsite migration via storm sewers, utility corridors, etc.
9. Within 150m of a sensitive aquatic habitat, generally including streams and shoreline areas that have not been significantly altered by culverts, shoreline development, etc., or otherwise protected habitat areas.
10. Consider No Further Action regardless of contaminant concentrations if plume is not migrating, area of remaining free product $<100m^2$, no vapor intrusion or methane buildup concerns and depth to groundwater is greater than five meters (see text).
11. Vapor intrusion or methane buildup concerns in the absence of engineered controls.
12. Case remains open under HDOH oversight. Submittal of updated site assessment, *Environmental Hazard Assessment* and *Environmental Hazard Management Plan* required. Option to petition HDOH for *No Further Remedial Action Required* letter.
13. Case closed. Submittal of summary report, *Environmental Hazard Assessment* and *Environmental Hazard Management Plan* required. No further monitoring required. Manage remaining contamination in accordance with the EHMP.

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ADVISORY ON
METHANE ASSESSMENT AND COMMON REMEDIES AT SCHOOL SITES

SCHOOL PROPERTY EVALUATION AND CLEANUP DIVISION
DEPARTMENT OF TOXIC SUBSTANCES CONTROL

This document is released as an advisory subject to review and revision as necessary. The information in this advisory should not be considered enforceable or regulatory in nature (i.e., this advisory does not have the force or effect of law). Mention of trade names or commercial products does not constitute DTSC's endorsement or recommendation.

Advisory Contents

1.0 INTRODUCTION

This advisory provides guidance on investigations and common remedies for school sites where methane gas is the only chemical of concern present in subsurface soils. This advisory may be used to supplement remedies for sites with multiple contaminants in soil gas, e.g., hydrogen sulfide or volatile organic compounds (VOCs), in addition to methane. However, care should be taken to address the risks associated with the other contaminants. For example, passively venting methane on a site may be appropriate, but the presence of hydrogen sulfide commingled with methane may make passive venting unacceptable.

Methane is considered a naturally-occurring hazardous material under Education Code section 17210.1. If a response action is necessary to address the presence of methane, a Removal Action Workplan (RAW) or Remedial Action Plan should be submitted for DTSC review and approval pursuant to Health and Safety Code section 25356.1. Most response actions at school sites will be removal actions, pursuant to a RAW. Whenever a removal action has an impact on the design of a school facility, DTSC will notify the Division of the State Architect (DSA) and specify conditions for the RAW to be properly implemented during the school construction pursuant to Education Code section 17213.2, subsection (g).

This advisory provides a consistent statewide approach in addressing methane-only concerns. However, due to the variability of local regulations and site-specific conditions, compliance with all applicable or relevant and appropriate requirements (ARARs), e.g., applicable federal, state or local laws, regulations, ordinances or building codes for methane is required. In addition, compliance with the requirements of utility (e.g., power) companies regarding gas mitigation measures for vaults, transformers, electrical conduits, or other improvements is needed.

2.0 METHANE HAZARDS AND RECOMMENDED ACTION LEVELS

Methane is lighter than air, colorless, odorless, non-carcinogenic**,** and flammable. When methane is mixed with other gases, e.g., carbon dioxide, hydrocarbons, the methane gas mixtures typically have densities comparable to, or less than, air. Methane occurs as natural gas in coal mines, oil and gas fields, and other geological formations; as a byproduct of petroleum refining; and as a product of decomposition of organic matter in natural settings (e.g., wetlands), and man-made settings (e.g., landfills, engineered fill, hydrocarbon waste, food processing facilities, sewer lines, septic systems, dairies and concentrated animal feedlots).

There are two primary mechanisms by which methane is produced. Thermogenic methane is generated at depth under elevated pressure during and following the formation of petroleum (e.g., in oil fields). Biogenic methane is formed at relatively shallow depths by the bacteriological decomposition of organic matter in the soil (e.g., in landfills). Biogenic methane is rarely found under a pressure in excess of a few inches of water.

The primary mechanisms for methane migration in the subsurface are pressure driven flow and diffusion. Methane will migrate from areas where it is present at higher pressures or concentrations to areas where it is present at lower pressures or concentrations. Since methane is lighter than air, it has a tendency to rise from depth to the ground surface where it dissipates into the atmosphere. Where a relatively impermeable barrier, e.g., a concrete slab, is present at the ground surface, the potential exists for methane to accumulate beneath that barrier.

2.1 Methane Hazards

Methane is an asphyxiant and is combustible and potentially explosive when it is present at concentrations in excess of 53,000 parts per million by volume (ppmv) in the presence of oxygen. This concentration is referred to as the Lower Explosive Limit (LEL). In order to provide some margin of safety, a concentration of approximately ten percent (10%) of the LEL or 5,000 ppmv is commonly utilized as an “action level” above which mitigative measures are recommended. Where it is present at concentrations in excess of 5,000 ppmv, it is often conservatively presumed that methane may infiltrate through flooring material or cracks, accumulate under footings and in enclosed spaces (e.g., small rooms, vaults, wall spaces), and then cause a fire or explosion when an ignition source (e.g., pilot flame, electrical spark, cigarette) is present.

For the purposes of this advisory, a methane hazard is defined as an accumulation, or the potential accumulation, of methane in the subsurface immediately beneath the footprint of an existing or proposed school building, including associated improvements, at concentrations in excess of 5,000 ppmv.

2.2 Recommended Action Levels for Methane Concerns

A. The following screening levels may be used as a guide for further action on school sites where methane is the only chemical of concern, present in subsurface soil. These levels are, in part, based upon a survey of local regulations and ordinances:

1. Methane detection of 1,000 ppmv (a cautionary value) – Further investigation is recommended to determine the extent of methane in subsurface soil, potential source, and/or soil lithology.

2. Methane detection of 5,000 ppmv (10% of the LEL) – Further response action (e.g., periodic monitoring, removal action) may be needed.

3. Methane pressure of 0.1 pounds per square inch (psi), 2.8 inches of water, or 0.2 inches of mercury – Further investigation is recommended to determine the extent of methane in subsurface soil, potential source, and/or soil lithology.

4. Methane pressure of 0.5 psi, 13.9 inches of water, or 1 inch of mercury – Further response action (e.g., periodic monitoring, removal action) may be needed.

B. While specific remedies are not discussed herein for sites where subsurface methane levels fall between 1,000 and 5,000 ppmv or methane pressures are between 0.1 to 0.5 psi, a combination of enhanced interior ventilation systems (e.g., blower with a larger capacity), conduit seals, utility trench dams, and other easily installed mitigative improvements should be considered for structures on these sites based on site-specific conditions.

3.0 METHANE ASSESSMENTS

A potential problematic accumulation of methane within a structure may be caused by the following conditions:

- Methane concentration in excess of 53,000 ppmv and sufficient volume to produce elevated gas levels on the interior of the structure; or
- An elevated gas pressure (e.g., 0.1 psi) to induce flow into the building.

Although methane will accumulate under appropriate conditions, methane typically does not accumulate to a concentration that exceeds the maximum concentration of the source. Accordingly, the source(s) of methane at a site should be determined. The maximum concentration of methane associated with each source may need to be identified through the installation and monitoring of subsurface gas probes. It should be recognized that multiple sources may be present. In addition, any subsurface methane investigation needs to screen for the possible presence of large zones of methane accumulation, or smaller zones where gas is present at elevated pressures.

Any methane investigation should be conducted to determine the nature and extent of methane concerns, consistent with the current version of DTSC's "Advisory – Active Soil Gas Investigations, dated January 28, 2003 (ASGI)." Rationale should be provided for the proposed sample number, locations, depths, and analyses.

3.1 Methane Investigation Strategy

A methane investigation strategy generally includes the following:

A. Methane sampling depths generally include five (5) and 15 feet, and may extend to 40 feet, below ground surface (bgs), as appropriate. Deeper probes may be necessary, depending on site conditions.

