

## Paula Wilson

---

**From:** Michael Backe <MBacke@olytech.com>  
**Sent:** Wednesday, August 31, 2011 4:41 PM  
**To:** Paula Wilson; Orville Green; Keith Donahue; Bruce Wicherski  
**Cc:** Hugh O'Riordan; Michael Brush  
**Subject:** REM Guidance Appendices  
**Attachments:** Appendix A\_Default Exposure Factors\_public comment draft 8-31-11 ots.pdf; Appendix B\_Default Fate and Transport Parameter Values\_public comment draft 8-31-11 ots.pdf; Appendix C\_Default Physical and Chemical Properties\_public comment draft 8-31-11 ots.pdf; Appendix D\_Default Toxicity Values\_public comment draft 8-31-11 ots.pdf; Appendix E\_Models and Equations\_public comment draft 8-31-11 ots.pdf; Appendix F\_Methodology and Example Calculation for RATLs\_public comment draft 8-31-11ots.pdf; Appendix H\_Application of Natural Attenuation\_public comment draft 8-31-11 ots.pdf; Appendix J\_Sample Table of Contents for a Risk Evaluation Report\_public comment draft 8-31-11.pdf; Appendix L\_QAPP Template\_public comment draft 8-31-11 ots.pdf

Paula,

Attached are our review/comments for the Idaho Risk Evaluation Manual for Petroleum Releases Draft Appendices A, B, C, D, E, F, H, J, and L. Document format is Adobe Acrobat X (Portable Document Format - unsecured). We will be discussing Appendices K and parts of I at our meeting on Tuesday; I will provide comments before our meeting, hopefully tomorrow afternoon at the latest. We are still reviewing Appendices G; I hope to have them finished later tonight or tomorrow morning. I will forward them when complete..

We can discuss the changes, as appropriate, at our Tuesday-scheduled meeting.

Thanks,

Mike Backe

Olympus Technical Services, Inc.  
5956 West Victory Road  
Boise, Idaho 83709  
Telephone (208) 562-5500  
Facsimile (208) 562-5503

Please consider the environment before printing this E-mail.

### **PRIVILEGED AND CONFIDENTIAL COMMUNICATION**

The information contained in this E-mail transmission is a CONFIDENTIAL COMMUNICATION and may be protected by one or more legal privileges. It is intended solely for the use of the recipient(s) identified above. If you are not the intended recipient or if this transmission has been inadvertently directed to your attention, you are hereby notified that you have received this transmission and any attached document(s) in error and that any review, dissemination, distribution, or copying of this transmission is STRICTLY PROHIBITED. The sender has not waived any applicable privilege by sending the accompanying transmission. If you have received this transmission in error, please notify us immediately by return E-mail and delete and destroy all copies of the original transmission and any attachments.



**Appendix A: Default Exposure Factors**

*This page intentionally left blank for correct double-sided printing.*

## Exposure Factors

Risk assessment requires quantifying the magnitude, frequency, and duration of exposure for the receptor populations and exposure pathways selected for analysis. To determine pathway-specific intake estimates, it is necessary to select values for a number of variables in the equations used to calculate intake. The following variables were selected based on an assessment of recommendations in various guidance documents and scientific literature. When determining these values, it is often necessary to make assumptions, and in these cases, the rationale for the assumption is provided. These exposure factors are summarized in Table 1.

### Averaging Time

The period over which exposure to chemicals is averaged depends on the type of toxic effect being assessed. For chronic exposure to noncarcinogenic toxicants, intakes are averaged over the period of exposure, so the averaging time is equal to the exposure duration. Intakes of carcinogens are calculated by prorating the total cumulative dose over a lifetime. The different approach is based on the idea that for carcinogens, a higher dose received over a shorter period is equivalent to a corresponding lower dose spread over a lifetime. The averaging time selected for carcinogens, 70 years, is based on the U.S. Environmental Protection Agency's (EPA) *Risk Assessment Guidance for Superfund* (EPA 1989).

### Body Weight

It is appropriate to use an average value for this parameter. The default body weight for adult receptors is 70 kilograms (kg) and represents the EPA standard default exposure factor (EPA 1991a). There is evidence presented in the *Exposure Factors Handbook* (EPA 1997) that Americans are getting slightly heavier, and currently the actual average adult body weight is 72 kg. However, the derivation of cancer slope factors assumes a body weight of 70 kg, so it is more appropriate to also use this value for average body weight. The child body weight value is 15 kg, which is the mean value for children aged 6 months to 6 years (EPA 1997). It is also a standard default value in EPA's 1991 *Risk Assessment Guidance for Superfund* (EPA 1991a).

### Exposure Duration

The residential exposure duration is the EPA standard default of 30 years (EPA 1991a). This period is divided into 6 years of exposure as a child and 24 years as an adult. These time periods are used in combination with other age group-specific exposure parameters to assess exposure to carcinogenic chemicals. Noncarcinogenic chemical exposure is conservatively assessed using the child receptor and an exposure duration of 6 years. For the nonresidential adult receptor, the exposure duration is 25 years, which is an EPA standard default exposure factor (EPA 1991a) and is also used in *Risk Assessment Guidance for Superfund, Part B* (EPA 1991b). This value was a 95th-percentile value for men in the manufacturing sector, based on an analysis of U. S. Bureau of Labor Statistics data (EPA 2002). An exposure duration of 25 years is considered protective across a wide spectrum of industrial and commercial sectors (EPA 2002) and so is an

appropriate default for nonresidential receptors. The exposure duration for the construction worker is 30 days (0.08 year); this is assumed to be a conservative estimate of exposure for most construction projects.