B. Methane sampling spacing generally requires a 100-foot grid system to screen the site. In potential source areas or areas with known high methane concern (e.g., settling pond areas, manure pile areas), a higher density sampling should be conducted. Step-out samples and, if appropriate, off-site samples should be collected up to 200 feet away from a proposed or existing structure.

C. Consideration should be given to field conditions (e.g., irrigation, fine grained sediments), weather conditions (e.g., rising barometric pressure, high wind speeds of 25 miles per hour or more, significant rainfall events of ½ inch or greater) which may affect collection of methane data.

D. The detection limit for methane analysis should not exceed 500 ppmv (see Sections 8.5.D and F).

E. The use of a properly calibrated hand-held instrument for methane monitoring is acceptable. When a hand-held instrument is used to measure methane concentrations, DTSC recommends at least 10 percent of all positive methane samples (with methane concentrations of 5,000 ppmv or greater), rounded to the nearest whole number, be confirmed by another hand-held instrument (different unit or different brand) or by a gas chromatograph method (on-site or off-site).

F. At sites where methane is detected at a level of 5,000 ppmv or above, fixed gas (oxygen and carbon dioxide) data and barometric pressures should be obtained.

G. At sites where the presence of hydrogen sulfide or volatile organic compounds (VOCs) is suspected (e.g., oil fields, landfills), hydrogen sulfide or VOC data should also be obtained.

H. Accurate molar ratios of alkanes to alkenes, presence or absence of carbon dioxide, presence or absence of hydrogen sulfide, presence of ethanes, propanes and butanes, and isotopic abundance analyses ($^{13}C/^{12}C$ and D/H ratios) can be used to differentiate methane generation sources (e.g., thermogenic, biogenic origins).

I. Soil parameters (e.g., soil grain size, porosity, moisture, bulk density, total organic carbon content, vapor permeability, soil redox potential) may be required to fulfill design requirements of the mitigation measures (see Sections 3.2, 5.3.A.2 and 5.4.A.1).

3.2 Evaluation of Fill Materials

When import soils are necessary, the current version of DTSC's "Information Advisory – Clean Imported Fill Material" should be followed to evaluate for the presence of contaminants prior to use as fill material. The fill material should also be evaluated for the presence of elevated total organic carbon (TOC). When the fill depth is anticipated to be 10 feet or thicker, any import fill source with TOC of 0.5% or above should be rejected or a methane evaluation should be conducted at least 30 days after fill placement and compaction.

All available data regarding fill materials emplaced onsite should be evaluated for potential presence of contaminants. When fill depth exceeds 10 feet, the soil should also be evaluated for the potential presence of methane or methane generation. If TOC or methane data regarding the fill material is not available, or if methane concern can not be ruled out for the fill material with proper justifications, it is advisable to collect and analyze two (2) soil samples (at 5-foot bgs and the inter-phase between native soil and fill material) for TOC, or two (2) soil gas samples (at 5- and 15-foot bgs) for methane, for each 5,000 square feet of proposed building footprint. TOC data may be obtained during a geological and soil engineering study required by Education Code section 17212.5, or during a Phase I Environmental Site Assessment required by Education Code section 17213.1. See Section 5.2.A.2 for more information.

4.0 METHANE RESPONSE ACTION OBJECTIVES

Response Action Objectives (RAOs) should be protective of human health, the environment and public safety. The primary RAOs for a site with methane as the only chemical of concern may include the following:

- Reduce or monitor the potential for methane accumulation underneath proposed and/or current structures, not necessarily to remove the source as for normal response actions;
- Remove or treat impacted soils that contain methane at a concentration of 5,000 ppmv or above;
- Minimize the potential for migration of methane from the site to other areas; and/or
- Obtain a certification by DTSC as specified in Section 7.0 for the site, after completion of the response action and prior to any school occupancy.

Additional RAOs should be provided based on site-specific conditions.

5.0 COMMON REMEDIES FOR METHANE SITES

Any potential changes in site conditions that could have a significant impact on the subsurface methane concentration should be discussed and evaluated. Those areas for which the potential exists for methane to accumulate to the LEL immediately beneath a school building or associated improvement should require mitigation (see Section 2.2.A).

Most response action activities at school sites have historically been removal actions, which require a RAW. Based on historical patterns of remedy selection for sites where methane is the only chemical of concern and DTSC's scientific and engineering evaluation, DTSC has considered four (4) remedies to be common remedies for subsurface methane. They were selected based on an evaluation of three technology evaluation criteria: effectiveness, implement ability, and cost. These remedies may be used for methane-only sites, based on site-specific conditions. However, other remedies may be proposed for DTSC review and approval. Based on site-specific conditions, additional methane detection or reduction measures (e.g., a combination of gas monitoring, gas control, sensors, alarms, conduit seals, utility trench dams, enhanced ventilation systems) may also be needed.

When the approved remedy for a site requires long-term Operation and Maintenance (O&M) activities, DTSC will enter into an O&M Agreement with the school district prior to site certification. Once signed, this enforceable document requires the school district to implement the required O&M activities in accordance with an approved O&M Plan under DTSC oversight (see Section 7.0).

All design, construction, or O&M activities associated with methane remedies should be conducted or supervised by a methane engineer. For the purposes of this advisory, the methane engineer is a professional engineer (e.g., Civil or Geotechnical Engineer) licensed in California and experienced in methane investigation and mitigation for protection of structures.

The following four (4) common remedies have been identified:

- Excavation of Shallow or Limited Methane Sources
- Methane Monitoring Program
- Methane Collection and Passive Vent System (Without Membrane)
- Methane Collection, Membrane and Passive Vent System

5.1 Excavation of Shallow or Limited Methane Sources

Example: Soil excavation at a site where a shallow (e.g., less than 10 feet in depth) or limited (e.g., less than 5,000 cubic feet in volume) methane source is identified and excavation is economically and practically feasible.

This remedy is the excavation and disposal of organic-rich soils where methane gas is generated in excess of 5,000 ppmv. This remedy may be proposed for shallow or limited methane sources where a cleanup below the action level specified in Section 2.0 is economically and practically feasible. The purpose of this remedy is to remove the organic matter which provides a food source for the bacteria that produce the methane. To be an acceptable remedy, it should provide a permanent solution to reduce subsurface methane levels and any associated threat to human health and safety.

All excavations should be backfilled with clean fill material (see Section 3.2). Consideration should be given to the presence of additional sources and onsite migration of methane from offsite sources when considering this alternative.

5.2 Methane Monitoring Program

Example: Methane monitoring at a joint-use city park adjacent to a school

This monitoring program involves the installation and monitoring of gas probes which provide a means of identifying the extent, distribution, concentration, and pressure of combustible gas in the subsurface. A methane monitoring program may be acceptable in place of other mitigative actions for low risk areas of concern (e.g., open space areas where the potential for methane accumulation to problematic levels is shown to be low).

A. Monitoring Program Considerations

Considerations for this monitoring program include:

1. If only a monitoring program is proposed as a precautionary measure for a school site (e.g., for open space areas), DTSC may recommend the school district enter into an O&M agreement with DTSC. In this case, a RAW may not be required;

2. Open space areas of concern will be subject to review and/or approval by DTSC whenever there is a site condition change (e.g., grading or addition/modification of a structure). Aerobic conditions in the subsurface soil will cause methane to be consumed or degraded by methanotropic bacteria. Elevated levels of carbon dioxide in the subsurface soil are typically indicative of the ongoing biodegradation of organic matter in an aerobic environment. This can make it difficult to estimate the methane concentration after the site is developed. The absence of methane does not mean that elevated levels of methane will not occur in the future. Because the distribution of the organic material, oxygen and soil moisture may be altered by grading activities, school sites that have, or may potentially have, methane gas associated with biodegradation of organic material entrained within the soil, may require reassessment of soil and soil gas conditions after completion of the mass (rough site) grading activities. The placement of fill containing elevated levels of organic matter can result in higher and/or more extensive post-grading methane levels; and

3. Buildings, paved surfaces, and irrigated fields can affect air diffusion and barometric pumping through the soil. The improvements also act to block methane venting. Oftentimes the building becomes the easiest vent point because the vent trenches and pipes installed below the building provide a relief point. Therefore, the installation of hard-scape covering 5,000 square feet (ft^2) or more within fifteen (15) feet of any structure of concern may require the installation of methane mitigation improvements (e.g., methane collection and passive venting systems), in addition to a methane monitoring program, to protect the structure.

B. <u>Design of Methane Monitoring Program</u>

When a methane monitoring program is proposed, a detailed outline for the program should be prepared and submitted to DTSC for review and approval. The outline should specify monitoring procedures, locations, frequencies, and equipment. A contingency plan should also be provided along with a description of the conditions (e.g., action levels) at which the contingency plan would be implemented. See Sections 8.2 and 8.5 for recommendation on O&M frequency and contingency plan, respectively. The design of the methane monitoring program should incorporate the following considerations:

1. Monitoring of subsurface gas probes should include the measurement of the concentrations of methane, oxygen, and carbon dioxide as well as the measurement of the gas pressure within the probe and the barometric pressure at the time of the monitoring. For oil fields, landfills, or other sites where the presence of hydrogen sulfide is suspected, analysis of hydrogen sulfide should also be included;

2. Periodic monitoring of combustible gas levels along the ground surface in open areas, within crawl spaces beneath a structure, and/or inside a building may also be included as part of this program; and

3. All gas probes should be properly secured, capped and completed to prevent infiltration of water and ambient air into the subsurface and to prevent accidental damage or vandalism of the probes. Replacement or repair may be needed due to the conditions of the gas probes or disturbance due to construction activities. For probe surface completions, the following components should be installed:

    a. Surface seal;

    b. Utility vault or meter box with ventilation holes and lock; and

    c. Gas-tight valve or fitting for capping the sampling tube.

C. Operation and Maintenance Requirements

If an O&M agreement is developed, typical O&M activities that may be required under this agreement include the following:

1. Routine inspection of the area of concern (including multi-stage gas probes) to ensure there are no signs of degradation of the gas probes and no significant site condition changes; and

2. Routine monitoring of gas probes and surface sweeps with a Flame Ionization Detector to determine if significant changes in subsurface gas concentrations or pressure have occurred.

See Section 8.2 for recommendation on O&M frequency.

5.3 Methane Collection and Passive Vent Systems (Without Membrane)

Example: Retrofit existing classroom buildings with methane mitigation.

This mitigative approach involves the installation of a sub-slab collection and passive vent system to retrofit existing structures where installation of a membrane system is not feasible.

A. Design Requirements

The following recommendations should be incorporated in the design of a methane collection and passive vent system:

1. Methane Monitoring Program

   All design recommendations for a methane monitoring program specified in Section 5.2 are generally applicable.

2. Collection Pipe Spacing and Diameter

   Soil properties (e.g., soil gas transmissivity and diffusivity coefficients) should be considered in the spacing of the sub-slab collection piping system. At a minimum, a methane collection pipe system should be placed such that all points immediately beneath the slab are located within 20 feet of a collection pipe. The subsurface gas collection pipes should be perforated and two (2) inches in diameter (or greater). Flat drains may be used as an alternative to round collection pipes.

3. Collection Pipe Layout

   The gas collection piping should be installed within horizontal, or near horizontal trenches excavated beneath the building which is to be protected. The collection piping should extend the full width of the building and be located no more than five (5) feet beneath the ground surface. The piping system should be connected using threads, not solvent-welded. The need for drainage or de-watering improvements to prevent flooding of any portion of the collection/vent piping should be evaluated and suitable improvements should be installed, as necessary, to insure the proper operation of the collection pipe system.

4. Vent Riser Design

The underground gas collection pipes should be connected to solid vent risers that extend above the building. The vent risers should be equipped with a sampling port and fitted with a non-restricting rain guard to prevent precipitation and debris from entering the piping system. Vent risers should be properly secured (e.g., enclosed within wall cavities or pipe chases) to protect them from damage. A minimum of two (2) vertical vent risers (equivalent two 2-inch diameter) for the first 10,000 ft^2 of building foot print area and one additional vertical vent riser for each additional 10,000 ft^2 of building foot print should be provided. Vent risers should terminate at least two (2) feet above the non-combustible roof of the structure, at least 10 feet away from any window or air intake into the building, and at different elevations to promote methane ventilation.

5. Vent Riser Diameter

Each vent riser piping should consist of two (2)-inch diameter cast iron pipes or equivalent. The size of the vent risers may be reduced to 1-1/2 inches where necessary for structural reasons – provided additional vent risers are installed to provide a flow capacity equivalent to the appropriate number of 2-inch diameter vent risers. Table 1, included as Attachment A, shows the relative flow capacity of different size vent risers.

6. Utility Trench

Utility trench dams should be installed as a precautionary measure to reduce the potential for methane to migrate beneath a structure through the relatively permeable trench backfill whenever new or replacement utility lines (e.g., water, sewer, plumbing, phone, electrical, cable, gas) are installed beneath the building foundation. A relatively impermeable dam or plug constructed of compacted soil (a minimum of 90% compaction), bentonite-soil mixture, sand-cement slurry, or equivalent, should be installed in all utility trenches that are backfilled with sand or other permeable material during new or replacement installation of utility lines. These dams should extend for a distance of at least five (5) feet from the perimeter of the structure and from at least six (6)-inches above the bottom of the perimeter footing to the base of the trench.

7. Conduit Seals

   Conduit seals should be provided at the termination of all utility conduits to reduce the potential for combustible gas migration along the conduit to the interior of the building. These seals should be constructed of inert gas-impermeable material [e.g., closed cell expanding polyurethane foam (EPF), EYS fitting] in compliance with National, California and local Electrical Codes. If closed cell EPF is utilized to construct the seal in unclassified areas (as defined below), the EPF should be located at, or near, the termination of the conduit and it have a minimum length of six (6) conduit diameters or six (6) inches, whichever is greater.

8. Underground Conduits: Buried conduits should be treated according to the appropriate requirements of the National, California and local Electrical Codes. Proper classification of the subsurface soil is important to properly design the underground conduit. The following guidelines are suggested for determining electrical classification, based on the methane content in surface soils in the area within 200 feet horizontally of a structure. The deepest part of structure is extended by any man-made potential pathways (e.g., sub-drains, elevator pistons) below the structure. The actual classification should be reviewed by an environmental assessor [as defined in Education Code section 17210(b)] in conjunction with a professional electrical engineer licensed in California to make specific recommendations for electrical classification.

   a. Unclassified areas

      Subsurface soil classification is not required:

      i. if methane concentrations in subsurface soil are not greater than 12,500 ppmv (1.25%) or methane pressures are less than one (1) psi from ground surface to 20 feet below the deepest part of a structure; and

      ii. if methane concentrations in subsurface soil are not greater than 50,000 ppmv (5%) or methane pressures are less than one (1) psi at depths deeper than 20 feet below the deepest part of a structure.

   b. Class 1 Division 2 Group D

      Subsurface soil should be classified as Class 1 Division 2 Group D:

        i. if methane concentrations in the soil are between 12,500 ppmv (1.25%) and 50,000 ppmv (5%) or methane pressures are at one (1) psi or larger from ground surface to 20 feet below the deepest part of a structure; or

        ii. if methane concentrations in the soil are greater than 50,000 ppmv (5%) or methane pressures are at one (1) psi or larger at depths deeper than 20 feet below the deepest part of a structure.

    c. Class 1 Division 1 Group D

    Subsurface soil should be classified as Class 1 Division 1 Group D if methane concentrations in the soil are not less than 50,000 ppmv (5%) from 0 to 20 feet below the deepest part of a structure.

9. Air Emission Permits

Permits or authorizations from the local air pollution control district (APCD) or air quality management district (AQMD) are typically not required for a passive methane collection and venting system (i.e., passive venting of non-landfill methane) that exhausts to atmosphere. However, the local APCD or AQMD should be consulted to determine if compliance with air emission requirements is necessary.