## Exposure Frequency

The exposure frequency for residential receptors is 350 days per year for all exposure routes that do not involve direct contact with soil. This exposure frequency is the EPA standard default exposure factor (EPA 1991a). The nonresidential scenario assumes an exposure frequency of 250 days per year. This value is the EPA standard default for commercial or industrial scenarios (EPA 1991a) and so was considered appropriate for all nonresidential receptors except for construction workers. For the construction worker scenario, the exposure frequency is 30 days per year.

## Exposure Frequency for Direct Contact with Soil

For exposure routes involving direct contact with soil—including soil ingestion, dermal exposure, and vapor and particulate inhalation—it is assumed that receptors have contact with soil primarily in warmer months when the ground is not frozen or snow covered. For this reason, an exposure frequency of 270 days per year is used for these exposure routes for the residential scenario; 180 days per year is used for the nonresidential scenario. The direct contact exposure frequency for construction workers is 30 days per year.

## Soil Ingestion Rate

The soil ingestion rate for residential child and adult receptors is 200 milligrams per day (mg/day) and 100 mg/day, respectively. These values are EPA standard default exposure factors (1991a). Although both EPA (1991a) and the *Exposure Factors Handbook* (EPA 1997) recommend a soil ingestion rate of 50 mg/day for workers other than construction workers, it was decided to use a value of 100 mg/day to adequately address the potential soil exposures encountered by all nonresidential adult receptors.

For example, a value of 50 mg/day might be appropriate for office workers, but it would not adequately address exposure of outdoor workers, for whom a value of 100 mg/day is more appropriate (EPA 2002). The construction worker soil ingestion rate is 330 mg/day. This value is based on the 95th percentile for adult soil intake rates reported in a soil ingestion mass-balance study (Stanek et al. 1997, cited in EPA 2002).

## Water Ingestion Rate

The water ingestion rate for children is 1 liter per day (L/day). Currently EPA uses 1 L/day as a default drinking water ingestion rate for infants and children, and it is considered to be an appropriate upper percentile tap water ingestion rate for children less than 10 years of age (EPA 2008). The residential adult receptor ingestion rate is 2 L/day. This value is an EPA standard default exposure factor (EPA 1991a). According to EPA (1997), the intake rate of 2 L/day corresponds to the 84th percentile of the intake rate distribution among adults in a study

by Ershow and Cantor (1989). EPA (1997) lists an average tap water intake for adults of 1.41 L/day. The nonresidential adult ingestion rate is 1 L/day; this value is an EPA standard default exposure factor (EPA 1991a).

### **Exposure Time for Outdoor Inhalation**

Residential receptors are assumed to spend 2 hours outdoors at their residence. This is an EPA-recommended value (1997). Nonresidential receptors are assumed to spend 6 hours outside; this value overestimates exposure of indoor workers, but it is appropriate for outdoor workers. Construction workers are assumed to spend 10 hours per day outdoors, as construction workers often work 10-hour days.

### **Dermal Relative Absorption Factor**

The dermal relative absorption factor values are based on recommendations contained in the EPA's *Risk Assessment Guidance for Superfund, Part E, Supplemental Guidance for Dermal Risk Assessment* (EPA 2007). The EPA recommends an absorption factor of 0.13 for benzo(a)pyrene and other polynuclear aromatic hydrocarbons (PAHs) and 0 for volatile organic compounds (VOCs).

### **Soil-to-Skin Adherence Factor**

The soil-to-skin adherence factor values are derived from recommendations from an analysis of soil adherence study data by the EPA (EPA 2007). This analysis calculated body-part-weighted adherence factor values using studies involving upper-end activities for soil-skin adherence and median values of body surface area. The recommended adult residential value, based on a central-tendency-weighted adherence factor of a high-end soil contact activity (e.g., gardening), is consistent with a reasonable maximum exposure (RME) for contact rates in a variety of activities. The same approach of using the high end of a mean is used for the recommended child value, which is the 50th percentile weighted adherence factor for children playing in wet soil. Similarly, the commercial/industrial worker recommended adherence factor is based on the 50th percentile weighted adherence factor for utility workers, a high-end contact activity. For the construction worker, a 95th percentile weighted adherence factor is used to represent RME.

### **Skin Surface Area for Dermal Contact with Soil**

Skin surface areas for dermal soil contact are based on residential and industrial RME recommended values contained in EPA's *Risk Assessment Guidance for Superfund, Part E, Supplemental Guidance for Dermal Risk Assessment* (EPA 2007).