B. Operation and Maintenance Requirements

Typical O&M activities for the improvements described above may include:

1. Routine inspection of the area of concern, including all visible components of the methane venting systems and the multi-stage gas probes, to ensure there are no significant site condition changes and no signs of degradation of the methane remedy system components;

2. Routine monitoring of designated gas probes, lowest accessible floor and enclosed areas of the structures of concern, and grade surface areas to ensure there are no potentially significant changes in subsurface gas concentrations or pressure;

3. Routine monitoring of vent risers for flow rates and gas concentrations to confirm the methane venting systems are functioning as intended; and

4. Other activities, e.g., routine maintenance, calibration and testing of functioning components of the methane venting systems in accordance with the manufacturers' schedule and recommendation, if appropriate.

See Section 8.2 for recommendation on O&M frequency.

C. Special Recommendations for High-Risk Sites

An active collection and vent system or an equivalent system should be considered for **high-risk sites** where a **sustained** soil methane pressure of one (1) psi or above is confirmed. Permits or authorizations from the local APCD or AQMD are typically required for an active methane collection and venting system that includes a fan or a blower, depending on the rate of extraction, the gas composition, etc. Consultation with the local APCD or AQMD for specific requirements is necessary.

For sites where subsurface methane concentrations are above the LEL and a subsurface gas pressure of one (1) psi or more is present, the school site should be carefully evaluated and a deep well pressure relief/vent system or other improvements, which reduce or eliminate subsurface gas levels and/or pressures, should be considered in addition to the building protection system. Mitigation of the elevated gas pressures at these sites may be required as a condition of site approval.

NOTE: Any existing school located within 1,000 feet of a landfill or 100 feet of an oil well (abandoned, inactive or active) should be carefully evaluated as a high risk site.

5.4 Methane Collection, Membrane and Passive Vent Systems

Example: New classroom buildings, where remedies will be installed concurrently with building constructions.

This new structure improvement remedy involves installation of a passive sub-slab methane collection and vent piping and a membrane system for new structures.

A. Design, Operation and Maintenance Requirements

All considerations for the existing structure retrofit remedy (specified in Section 5.3) are also generally applicable for this new structure improvement remedy, except that:

1. If an appropriate permeable bedding material is provided for the collection piping (e.g., sand or gravel), evaluation of native soil permeability characteristics may not be necessary for the pipe spacing design.

2. Gas Barrier/Membrane System should meet the following requirements:

    a. Gas membranes should be constructed with approved materials and thicknesses, e.g., 60-mil or 0.060 inches of high-density polyethylene (HDPE), 100-mil or 0.10 inches of liquid boot or equivalent;

    b. Gas membranes should be placed a maximum of one (1) foot below the floor slab and a maximum of six (6) inches above the gas collection piping;

    c. Protective layers consisting of sand [at a minimum, two (2) inches or thicker] and geotextile [at a minimum, six (6) ounces per square yard] should be laid below and above the membrane;

    d. Without a careful evaluation and confirmation data to support the beneath footing passage, the membrane should not pass below footings and/or stiffener beams of the structure of concern due to seismic concerns;

    e. Gas tight seals (e.g., boots) should be provided at all pipe or conduit penetrations through membrane. Gas tight seals should be provided where the membrane attaches to interior and perimeter footings; and

    f. A smoke test of the membrane system (as recommended by the membrane manufacturer) should be conducted to ensure no leaks exist. Where leaks are identified, appropriate repairs should be undertaken and smoke testing should be repeated until no leaks are detected.

B. Perimeter Methane Monitoring

A perimeter methane monitoring system may be required to evaluate the potential for combustible gas to migrate onto, or off of, the site in question under some circumstances. The perimeter methane monitoring system should include a network of multi-stage soil gas monitoring probes, evenly spaced approximately 1,000 feet apart, and at a minimum of four (4) locations, along the perimeter of the site (between the property boundary and the outside edge of the membrane system). However, placement may vary in order to target permeable soils/features. The multi-stage sampling probes should be installed approximately 5 and 15-feet bgs (if possible, one above and one below the membrane liner elevation), depending upon the geology, depth of fill material, and depth of groundwater at each monitoring probe location.

C. Active Injection of Air Under Buildings

Injecting air into a methane collection system immediately beneath a membrane-protected structure in order to enhance methane venting may be considered, provided that a detailed design has been included so that:

- The system does not create increased pressures under the building that may force methane into the building or into unprotected neighboring properties or structures. Sensors to monitor subslab pressures should be considered.

- The amount of air injected is equal to or less than the flow from vent risers. Sensors to monitor vent riser gas flow should be considered.

- Utility trench dams are included to prevent methane from being forced into utility trenches, pavement subgrade and/or other conduits.

Although an air permit from local APCD or AQMD is typically not required for an active air injection system, the APCD or AQMD should be consulted to determine if compliance with air emission requirements is necessary.

6.0 DTSC METHANE MITIGATION PROJECT APPROVAL PROCESS

If the school district chooses to proceed with site remediation, a RAW as described in Section 25323.1 of the Health and Safety Code will be required to carry out the selected remedies. The typical RAW process may be followed for an excavation remedy or a methane collection and passive vent system remedy. The process for approving a methane RAW with a methane collection, membrane and passive vent system remedy is unique since the methane remedy must be implemented in the design and construction of the school facilities. Such a unique process is described in the following sections.

6.1 Methane RAW with Methane Collection, Membrane and Passive Vent System

Unlike excavation or other cleanup actions, structural improvement remedies for methane concerns should be incorporated into the new school construction design. In order for the methane RAW implementation to occur concurrently with construction of the school facility, DTSC's approval of the methane RAW project will be completed in five (5) phases as described below. A DTSC approval process matrix for all responsible parties is included as Attachment B.

A. Approval of a methane RAW based on an approvable 60% design;

B. Approval of final detailed designs;

C. Field oversight of methane RAW implementation;

D. Certification for school occupancy after approval of the RAW completion report, including final acceptance of the detailed as-built methane mitigation plans and certifications; and

E. Oversight of ongoing operation, maintenance and monitoring activities.

6.2 Approval of Methane RAW with 60% Design

DTSC may approve a methane RAW with a 60% design package that reflects the concepts, principles and proposed layouts of the structure improvement remedies. The school district should contact the Department of Education for issues concerning the state funding process.

The 60% design package should be complete for independent implementation without necessarily considering interface with, or interference by, other building elements or underground utilities. As an appendix to the RAW, the 60% design package should include 60% design plans, specifications, drawings and estimates, prepared by a methane engineer as specified in Section 5.0.

The 60% design package should provide information on construction procedures and materials, specify appropriate construction quality control requirements, identify the projected O&M requirements, and be formatted in accordance with Construction Specifications Institute (CSI) requirements (see website: http://www.csinet.org/). Sixty percent design drawings should detail the components of the methane mitigation systems with dimensions and include drawings for grading/paving, foundation, electrical, structural and mechanical elements which may impact or affect the remedial design of the methane mitigation systems.

At a minimum, three (3) sets of the RAW (including the 60% design package) should be submitted for DTSC review and 60% design approval. After completion of the required public participation activities and DTSC review, DTSC will approve the RAW.

6.3 Approval of Final Detailed Design

Prior to implementation of the approved methane RAW, a final design package should be completed according to the approved methane RAW. The methane engineer (as specified in Section 5.0) will work with the project architect and DSA to conduct a “conflict/feasibility check” for accommodation of the local conditions, e.g., other building elements or utilities, determine the construction dimensions, select the precise locations for the proposed system layout, and prepare final construction drawings. This final design package, including 100% design specifications and drawings, will address how the remedial system will be adapted and fitted to site-specific features. The final design package should be signed and stamped by the methane engineer (as specified in Section 5.0).

At a minimum, three (3) sets of the final design package should be submitted for DTSC review and approval for actual construction. Upon approval of the final design package, DTSC will inform the school district and the DSA. In addition, DSA approval of the final 100% design and drawings package is also needed prior to project bidding and construction.

6.4 Field Oversight

DTSC may provide field oversight during implementation of the RAW. A 48-hour written notification of the following activities should be provided to DTSC:

A. Remedy material acceptance;

B. Final grading and preparation;

C. Installation of sub-slab combustible gas collection piping system;

D. Installation of gas membrane systems;

E. Bedding and backfill;

F. Installation of vent piping system; and

G. Post construction testing, including smoke testing of seams and penetrations, vent riser flow monitoring, gas probe monitoring, indoor air monitoring, and vent capacity testing.

DTSC will organize a project team for each project to closely monitor the above activities. Team members may include project senior, project manager, geologists, engineers, scientists, and industrial hygienist. A checklist for field inspection is included as Attachment C. Additional requirements, changes or relocations may be deemed necessary during the field oversight activities. As part of the project quality assurance and quality control (QA/QC) program, an inspection and conformance program should be implemented by the school district.

6.5 Change Order(s) During Construction of Methane Remedies

When a change order is necessary during construction of methane remedies, the methane engineer (as specified in Section 5.0) should evaluate and determine the nature whether the change is minor or major. A major change means a substantial change to the design layout, material, operation, construction methods or costs (i.e., more than $5,000.00) of the approved system design. The school district may proceed with a minor change after receipt of verbal approval from DTSC. A written approval should be obtained from DTSC prior to implementing a major change. DTSC will expedite its review of a major change.

7.0 CERTIFICATION

Where DTSC requires a response action at a school site, Education Code section 17213.2, subsection (d)(2), provides that the school district may not occupy a school building following construction until it obtains a certification from DTSC. The certification indicates that post-RAW site conditions including ongoing O&M activities do not pose a significant risk to human health or the environment. DTSC will issue certification for school sites where O&M activities are required, when all of the following conditions have been met:

- Completion of all necessary response actions, except for ongoing operation and maintenance activities if required;
- Compliance with the approved response action standards and objectives;
- Issuance of DTSC approval of the RAW Completion Report, including detailed as-built methane mitigation plans, drawings and certifications; and
- Execution of a required O&M Agreement between the school district and DTSC for implementation of the approved O&M Plan.

The final O&M Plan, as modified and/or approved, should be implemented upon installation of mitigation measures, and remain in effect until DTSC releases the school district in writing from its implementation, pursuant to termination procedures specified in the O&M Agreement. At a minimum, a first run of O&M (inspection and monitoring) activities should be conducted as part of the RAW completion certification and data be included in the RAW Completion Report.

8.0 OPERATION AND MAINTENANCE

When the selected remedy includes long-term O&M activities, an O&M Agreement is required prior to site certification. The O&M Agreement is an enforceable document which requires the school district to implement the required O&M activities in accordance with an approved O&M Plan under DTSC oversight.

8.1 Operation and Maintenance Plan

An O&M Plan should be reviewed and approved by DTSC **prior to** site certification. The objective of the O&M Plan is to describe in detail the procedures required for continued operation and monitoring of the mitigation measures. The O&M Plan should include a detailed description of the mitigation system and its components, as well as comprehensive protocols for operation, monitoring, data acquisition, reporting, and maintenance activities. An outline of a typical O&M Plan is included as Attachment D. Main components of a typical O&M Plan are discussed in the following sections.

8.2 Frequency

The O&M activities should be performed, at a minimum, on a monthly basis and after each significant seismic event, following completion of construction. Specific O&M activities after a significant seismic event are recommended in Section 8.5.F. A significant seismic event is defined as below:

A. An earthquake of 5.0 on the Richter scale recorded at a seismometer station within 10 miles of the site; or

B. An actuation of an earthquake actuated automatic gas shutoff device/valve at the site during an earthquake.

Based upon site specific monitoring results and conditions, the frequency and/or scope of subsequent O&M activities may be modified (e.g., the frequency is changed from monthly to quarterly) in consultation with DTSC. Once the long-term performance of the methane mitigation system is confirmed and/or subsurface gas concentrations attenuate to non-regulated levels (based on the trend of O&M results), DTSC may allow all O&M activities be terminated after an evaluation of the latest five (5)-year review report (see Section 9.0).

8.3 Qualifications of Operation and Maintenance Personnel

All O&M activities should be performed by qualified personnel who have been properly trained and authorized to conduct such activities, under the direction and supervision of a qualified methane engineer (as specified in Section 5.0). The methane engineer should be familiar with the methane remedy system installed at the site.

8.4 Maintenance and Repair

The methane remedy system will not require maintenance under normal circumstances. If inspection and monitoring activities suggest the methane remedy system is in need of maintenance or repair, the school district should initiate appropriate action in consultation with DTSC.

Prior to any construction or repair activities that may affect the methane remedy system, the school district should submit a workplan to DTSC for review and approval. These activities may include, but are not limited to, addition of portable structures, removal of building floor slabs, penetrations through the gas membrane or any improvements that could expose gas membrane and/or vent piping, improvements or alterations to vent risers, subsurface permanent gas probes, or other components of the methane remedy system.

8.5 Contingency Plan

A Contingency Plan should be developed for use by school officials and O&M personnel to assist in selecting an appropriate response action and providing guidance in evaluating the concentration of methane in buildings and enclosed areas, exterior paved areas and exterior open areas. A copy of the Contingency Plan and all revisions to the plan should be maintained at the school and submitted to the DTSC, local fire authority and emergency response teams that may be called upon to provide emergency services. At all times, there should be at least one school employee either on the school campus or on call with the responsibility for coordinating all emergency response measures due to methane concerns.

In the event of contingencies, emergencies or failures of the methane remedy systems, the Contingency Plan should be activated and implemented.

DTSC recommends the following criteria be used to evaluate the safety of school occupants and initiate appropriate response actions, if needed:

A. Ventilation Layer Monitoring

If the concentration of methane gas in the ventilation layer (e.g., crawl spaces) beneath buildings, exterior paved areas and/or exterior open areas consistently exceeds two (2) percent of the LEL (i.e., 1,000 ppmv) for methane, the following immediate responses should be taken:

1. The indoor air exchange rate of the Heating, Ventilation and Air Conditioning (HVAC) system should be increased (e.g., to a level of at least two full air exchanges per hour); and

2. The affected buildings should be monitored until the elevated methane concentrations are reduced below 1,000 ppmv.

In addition, the level of ventilation in the crawl space or other areas where elevated methane concentrations are detected should be enhanced.

B. Vent Riser Monitoring

If a significant increase of 5,000 ppmv or more from the previous monitoring event, or exceeding of 12,500 ppmv, in methane concentrations is detected at vent riser outlets, the following responses should be taken immediately:

1. The building HVAC system should be activated to increase the air exchange within the building (e.g., to a level of at least two full air exchanges per hour);

2. A sweep monitoring of the lowest level interior spaces should be performed; and

3. DTSC should be notified within 24 hours of such an event and the monitoring frequency should be increased in consultation with DTSC (e.g., by a factor of two).

C. Subsurface Probe Monitoring

If a significant increase of 5,000 ppmv or more in methane concentrations, or 0.1 psi or more in methane pressure, from the previous monitoring event is detected at an onsite permanent subsurface probe, DTSC should be notified within 24 hours of such a detection and the monitoring frequency of subsurface probes should be increased in consultation with DTSC (e.g., by a factor of two).

D. Indoor Methane Monitoring

If indoor methane gas concentrations exceed 1% of the LEL (i.e., 500 ppmv) for methane, the following responses should be taken immediately:

1. The building HVAC system should be activated until a monitoring of the entire lowest level interior spaces confirms that methane concentrations are reduced and maintained below 500 ppmv; and

2. DTSC should be notified within 24 hours of such an event and the monitoring frequency should be increased in consultation with DTSC (e.g., by a factor of two).

E. Evacuation

If indoor methane gas concentrations exceed 10% of the LEL (i.e., 5,000 ppmv) for methane, the following responses should be taken immediately:

1. The local fire authority should be notified immediately;

2. The buildings should be evacuated until the source of the methane intrusion is identified and abated; and

3. DTSC should be notified within 24 hours of such an event and the monitoring frequency should be increased in consultation with DTSC (e.g., by a factor of four).