**Table 1. Default Exposure Factors**

Exposure Parameter	Symbol	Units	Default Value	Reference
<b>Averaging Time (AT)</b>				
Averaging Time—Carcinogen	ATc	years	70	EPA 1989 (p. 6-23)
Averaging Time—Noncarcinogen	ATnc	years	Equivalent to exposure duration	EPA 1989 (p. 6-23)
<b>Body Weight (BW)</b>				
Child	BWc	kg	15	EPA 1991a (p. 15)
Adult	BWa	kg	70	EPA 1991a (p. 15)
<b>Exposure Duration (ED)</b>				
Resident (child)	EDc	years	6	EPA 1991a (p. 15)
Resident (adult)	EDa	years	24	EPA 1991a (p. 15)
Nonresidential Worker	ED	years	25	EPA 1991a (p. 15)
Construction Worker	ED	years	1	EPA 2002 (Exhibit 5-1)
<b>Exposure Frequency (EF)</b>				
Resident	EFr	days/yr	350	EPA, 1991a (p.15)
Nonresidential Worker	EF	days/yr	250	EPA 1991a (p.15)
Construction Worker	EF	days/yr	30	Professional judgment
<b>Exposure Frequency for Direct Contact Pathways (EF)</b>				
Resident	EFres	days/yr	270	Professional judgment
Nonresidential Worker	EFd	days/yr	180	Professional judgment
Construction Worker	EFd	days/yr	30	Professional judgment
<b>Soil Ingestion Rate (IR)</b>				
Resident (child)	IRs-c	mg/day	200	EPA 1991a (p. 15)
Resident (adult)	IRs-a	mg/day	100	EPA 1991a (p. 15)
Nonresidential Worker	IRs	mg/day	100	EPA 2002 (Exhibit 1-2)
Construction Worker	IRs	mg/day	330	EPA 2002 (Exhibit 1-2)
<b>Daily Water Ingestion Rate (IRw)</b>				
Resident (child)	IRw-c	L/day	1	EPA 2008
Resident (adult)	IRw-a	L/day	2	EPA 1991a (p. 15)
Nonresidential Worker	IRw	L/day	1	EPA 1991a (p. 15)

Exposure Parameter	Symbol	Units	Default Value	Reference
<b>Exposure Time for Inhalation (ET)</b>				
Resident (child)	ETo-c	hr/day	Outdoor: 2 Indoor: 24	EPA 1997 (p. 15-17)
Resident (adult)	ETo-a	hr/day	Outdoor: 2 Indoor: 24	EPA 1997 (p. 15-17)
Nonresidential Worker	ETo	hr/day	Outdoor: 6 Indoor: 8	Professional judgment
Construction Worker (outdoor only)	ETo	hr/day	10	Professional judgment
<b>Oral Relative Absorption Factor (RAF)</b>				
Oral Relative Absorption Factor	RAFo	—	Assume 100%	EPA 2007 (p. 4-2)
<b>Dermal Relative Absorption Factor (RAF<sub>d</sub>)</b>				
Volatile organic compounds	RAF <sub>d</sub>	—	0	EPA 2007 (pg. 3-18)
Benzo(a)pyrene and other polynuclear aromatic hydrocarbons	RAF <sub>d</sub>	—	0.13	EPA 2007 (Exhibit 3-4)
<b>Soil-to-Skin Adherence Factor (M)</b>				
Residential (child)	Mc	mg/cm <sup>2</sup>	0.2	EPA 2007 (p.3-14)
Residential (adult)	Ma	mg/cm <sup>2</sup>	0.07	EPA 2007 (p. 3-14)
Nonresidential Worker	M	mg/cm <sup>2</sup>	0.2	EPA 2007 (p. 3-17)
Construction Worker	M	mg/cm <sup>2</sup>	0.3	EPA 2007 (Exhibit 3-3)
<b>Skin Surface Area for Dermal Contact with Soil (SA)</b>				
Child Receptors	SAC	cm <sup>2</sup> /day	2800	EPA 2007 (Exhibit 3-5)
Adult Receptors	SAa	cm <sup>2</sup> /day	5700	EPA 2007 (Exhibit 3-5)
Nonresidential Worker Receptors	SA	cm <sup>2</sup> /day	3300	EPA 2007 (Exhibit 3-5)
Construction Worker Receptors	SA	cm <sup>2</sup> /day	3300	EPA 2007 (Exhibit 3-5)

Comment [MAB1]: Previous request for clarification of how values are used.

Note: Exposure factors for the age-adjusted resident are calculated from the values listed for child and adult receptors using the equations in Appendix E.

## Exposure to Mutagenic Carcinogens

Exposure to these chemicals carries greater risk when it occurs early in life. Therefore, the age at which exposure occurs must be considered for residential receptors. For these receptors, the 30-year exposure duration is divided into four periods: exposures occurring between the ages of 0–2 years, 2–6 years, 6–16 years, and 16–30 years (EPA 2005).

Different multipliers are incorporated for these time periods so that early-life exposure is weighted more heavily. The 0–2 year and 2–6 year exposure periods use the child-specific values for several exposure parameters: body weight, soil ingestion rate, soil-to-skin adherence factor,

and skin surface area for dermal contact. The corresponding adult-specific values are used for the 6–16 year and 16–30 year exposure periods.

## References

- EPA (U.S. Environmental Protection Agency). 1989. *Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation Manual, Part A*. EPA/540/1-89/002. United States Environmental Protection Agency, Office of Emergency and Remedial Response.
- EPA (U.S. Environmental Protection Agency). 1991a. *Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation Manual Supplemental Guidance, Standard Default Exposure Factors, Interim Final*. OSWER Directive: 9285.6-03. United States Environmental Protection Agency, OSWER.
- EPA (U.S. Environmental Protection Agency). 1991b. *Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation Manual, (Part B Development of Risk-based Preliminary Remediation Goals)*. EPA/540/R-92/003. United States Environmental Protection Agency, Office of Emergency and Remedial Response.
- EPA (U.S. Environmental Protection Agency). 1997. *Exposure Factors Handbook*. EPA/600/P-95/002Fa. United States Environmental Protection Agency, ORD.
- EPA (U.S. Environmental Protection Agency). 2002. *Supplemental Guidance for Developing Soil Screening Levels at Superfund Sites*. Office of Emergency and Remedial Response, United States Environmental Protection Agency, OSWER 9355.4-24. December 2002.
- EPA (U.S. Environmental Protection Agency). 2005. *Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens*. Risk Assessment Forum, United States Environmental Protection Agency, EPA/630/R-03/003F. March 2005.
- EPA (U.S. Environmental Protection Agency). 2007. *Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation Manual, Part E, Supplemental Guidance for Dermal Risk Assessment, Final*. OSWER Directive: 9285.7-02EP. EPA/540/R/99/005. United States Environmental Protection Agency, OSWER. October 2007.
- EPA (U.S. Environmental Protection Agency). 2008. *Child-Specific Exposure Factors Handbook*. EPA/600/R-06/096F. United States Environmental Protection Agency, NCEA, ORD. September, 2008
- Ershow, A.G., and K.P. Cantor. 1989. Total water and tapwater intake in the United States: population-based estimates of quantities and sources. Life Sciences Research Office, Federation of American Societies for Experimental Biology.
- Stanek, E.J., E.J. Calabrese, R. Barnes, and P. Pekow. 1997. Soil Ingestion in Adults—Results of a Second Pilot Study. *Ecotoxicology and Environmental Safety* 36:249–257.

**Appendix B: Default Fate and Transport Parameter Values**

*This page intentionally left blank for correct double-sided printing.*

## Introduction

Several routes of exposure evaluated in the *Idaho Risk Evaluation Manual for Petroleum Releases* (REM) involve pathways where chemicals transfer across media. These pathways include inhalation of vapors originating from the volatilization of chemicals of interest (COI) from petroleum-impacted soil or ground water in indoor air, ingestion of ground water containing chemicals leached from soil, and inhalation of volatiles and particulates from surficial soil. Models are used to simulate these cross-media transfer processes, estimate exposure point concentrations, and calculate target levels. This appendix describes the models and selection criteria for the default fate and transport parameter values used to develop the Idaho default target levels and to some degree the remedial action target levels. A summary of the parameters and sources used to develop them is provided in Table 1 at the end of this appendix.

## Soil Properties

### Unsaturated Zone

Generic unsaturated zone soil properties were based on an assumed sandy loam soil textural class. Nielson and Rogers (1990) and Hers (2002) present data on average soil physical and hydraulic properties for 12 Natural Resources Conservation Service soil textural classes. Data obtained from these compilations include mean particle diameter, total porosity, saturated moisture content, residual moisture content, van Genuchten parameters describing the shape of the moisture characteristic curve, and saturated hydraulic conductivity. Bulk density was calculated from total porosity. Soil vapor permeability was calculated using van Genuchten equations described in the U.S. Environmental Protection Agency's (EPA) *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings* (EPA 2003), the hydraulic properties of the sandy loam soil noted above, and average moisture content conditions. Derivation of the average moisture contents is described below.

Infiltration rates for high- and low-precipitation areas of Idaho were developed, and the value for high-precipitation areas is used as the Idaho default target level value. The high-precipitation area annual infiltration rate of 25 centimeters is based on field studies and water balance calculations done in northern Idaho on the Rathdrum Prairie (Hammel et al. 1995). This value represents about 40% of the total annual precipitation. The annual infiltration rate for low-precipitation areas (1.4 centimeters) is based on investigations by Cecil et al. (1992). This latter work was conducted in areas of native vegetation at the Idaho National Laboratory in eastern Idaho. Using stable isotopes and other tracers, a long-term estimate of 1 centimeter per year infiltration was calculated.

This infiltration rate represents approximately 5% of total annual precipitation. This percentage was applied to the total annual precipitation in Boise (11.7 inches/year), with the assumption that Boise conditions represent average low-precipitation conditions.

Average soil moisture content values for low- and high-precipitation conditions were derived by simulating infiltration into a homogeneous soil profile with the sandy loam hydraulic properties discussed above. The variably saturated flow and transport code HYDRUS-1D (Kool and van Genuchten 1991) was used to conduct the simulations. The simulation was run until steady-state conditions were achieved, and the moisture content at that time was noted.

The moisture content in the capillary fringe and the capillary fringe thickness were derived using methods and equations described in the EPA *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings* (2003). The mean particle diameter of 0.03 centimeters used in these calculations is typical of a sandy loam soil type.

## Saturated Zone

The default scenario selected to represent the saturated zone is a sandy, alluvial aquifer of moderate hydraulic conductivity. Selected saturated zone properties and ground water mixing zone thickness were taken from those developed for the soils protective of ground water pathway in Appendix A of the *Risk Based Corrective Action Guidance Document for Petroleum Releases* (DEQ 1996). Total porosity, bulk density, and fraction organic carbon are similar to that of the unsaturated zone soil.

## Enclosed Space Parameters

The enclosed space parameters are used in combination with soil and ground water properties to define the conditions controlling the volatilization of COI vapors from petroleum-impacted soil, ground water, and soil vapor into indoor spaces and to predict exposure point concentrations of chemicals in indoor air. Scenarios were developed for residential and nonresidential settings. Both the residential and nonresidential scenarios selected consist of one-story, slab-on-grade structures lying directly over the source of contamination. The primary differences between the two scenarios are the size of the structure and the number of air exchanges per time period. The nonresidential structure is larger and exchanges more air than the residential structure.

The size of structure for each scenario was based on residential and commercial building survey data collected by the U.S. Department of Energy (DOE 1995, 2001). Data from the western census region of the 1993 housing survey (DOE 1995) were used to further describe residential structures. In this region, 33% of all homes had heated floor space square footage between 1,000 and 1,599 square feet, constituting the largest proportion of all size classes. Approximately 50% of all homes were one-story, single-family homes. The next largest category was multistory apartment buildings, accounting for 29% of all residential structures. Homes with concrete slabs or crawl spaces each constituted about 33% of all homes, while 15% had basements. A sensitivity analysis evaluating the impact of concrete slabs versus crawl spaces on target levels showed little difference.