F. Significant Seismic Events

The following O&M (inspection and testing) activities should be conducted after each significant seismic event (as defined in Section 8.2):

1. Level I O&M Activities

   Conduct a visual inspection of interior and exterior of mitigated structures, including vent risers and conduit seals. Perform complete round of monitoring of any onsite gas probes or other methane monitoring devices. Identify, evaluate, and report any anomalies.

   If foundation displacement or structural damage is evident, or if a significant increase (e.g., more than 5,000 ppmv) in methane concentrations at methane gas probes or monitoring devices is detected, perform Level II O&M activities.

2. Level II O&M Activities

   Screen for elevated combustible gas levels on the interior of mitigated structures, and around the perimeter of the structure foundation. Take measurements during period of falling barometric pressure. Confirm positive outflow of soil gas at vent riser outlets during diurnal decrease in barometric pressure. Identify, evaluate, and report any anomalies.

   If a significant increase (e.g., more than twice of last detected concentration and more than 500 ppmv) in interior methane concentrations is detected, perform Level III O&M activities.

3. Level III O&M Activities

   Conduct a smoke test of the sub-slab vent system to confirm the Integrity of the methane remedy system with non-toxic smoke injected through vent riser outlets under a pressure of 4” to 6” of water. Confirm connectivity of all vent risers. Screen for emergence of smoke on interior of structure. Identify and repair ay leaks/penetrations in gas membrane or vent risers. Repeat smoke tests following completion of any repairs.

8.6 Operation and Maintenance Reports

An O&M report should be submitted to DTSC within 30 days after each O&M event (routinely scheduled or after each significant seismic event) to DTSC for review and approval. Reports should include:

A. Results of visual inspection;

B. Results of sample analyses and tests;

C. Description of actions taken since completion of the previous O&M event, including:

   1. Any repairs to gas mitigation improvements that were carried out or needed;

   2. Any significant changes in site conditions or usage, e.g., paving, grading, utility trenching, playgrounds, or picnic areas; and

   3. Any additional onsite construction or other significant information that may relate to the gas mitigation improvements or impact their function, e.g., installation of portables or maintenance facilities.

D. Description of any findings identified during the current O&M event; and

E. Description of actions planned or expected to be undertaken before the next O&M event.

DTSC will review each O&M report. Based upon the review, additional methane investigation, monitoring and/or mitigation may be required.

8.7 Five (5)-Year Review Report

A five-year review of the completed remedial or removal action should be conducted no less often than every five (5) years after initiation of the selected remedial or removal action. A five-year review report should be submitted within 30 days after each scheduled five-year review to DTSC for review and approval. Reports should include the following components: Introduction, Site Background, Site Chronology, Removal Actions, Progress Since Last Review, Five-Year Review Process, Technical Assessment, Issues, and Conclusions and Recommendations.

The technical assessment (of the protectiveness of the remedy) of the five (5)-year review should address the following questions:

A. Is the remedy functioning as intended by the decision documents?

B. Are the removal action objectives, goals and criteria used at the time of the remedy selection still valid?

C. Have there been any significant changes in the distribution, concentration, or pressure of the subsurface gas at the site?

D. Has any other information come to light that could call into question the protectiveness of the remedy?

DTSC will review each five (5)-year review report. Based upon the review, additional methane investigation, monitoring and/or mitigation may be required.

9.0 SYSTEM CLOSURE AND DECOMMISSIONING

Based on review of the first Five-Year Review Report or a subsequent O&M report, DTSC may determine if the methane mitigation system has met the following performance criteria required for termination of O&M activities:

- Methane concentrations of less than 5,000 ppmv in all onsite subsurface permanent gas probes have been consistently demonstrated at least twice and over one (1) year of monitoring;
- Methane concentrations of less than 500 ppmv in crawlspaces, utility boxes, and indoor air have been consistently demonstrated at least twice and over one (1) year of monitoring; and
- Methane concentrations of less than 1,000 ppmv in vent risers have been consistently demonstrated at least twice and over one (1) year of monitoring.

DTSC will notify the school district in writing when continued O&M activities of the methane mitigation system are no longer required. The methane mitigation system improvements are not anticipated to have an adverse impact on building foundation systems or other components. Accordingly, removal or decommissioning of the methane mitigation improvements following termination of the O&M activities of the methane mitigation system will not be required.

10.0 REFERENCES

Additional information may be found in the following documents:

A. Methane Mitigation Standards, City of Los Angeles, Department of Building and Safety (www.ladbs.org/rpt_code_pub/methane.htm), February 3, 2004

B. Development and Land Use Guideline for Combustible Soil Gas Hazard Mitigation, Guideline C-03, Orange County Fire Authority, Planning and Development Services Section, January 31, 2000 (www.ocfa.org/business/pandd/guidelin.htm)

C. San Diego County Code of Regulatory Ordinances, Title 8 Zoning and Land Use Regulations, Division 6, Chapter 3 Methane Gas Testing in the Unincorporated Areas of San Diego County (www.amlegal.com/sandiego_county_ca/)

D. Methane Mitigation Protocol (Vacant Lots), Riverside County Health Services Agency, Department of Environmental Health, July 27, 2001 (Contact: Chuck Strey at 909-955-4053)

E. Building Code 17.04.085, City of Huntington Beach, July 1999 (www.hb-building.org/)

F. Ordinance No. 96-769, Amending Chapter 15-08 (Fire Code), City of Yorba Linda

G. California Code of Regulations, Title 27, Division 2, Subdivision 1, Chapter 3.0, Subchapter 4, Article 6, Gas Monitoring and Control at Active and Closed Disposal Sites, California Integrated Waste Management Board

H. California Code of Regulations, Title 14, Chapter 4, Department of Conservation, Division of Oil, Gas, and Geothermal Resources

I. Preliminary Draft Soil Gas Mitigation Standard 3384, Summary Report, San Diego Gas and Electric, March 15, 2001

J. Advisory – Active Soil Gas Investigations, Department of Toxic Substances Control, January 2003 (www.dtsc.ca.gov/)

K. Interim Guidance for Active Soil Gas Investigation, California Regional Water Quality Control Board, Los Angeles Region, February 25, 1997

L. Information Advisory - Clean Imported Fill Material, Department of Toxic Substances Control, October 2001 (www.dtsc.ca.gov/)

M. Methane Gas Mitigation Discussion at DTSC for Woodcrest School, GeoKinetics, Inc., January 4, 2001

N. Preliminary Methane Gas Site Investigation and Mitigation Guidelines (Draft), GeoKinetics, Inc., March 22, 2002

O. Methane Gas Plan Protection System, County of Los Angeles, Department of Public Works, Environmental Programs Division (Contact: Mr. Carlos Ruiz at 626-458-3502)

O&M References:

A. DTSC Management Memo #EO-93-036-MM, titled “Operation and Maintenance Enforceable Agreement (02/07/94).”

B. Memo to Division Chiefs and Branch Chiefs from Stanley R. Phillipe, titled “Completions for Site Mitigation Program,” (06/19/95)

C. U.S. EPA Fact Sheet, titled “Operation and Maintenance in the Superfund Program,” OSWER 9200.1-37FS, EPA 540-F-01-004, May 2001

D. U.S. EPA Comprehensive Five-Year Review Guidance, U.S. EPA 540R-01-007, OSWER No. 9355.7-03 B-P, June 2001

E. U.S. EPA Fact Sheet, titled “Structure and Components of Five-Year Reviews,” Directive 9355.7-02FSI, August 1991

F. U.S.EPA Fact Sheet, titled “Five-Year Review Process in the Superfund Program,” OSWER Directive 9355.7-08FS, EPA 540-F-02-004, April 2003

FOR MORE INFORMATION

Please contact the following person if you need additional information or if you have comments:

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ATTACHMENT A

Table 1: Relative Flow Capacities of Methane Vent Risers

Pipe Diameter (Inches)	***Flow Capacity Relative to 2-Inch Pipe***
1.5	***46%***
2.0	***100%***
2.5	***181%***
3.0	***295%***
4.0	***635%***