For nonresidential structures, data from the mountain division of the western region of the 1999 Commercial Building Energy Consumption Survey was used (DOE 2001). The median square footage per commercial building in this area was 5,000 square feet, and 66% of all buildings in

**Comment [MAB1]:** Previous request - This should be updated, as appropriate - add basements/crawl space scenarios

this area were one story. A slab-on-grade foundation and indoor building height of 8 feet were assumed.

**Comment [MAB2]:** Previous comment - This may be too low for nonresidential. Assumed by whom?

The default value chosen for air exchange rates in commercial buildings is based on expected values for buildings built to meet ventilation standards of the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE 2004). The default value for residential structures is based on an analysis by the Michigan Department of Environmental Quality (MDEQ 1998). Values for other structural parameters—specifically the dimensions of foundation cracks, wall/foundation thickness, and pressure differentials between the space and the outdoors—are based on data presented in the *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings* (EPA 2003).

In the Johnson-Ettinger model equations, there is a dependent relationship between the width of foundation cracks (equivalent crack radius) and the fraction of the total floor space below grade occupied by cracks. It was decided to fix the equivalent crack width at 0.1 centimeters and allow the fraction of cracks to vary, with a minimum value of 0.0005 specified, during the calculation of the total area of cracks in the default structure. This minimum value is what is suggested as a reasonable lower end of the range for this parameter by Johnson (2005).

Source characteristics for calculation of indoor air pathways assumed a 1-foot separation distance between the top of the soil or ground water source and the building foundation. This distance is the minimum that can be considered by the model and was considered extremely conservative with respect to maximizing vapor migration into a structure.

For ground water sources, this soil separation distance includes the capillary fringe thickness of 25 centimeters. In making finite mass calculations, the soil source was assumed to be 5 feet (153 centimeters) thick.

## Particulate Emission Factor Parameters

All parameter values used in the calculation of the particulate emission factor are taken directly from the EPA's *Soil Screening Guidance* (EPA 1996). Idaho-specific values for the Q/C dispersion factor for a 0.5-acre size source and the average wind speed for Boise were selected as default values.

## Models

The default models selected to estimate the transport of chemicals between various media and within select media, such as ground water, include the following:

- The Johnson-Ettinger model (Johnson and Ettinger 1991) for transport of volatile chemicals between soil, soil vapor, or ground water and indoor air—Implementation of the model includes the effects of advection near the building and diffusion to the building from the source and infinite and finite source masses. This model does not incorporate biodegradation of chemicals during transport from the source into the indoor air.
- The dilution attenuation factor model for the soil to ground water pathway implemented in the EPA *Soil Screening Guidance* (EPA 1996)—Soil leachate generated using the high

infiltration rate is mixed with ground water having the Darcy velocity described above. Target levels are estimated in ground water directly below the source.

- The Domenico model for transport of chemicals in the saturated zone—This is a steady-state model that includes advection, sorption, three-dimensional dispersion, and decay (Domenico 1990). Equations for calculating dispersivity values for use in the ground water transport model are those derived by Xu and Eckstein (1995).
- The Cowherd equation for transport and dispersion of particulates as described in the EPA *Soil Screening Guidance* (EPA 1996).

**Table 1. Default fate and transport parameter values**

Parameter	Symbol	Units <sup>a</sup>	Default Value	Reference
<b>Soil Parameters</b>				
<i>Unsaturated Zone Soil</i>				
Source-building separation	LTs	cm	30	Professional judgment, see discussion
Source bottom-building separation	LTsB	cm	183	Professional judgment, see discussion
Vapor permeability	kv	cm <sup>2</sup>	5.0E-9	Calculated
Mean particle diameter	D	cm	0.030	EPA 2003
Van Genuchten curve shape parameter	n	—	1.449	EPA 2003
Thickness of capillary fringe zone	hcap	cm	25	EPA 2003
Dilution attenuation factor (DAF) in the unsaturated zone (user-defined)	DAF <sub>unsat</sub>	—	1	No attenuation in the unsaturated zone is assumed to occur.
Total soil porosity in the vadose zone	θT	cm <sup>3</sup> /cm <sup>3</sup> -soil	0.39	EPA 2003
Volumetric water content in vadose zone	θ <sub>ws</sub>	cm <sup>3</sup> /cm <sup>3</sup>	0.17	Professional judgment, see discussion
Volumetric air content in vadose zone	θ <sub>as</sub>	cm <sup>3</sup> /cm <sup>3</sup>	0.22	Calculated
Dry soil bulk density	ρ <sub>s</sub>	g/cm <sup>3</sup>	1.64	Nielson and Rogers 1990; Hers 2002
Fractional organic carbon content in the vadose zone	foc	g-C/g-soil	0.001	Professional judgment
Volumetric water content in the foundation/wall cracks	θ <sub>wcrack</sub>	cm <sup>3</sup> /cm <sup>3</sup>	0.17	Assumed equal to that in the adjacent soil
Volumetric air content in the foundation/wall cracks	θ <sub>acrack</sub>	cm <sup>3</sup> /cm <sup>3</sup>	0.22	Calculated
Volumetric water content in capillary fringe zone	θ <sub>wcap</sub>	cm <sup>3</sup> /cm <sup>3</sup>	0.32	EPA 2003
Volumetric air content in capillary fringe zone	θ <sub>acap</sub>	cm <sup>3</sup> /cm <sup>3</sup>	0.07	EPA 2003
<i>Saturated Zone Soil</i>				
Dry soil bulk density	ρ <sub>ss</sub>	g/cm <sup>3</sup>	1.64	Nielson and Rogers 1990; Hers 2002
Fractional organic carbon content	focs	g-C/g-soil	0.001	Professional judgment

**Comment [MAB3]:** Previous comment - J&E default for sandy loam is 0.10

**Comment [MAB4]:** Previous comment - J&E default for sandy loam is 1.62

**Comment [MAB5]:** Discussion?

**Comment [MAB6]:** Previous comment - J&E default for sandy loam is 1.62

**Comment [MAB7]:** Discussion?

Parameter	Symbol	Units <sup>a</sup>	Default Value	Reference
Total soil porosity	θTs	cm <sup>3</sup> /cm <sup>3</sup> -soil	0.39	Nielson and Rogers 1990; Hers 2002
Volumetric water content	θwss	cm <sup>3</sup> /cm <sup>3</sup>	0.39	Equivalent to total porosity
Volumetric air content	θass	cm <sup>3</sup> /cm <sup>3</sup>	0.0	
<b>Air Property</b>				
Viscosity of air		g/cm-sec	1.8E-4	
<b>Ground Water Parameters</b>				
Water table-building separation	LTgw	cm	30	Professional judgment, see discussion
Ground water Darcy velocity	Ugw	cm/year	3340	DEQ 1996
Ground water mixing zone thickness	δgw	cm	153	DEQ 1996
Length of ground water source parallel to ground water flow direction	Lmz	cm	1220	Equivalent to source area dimensions
Width of ground water source perpendicular to ground water flow direction	Wgw	cm	1220	Equivalent to source area dimensions
Infiltration rate	I	cm/year	25	Hammel et al. 1995
<b>Enclosed Space Parameters</b>				
<i>Area of the Enclosed Space Below Grade</i>				
Residential	AB	cm <sup>2</sup>	1561600	Calculated
Nonresidential	AB	cm <sup>2</sup>	4782069	Calculated
<i>Enclosed Space Foundation/Wall Thickness</i>				
Residential	Lcrack	cm	15	EPA 2003
Nonresidential	Lcrack	cm	15	EPA 2003
<i>Total area of Cracks</i>				
Residential	Acrack	cm <sup>2</sup>	484	Calculated
Nonresidential	Acrack	cm <sup>2</sup>	861	Calculated
<i>Number of Air Exchanges per Hour</i>				
Residential	ER	1/hour	1	MDEQ 1998
Nonresidential	ER	1/hour	1	ASHRAE 2004
<i>Length of Enclosed Space</i>				
Residential	LB	cm	1220	DOE 1995
Nonresidential	LB	cm	2157	DOE 2001
<i>Width of Enclosed Space</i>				

Comment [MAB8]: Previous comment - J&E default is 0.25, DTSC default is 0.5

Comment [MAB9]: Previous comment - J&E default is 1000. Larger size residence yields lower indoor air concentrations

Parameter	Symbol	Units <sup>a</sup>	Default Value	Reference
Residential	WB	cm	1220	DOE 1995
Nonresidential	WB	cm	2157	DOE 2001
<i>Height of Enclosed Space</i>				
Residential	HB	cm	244	Professional judgment
Nonresidential	HB	cm	244	Professional judgment
<i>Floor-Wall Seam Perimeter</i>				
Residential	Xcrack	cm	4880	Calculated
Nonresidential	Xcrack	cm	8628	Calculated
Crack depth below grade	Zcrack	cm	15	Calculated
Equivalent crack radius	rcrack	cm	0.1	EPA 2003
Pressure differential between enclosed space and soil surface beneath	ΔP	g/cm-sec <sup>2</sup>	40	EPA 2003
<b>Cowherd Particulate Emission Model</b>				
Inverse of the mean concentration at the center of a square source	Q/C	(g/m <sup>2</sup> -sec)/ (kg/m <sup>3</sup> )	69.41	EPA 1996
Fractional vegetative cover	V	m <sup>2</sup> /m <sup>2</sup>	0.5	EPA 1996
Mean annual wind speed	Um	m/sec	3.98	EPA 1996
Equivalent threshold value of wind speed at 7 meters	Ut	m/sec	11.32	EPA 1996
Wind speed distribution function from Cowherd et al. 1985	F(x)	—	4.95E-2	EPA 1996
<b>Averaging Time For Vapor Flux</b>				
Resident child	AT	sec	1.89E8	Equal to exposure duration
Resident adult	AT	sec	9.46E8	Equal to exposure duration
Age Adjusted Resident	AT	sec	7.57E8	Equal to exposure duration
Nonresidential adult worker	AT	sec	7.88E8	Equal to exposure duration
Construction worker	AT	sec	3.15E7	Equal to exposure duration
<b>Ground Water Protection</b>				
Distance to the point of exposure	Xpoe	cm	0	Professional judgment
Distance to the point of compliance	Xpoc	cm	0	Professional judgment

Comment [MAB10]: Previous comment - J&E default is 1000. Larger size residence yields lower indoor air concentrations

<sup>a</sup> cm = centimeters; g = grams; C = carbon; m = meters; sec = seconds; kg = kilograms