Note: Relative Flow Capacities are for Standard Size, Nominal Diameter, Schedule 40 Pipe

ATTACHMENT B

DTSC APPROVAL PROCESS MATRIX

Methane Related Removal Action Workplan(s); Proposed Responsibility Matrix

	DESIGNER	DTSC	DSA	DIST - FAC	DIST - OEHS	ARCH	CONTRACTOR	IOR
Design System	P	O	-	R	M	R&S	-	-
Incorporate Design	S	-	O	R	R	P	-	-
RAW Approval	-	P	-	S	M	-	-	-
DTSC Design Approval	-	P	S	S	M	R	-	-
Plan Approval	-	-	P	M	-	S	-	-
Bid Documents	S	-	-	M	R	P	-	-
Construct System	O	O	-	M	O	O	P	I
Test System	O	O	-	M	O	-	P	S
O&M Plan + Agreement	R	P	-	M	R	-	-	-
RAW Certification	-	P	-	M	S	-	-	-
Certify School Occupancy	-	R	S	S	S	S	-	P

Definitions:

DESIGNER	Methane Mitigation System Engineer/Designer
DTSC	Department of Toxic Substances Control
DSA	Department of State Architects
DIST – FAC	District Office of Facility Management
DIST – OEHS	District Office of Environmental Health & Safety
ARCH	Project Architect
CONTRACTOR	Methane Mitigation System Contractor
IOR	Inspector of Record
P	Primary
S	Secondary
R	Review
O	Oversight
M	Manage
I	Inspect

ATTACHMENT C
FIELD INSPECTION CHECKLIST

Methane Gas Mitigation
Single-Pour Foundation Inspection Form

Mitigation Plans Dated:____________ **Lot No.:** ____________________

By:____________________________ **Tract No.:** ____________________

		DESCRIPTION	APPROVED
Material Approval	Sub-slab vent pipe		
	Sub-slab vent filter fabric		
	Sub-slab vent trench back fill material		
	Sub-slab vent pipe to concrete protection material		
	Gas membrane		
	Gas membrane bonding tape		
	Gas membrane pipe boots		
	Vent riser pipe		
	Vent riser rain cap		
	Conduit Sealant Material		
	Utility Dam Material		

		INSPECTOR	OK	NOT OK	NOTE #	INSPECTION DATE	CORRECTION DATE
Sub-Slab Vent Piping	Configuration of piping consistent with approved plans (Attach floor plan documenting any deviations)						
	Proper transitions through footings						
	Sand/Gravel below membrane: suitability and thickness of installation (_______ Inches)						
	Vent pipe positioning within collection blanket						
	End caps properly installed						
	Proper connection for active vent system						
	Filter fabric properly installed						
	Vent piping foam taped through footings						
	Vent risers properly secured to form boards						
	Final sub-slab vent pipe inspection--Ok to pour footings and install sand on sub-grade						
Gas Membrane	Proper stemwall/footing finish for membrane bonding						
	Gas membrane continuously bonded to perimeter footings						
	Geofabric placement acceptable						
	Gas membrane continuously bonded to Interior footings						
	Gas membrane seems continuously sealed						
	Pipe boots properly installed and sealed						
	Membrane properly sealed to sewer backflow valve conduit						
	Membrane smoke testing successfully completed						
	Ok to install sand on membrane						
	Sand/gravel above membrane: suitability and thickness of installation (_______ Inches)						
	Final membrane inspection--Ok to pour slab						
	Slab pouring/finishing protocol observed and acceptable with respect to protection of gas membrane						
	Slab membrane identification plate(s) properly installed						
Vent Risers	Vent riser location consistent with approved plans						
	Vent risers (do not penetrate)(properly penetrate) framing members						
	Vent riser holes through sill plate and top plate properly placed & dimensioned						
	Structural straps properly installed on sill & top plates where required						
	Nail plate properly installed on blocking where required						
	Vent pipe joints properly sealed						
	Vent pipe properly secured/strapped where exposed						
	Vent pipe properly stubbed through roof sheathing						
	Vent pipe outlet has proper roof clearance						
	Vent pipe outlet has proper clearance with respect to windows, etc.						
	Vent pipe rain cap properly installed						
	Vent pipe methane labels properly installed						
Utility Seals	Conduit Seals Properly Installed						
	Utility Trench Backfilled with Cement Bentonite Slurry or Native Material Compacted to 90% Relative compaction						

Final system approval

Inspector Signature:______________________ Inspector Name:______________________ Date: ______________

(DOC.PUB.4.02.02)

ATTACHMENT D

OPERATION AND MAINTENANCE PLAN OUTLINE

- 1. 0 INTRODUCTION
  - 1.1 Purposes and Uses
  - 1.2 Health and Safety Summary
  - 1.3 O&M Personnel Qualifications
  - 1.4 O&M Organization Chart
  - 1.5 Modification or Update Procedures

- 2.0 SITE BACKGROUND

- 3.0 OVERVIEW OF THE METHANE REMEDY SYSTEMS
  - 3.1 Gas Monitoring Probes
  - 3.2 Passive Ventilation Systems
    - 3.2.1 System Description and As-Built Drawings
    - 3.2.1 Protocols for Activities Potentially Affecting the Systems
  - 3.3 Impervious Membrane Liner Systems
    - 3.3.1 System Description and As-Built Drawings
    - 3.3.2 Protocols for Activities Potentially Affecting the Systems
  - 3.4 System Operations

- 4.0 INSPECTION PROCEDURES, SCHEDULE AND CHECKLIST
  - 4.1 Routine Inspection
    - 4.1.1 Site Conditions
    - 4.1.2 Remedy System Conditions
    - 4.1.3 Inspection Schedule and Checklist
  - 4.2 Remedy System Maintenance and Repair
    - 4.2.1 Maintenance and Repair Procedures
    - 4.2.2 Trouble-Shooting
    - 4.2.3 Spare Parts Lists
    - 4.2.4 Maintenance Schedule and Checklist
  - 4.3 Confined Space Entry

- 5.0 MONITORING PROCEDURES, SCHEDULE AND CHECKLIST
  - 5.1 Ambient Air Monitoring – Methane Concentrations
  - 5.2 Gas Probe Measurement - Methane Concentrations and Pressures
  - 5.3 Vent Riser Measurement - Methane Concentrations and Pressures
  - 5.4 Methane Sampling and Analysis
  - 5.5 Monitoring Schedule and Checklist

- 6.0 FIVE-YEAR REVIEW

- 7.0 DATA COLLECTION, DOCUMENTATION, AND REPORTING
  - 7.1 Data Collection
  - 7.2 Data Assessment
  - 7.3 O&M Reports
  - 7.4 5-Year Review Reports

- 8.0 CONTINGENCY PLAN
  - 8.1 Contingency Criteria
  - 8.2 Appropriate Response Actions
  - 8.3 Incident Report

- APPENDIX A Health and Safety Plan
- APPENDIX B Organization Chart
- APPENDIX C As-Built Drawings
- APPENDIX D Quality Assurance Project Plan

APPENDIX 10

UPDATES TO FEBRUARY 2005 EAL DOCUMENT

Hawai'i DOH
Summer 2008

APPENDIX 10
Updates to May 2005 HDOH EAL Document

March 2009: Technical Chlordane soil direct exposure action levels corrected to target 10^{-5} excess cancer risk and noncancer HQ of 1 (refer to Volume 1, Section 4.2 of EHE guidance; HDOH 2008). TPHmd gross contamination action level for deep soils corrected to 5,000 mg/kg (Appendix 1, Table F-3).
October 27, 2008: HDOH EALs updated to reflect September 2008 updates to May 2008 USEPA RSLs.
Refer to updated toxicity factors in Appendix 1, Table H (updates highlighted in red).

Chemicals with significant changes in EALs: Chloroaniline, p; Cobalt; Naphthalene

New Carcinogens: Chloroaniline, p; Cobalt; Naphthalene; 2-Nitrotoluene

Revised Cancer Slope Factors and/or IURs: Dioxins and Furans (affects action levels for TEQ Dioxins).