## References

- ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers). 2004. Ventilation for Acceptable Indoor Air Quality. Standard 62.1. American Society of Heating, Refrigeration, and Air Conditioning Engineers.
- Cecil, L.D., J.R. Pittman, T.M. Beasley, R.L. Michel, P.W. Kubik, U. Fehn, and H. Gove. 1992. Water Infiltration Rates in the Unsaturated Zone at the Idaho National Engineering Laboratory Estimated from Chlorine-36 and Tritium Profiles, and Neutron Logging. In: Proceedings of the 7th International Symposium on Water-Rock Interaction-WRI-7, Y.K. Kharaka and A.S. Maest (eds.), Park City, Utah.
- Cowherd, C., G. Muleski, P. Englehart, and D. Gillete. 1985. Rapid Assessment of Exposure to Particulate Emissions from Surface Contamination. Prepared for U.S. Environmental Protection Agency, Office of Health and Environmental Assessment. EPA/600/8-85/002.
- DEQ (Idaho Department of Environmental Quality). 1996. Risk Based Corrective Action Guidance Document for Petroleum Releases. Boise, ID: DEQ.
- DOE (U.S. Department of Energy). 1995. Housing Characteristics 1993. DOE, Energy Information Administration. DOE/EIA-0314 (93).
- DOE (U.S. Department of Energy). 2001. Commercial Building Energy Consumption Survey. DOE, Energy Information Administration. Summary Table B2. Available at <http://www.eia.doe.gov/emeu/cbecs/>
- Domenico, P.A. 1990. Physical and Chemical Hydrogeology. New York: John Wiley and Sons.
- EPA (U.S. Environmental Protection Agency). 1996. Soil Screening Guidance: Technical Background Document. EPA, Office of Solid Waste and Emergency Response. 9355.4-17A. EPA/540/R-95/128.
- EPA (U.S. Environmental Protection Agency). 2003. User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings (Revised). Washington, DC: EPA, Office of Solid Waste and Emergency Response.
- Hammel, J.E., R.L. Mahler, and J.J. Hutchings. 1995. Impact of Nitrogen Fertilizer Use in Bluegrass Production on Water Quality of the Rathdrum Prairie Aquifer. Moscow, ID: University of Idaho, Soil Science Department. Final Report. Contract No. 5207. Submitted to Idaho Division of Environmental Quality.
- Hers, I. 2002. Input Parameters for OSWER Wide Guidance for Vapor Intrusion Pathway. Technical memorandum to Debbie Newberry, U.S. Environmental Protection Agency, OSW, dated June 3, 2002.
- Johnson, P.C. 2005. Identification of Application-Specific Critical Inputs for the 1991 Johnson and Ettinger Vapor Intrusion Algorithm. Ground Water Monitoring and Remediation 25(1):63-78.

- Johnson, P.C., and R.A. Ettinger. 1991. Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings. *Environmental Science and Technology* 25:1445–1452.
- Kool, J.B., and M. Th. van Genuchten. 1991. HYDRUS, One-Dimensional Variably Saturated Flow and Transport Model, Including Hysteresis and Root Water Uptake. Research Report 124. Riverside, CA: U.S. Salinity Laboratory.
- MDEQ (Michigan Department of Environmental Quality). 1998. Part 201 Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria: Technical Support Document. Lansing, MI: MDEQ, Environmental Response Division.
- Nielson, K.K., and V.C. Rogers. 1990. Radon transport properties of soil classes for estimating indoor radon entry. In: *Proceedings of the 29th Hanford Symposium of Health and the Environment. Indoor Radon and Lung Cancer: Reality or Myth? Part 1.* F.T. Cross (ed.). Richland, WA: Battelle Press.
- Xu, M., and Y. Eckstein. 1995. Use of Weighted Least-Squares Method in Evaluation and Relationship Between Dispersivity and Field Scale. *Ground Water* 33(6):905–908.

*This page intentionally left blank for correct double-sided printing.*

## **Appendix C: Default Physical and Chemical Properties**

*This page intentionally left blank for correct double-sided printing.*

Risk Evaluation Manual for Petroleum Releases

Chemicals	CAS Number	Molecular Weight	Water Solubility (milligrams/liter)	Henry's Law Constant (liters air/liters water)	Organic Carbon Adsorption Coefficient Koc (milliliters/gram)	Vapor Pressure (millimeters mercury) <sup>a</sup>	Diffusion Coefficient in Air (square centimeters/second) <sup>b</sup>	Diffusion Coefficient in Water (square centimeters/second) <sup>b</sup>
Acenaphthene	83-32-9	154.2	3.9	7.5E-03	5027	1.6E-03	0.051	8.3E-06
Anthracene	120-12-7	178.2	0.0434	2.3E-03	16360	2.0E-04	0.039	7.9E-06
Benzene	71-43-2	78.1	1790	2.3E-01	145.8	9.500E+01	0.09	1.0E-05
Benzo(a)anthracene	56-55-3	228.3	0.0094	4.9E-04	176900	1.1E-07	0.045	5.1E-06
Benzo(a)pyrene	50-32-8	252.3	0.0016	1.9E-05	587400	5.5E-09	0.043	4.9E-06
Benzo(b)fluoranthene	205-99-2	252.3	0.0015	2.7E-05	599400	5.0E-07	0.043	4.9E-06
Benzo(k)fluoranthene	207-08-9	252.3	0.0008	2.4E-05	587400	9.6E-11	0.043	4.9E-06
Chrysene	218-01-9	228.3	0.002	2.1E-04	180500	6.3E-09	0.045	5.1E-06
1,2-Dichloroethane	107-06-2	99.0	8600	4.8E-02	40	8.7E+01	0.086	1.1E-05
Ethylbenzene	100-41-4	106.2	169	3.2E-01	446	1.0E+01	0.068	8.5E-06
Ethylene Dibromide	106-93-4	187.9	3910	2.7E-02	40	1.100E+01	0.043	1.0E-05
Fluoranthene	206-44-0	202.3	0.26	3.6E-04	55450	5.0E-06	0.048	5.6E-06
Fluorene	86-73-7	166.2	1.69	3.9E-03	9160	1.0E-04	0.044	7.9E-06
MTBE	1634-04-4	88.2	51000	2.4E-02	12	2.490E+02	0.075	8.6E-06
Naphthalene	91-20-3	128.0	31	1.8E-02	1544	2.3E-01	0.06	8.4E-06
Pyrene	129-00-0	202.3	0.135	4.9E-04	54340	6.9E-07	0.028	7.2E-06
Toluene	108-88-3	92.1	526	2.7E-01	234	2.2E+01	0.078	9.2E-06
Total Xylenes	1330-20-7	106.2	106	2.1E-01	383	8.80E+00	0.085	9.9E-06