Revised Reference Doses or RfCs: 1,1 Dichloroethane; 2-Nitrotoluene; 1,1,2,2-Tetrachloroethane; 1,2,4-Trichlorobenzene

Revised Skin Absorption Factors: 2-Amino, 4,6-Dinitrotoluene; 4-Amino, 2,6-Dinitrotoluene; HMX; RDX; 1,3,5-Trinitrobenzene; TNT

Other Updates:
1. 1-Methylnaphthalene, 2-Methylnaphthalene: Separate EALs provided for each, based on classification of 1-Methylnaphthalene as a potential carcinogen.

2. Ethylbenzene, Naphthalene & 1, Methylnaphthalene: Soil direct-exposure action levels. Target residential and commercial/industrial excess cancer risk adjusted to 10^{-5} based on classification as Class C carcinogens and expected high natural biodegradation potential (i.e., decreasing exposure point concentrations over time).

USEPA, 2008, Screening Levels for Chemical Contaminants: U.S. Environmental Protection Agency, May 2008 (updated September 2008), prepared by Oak Ridge National Laboratories, http://www.epa.gov/region09/waste/sfund/prg/

Summer 2008 Updates:
2004 USEPA Region IX PRGs replaced with 2008 USEPA Regional Screening Levels (RSLs, combined PRGs for all USEPA regions). Route-extrapolated inhalation toxicity factors referenced in PRGs deleted. Direct Exposure model revised to utilize inhalation Unit Risk Factors and Reference Concentrations. Numerous other adjustments to toxicity factors, although updated RSLs not significantly different from 2004 PRGs.

Other Updates

- Expanded discussion of *Environmental Hazard Evaluation* approaches added to Volume 1;
- Summary of Tier 2 action levels for arsenic, dioxins and technical chlordane;
- Summary of Batch Test Leaching Method and update to BTLM spreadsheet (option to evaluate unlisted, generic volatile and nonvolatile contaminant added);
- Summary of long-term management of petroleum-contaminated soil;
- Updated EAL Surfer;
- Updated Tier 1 Direct Exposure Model (2004 USEPA PRG model replaced with 2008 USEPA RSL model).
- AMINO,2- DINITROTOLUENE,3,6 replaced with AMINO,2- DINITROTOLUENE,4,6

Contaminants with Tier 1 EALs that were reduced more than one order of magnitude (cause, action level primarily affected):

- Bis(2-chloroisopropyl)ethyl (revised USEPA toxicity factor, direct exposure hazards);
- Chloromethane (revised USEPA toxicity factor, direct exposure hazards);
- Dibromo-3-chloropropane, 1,2- (revised USEPA toxicity factor, direct exposure hazards);
- Dichloroethane, 1,1- (revised USEPA toxicity factor, direct exposure hazards);
- Dichlorophenoxyacetic acid (2,4-D; revised USEPA koc constant, leaching hazards);
- Ethylbenzene (revised USEPA toxicity factor, direct exposure hazards);
- Hexachlorobutadiene (revised USEPA koc constant, leaching hazards);
- Hexachloroethane(revised USEPA koc constant, leaching hazards);
- Methlynaphthalene (total 1- & 2-; (revised USEPA toxicity factor, direct exposure hazards);
- Trichlorophenoxypropionic acid (2,4,5-TP; revised target HQ, direct exposure hazards; corrected error in 2005 groundwater action level);
- Tetryl (revised USEPA toxicity factor and target HQ, direct exposure hazards);

February 8, 2007 Update:
Final drinking water goal for 1,2 dichloroethane in Appendix 1, Table D-2, updated to 5 ug/L (HIDOH MCL), versus risk-based goal of 0.12 ug/L. This affected the final groundwater goal that is a source of drinking water noted in Tables D-1a and D-1b. Soil leaching action levels in Table E-1 were subsequent updated, as were final soil action levels in Tables A-1 and A-2. Volume 1 Summary Tables A and D were updated to reflect changes in the Appendix 1 tables. To date these updates have only been made in

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August 2006 Updates

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- Thirty-three chemicals added:

PETROLEUM-RELATED COMPOUNDS:

- ETHANOL

PESTICIDES:

- AMETRYN
- ATRAZINE
- DALAPON
- DICHLOROPHENOXYACETIC ACID (2,4-D)
- DIURON
- GLYPHOSATE
- HEXAZINONE
- ISOPHORONE
- PROPICONAZOLE
- SIMAZINE
- TERBACIL
- TETRACHLOROPHENOL, 2,3,4,6-
- TRICHLOROPHENOXYPROPIONIC ACID, 2,4,5- (2,4,5-TP)
- TRICHLOROPROPANE, 1,2,3-
- TRICHLOROPROPENE, 1,2,3-
- TRIFLURALIN

EXPLOSIVES-RELATED COMPOUNDS:

- AMINO,2- DINITROTOLUENE,3,6-
- AMINO,4- DINITROTOLUENE,2,6-
- CYCLO-1,3,5-TRIMETHYLENE-2,4,6-TRINITRAMINE (RDX)
- DINITROBENZENE, 1,3-
- DINITROTOLUENE, 2,4- (2,4-DNT)
- DINITROTOLUENE, 2,6- (2,6-DNT)
- NITROBENZENE
- NITROGLYCERIN
- NITROTOLUENE, 2-
- NITROTOLUENE, 3-
- NITROTOLUENE, 4-
- PENTAERYTHRITOLTETRANITRATE (PETN)
- TETRANITRO-1,3,5,7-TETRAAZOCYCLOOCTANE (HMX)
- TRINITROPHENYLMETHYLNITRAMINE, 2,4,6- (TETRYL)
- TRINITROTOLUENE, 1,3,5-
- TRINITROTOLUENE, 2,4,6- (TNT)

Summer 2008 Updates:
2004 USEPA Region IX PRGs replaced with 2008 USEPA Regional Screening Levels (RSLs, combined PRGs for all USEPA regions). Route-extrapolated inhalation toxicity factors referenced in PRGs deleted. Direct Exposure model revised to utilize inhalation Unit Risk Factors and Reference Concentrations. Numerous other adjustments to toxicity factors, although updated RSLs not significantly different from 2004 PRGs.

Other Updates

- Expanded discussion of *Environmental Hazard Evaluation* approaches added to Volume 1;
- Summary of Tier 2 action levels for arsenic, dioxins and technical chlordane;
- Summary of Batch Test Leaching Method and update to BTLM spreadsheet (option to evaluate unlisted, generic volatile and nonvolatile contaminant added);
- Summary of long-term management of petroleum-contaminated soil;
- Updated EAL Surfer;
- Updated Tier 1 Direct Exposure Model (2004 USEPA PRG model replaced with 2008 USEPA RSL model).
- AMINO,2- DINITROTOLUENE,3,6 replaced with AMINO,2- DINITROTOLUENE,4,6

Contaminants with Tier 1 EALs that were reduced more than one order of magnitude (cause, action level primarily affected):

- Bis(2-chloroisopropyl)ethyl (revised USEPA toxicity factor, direct exposure hazards);
- Chloromethane (revised USEPA toxicity factor, direct exposure hazards);
- Dibromo-3-chloropropane, 1,2- (revised USEPA toxicity factor, direct exposure hazards);
- Dichloroethane, 1,1- (revised USEPA toxicity factor, direct exposure hazards);
- Dichlorophenoxyacetic acid (2,4-D; revised USEPA koc constant, leaching hazards);
- Ethylbenzene (revised USEPA toxicity factor, direct exposure hazards);
- Hexachlorobutadiene (revised USEPA koc constant, leaching hazards);
- Hexachloroethane(revised USEPA koc constant, leaching hazards);
- Methlynaphthalene (total 1- & 2-; (revised USEPA toxicity factor, direct exposure hazards);
- Trichlorophenoxypropionic acid (2,4,5-TP; revised target HQ, direct exposure hazards; corrected error in 2005 groundwater action level);
- Tetryl (revised USEPA toxicity factor and target HQ, direct exposure hazards);

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