Note: Values for physical and chemical properties (with the exception of vapor pressure and some diffusion coefficients) are taken from the U.S. Environmental Protection Agency regional screening levels website (accessed November 2010) chemical specific parameter supporting table (available at [http://www.epa.gov/reg3hwmd/risk/human/rb-concentration\\_table/Generic\\_Tables/pdf/params\\_sl\\_table\\_run\\_NOVEMBER2010.pdf](http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/pdf/params_sl_table_run_NOVEMBER2010.pdf)).

<sup>a</sup> Values for vapor pressure at 20–25 degrees Celsius were obtained from the *Groundwater Chemicals Desk Reference, Volume 1* by John H. Montgomery and Linda M. Welkom (1991, Lewis Publishers) and the *Groundwater Chemicals Desk Reference, Volume 2* by John H. Montgomery (1991, Lewis Publishers).

<sup>b</sup> Diffusion coefficient values in air and water for selected polynuclear aromatic hydrocarbon chemicals (benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, fluoranthene, and chrysene) were not available in the U.S. Environmental Protection Agency regional screening levels table. These values were calculated using the EPA online chemical property calculator available at <http://www.epa.gov/athens/learn2model/part-two/onsite/estdiffusion-ext.html>.

Comment [MAB1]: Current table [http://www.epa.gov/reg3hwmd/risk/human/rb-concentration\\_table/Generic\\_Tables/pdf/master\\_sl\\_table\\_run\\_JUN2011.pdf](http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/pdf/master_sl_table_run_JUN2011.pdf)

*This page intentionally left blank for correct double-sided printing.*

**Appendix D: Default Toxicity Values**

*This page intentionally left blank for correct double-sided printing.*

The table below provides a list of the default carcinogenic and noncarcinogenic toxicity factors and oral and dermal relative absorption factors used in the risk evaluation process. All toxicity factor values, oral relative absorption factors, and dermal relative absorption factors for polynuclear aromatic hydrocarbons were obtained from the U.S. Environmental Protection Agency (EPA) regional screening level website and are current as of May 2011:

Comment [MAB1]: Current is June 2011

[http://www.epa.gov/reg3hwmd/risk/human/rb-concentration\\_table/Generic\\_Tables/index.htm](http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/index.htm)

In their *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual* (Part E, Supplemental Guidance for Dermal Risk Assessment), the EPA did not provide recommendations for dermal relative absorption factors for volatile organic compounds. The source of dermal relative absorption factors for volatile organic compounds in the table below is the June 2003 guidance issued by EPA Region 3 (available at <http://www.epa.gov/reg3hwmd/risk/human/info/dermalag.htm>).

Chemicals	CAS Number	Oral Slope Factor (kg-day/mg) <sup>a</sup>	Unit Inhalation Risk (µg/m <sup>3</sup> ) <sup>b</sup>	Oral Reference Dose (mg/kg-day) <sup>c</sup>	Inhalation Reference Concentration (mg/m <sup>3</sup> ) <sup>d</sup>	Oral Relative Absorption Factor	Dermal Relative Absorption Factor
Acenaphthene	83-32-9	NA	NA	6.0E-2	NA	1	0.13
Anthracene	120-12-7	NA	NA	3.0E-1	NA	1	0.13
Benzene	71-43-2	5.5E-2	7.8E-6	4.0E-3	3.0E-2	1	0
Benzo(a)anthracene	56-55-3	7.3E-1	1.1E-4	NA	NA	1	0.13
Benzo(a)pyrene	50-32-8	7.3E0	1.1E-3	NA	NA	1	0.13
Benzo(b)fluoranthene	205-99-2	7.3E-1	1.1E-4	NA	NA	1	0.13
Benzo(k)fluoranthene	207-08-9	7.3E-2	1.1E-4	NA	NA	1	0.13
Chrysene	218-01-9	7.3E-3	1.1E-5	NA	NA	1	0.13
1,2-Dichloroethane	107-06-2	9.1E-2	2.6E-5	2.0E-2	2.4E0	1	0
Ethylbenzene	100-41-4	1.1E-2	2.5E-6	1.0E-1	1.0E0	1	0
Ethylene Dibromide	106-93-4	2.0E0	6.0E-4	9.0E-3	9.0E-3	1	0
Fluoranthene	206-44-0	NA	NA	4.0E-2	NA	1	0.13
Fluorene	86-73-7	NA	NA	4.0E-2	NA	1	0.13
MTBE	1634-04-4	1.8E-3	2.6E-7	NA	3.0E0	1	0
Naphthalene	91-20-3	NA	3.4E-5	2.0E-2	3.0E-3	1	0.13
Pyrene	129-00-0	NA	NA	3.0E-2	NA	1	0.13
Toluene	108-88-3	NA	NA	8.0E-2	5.0E0	1	0
Total Xylenes	1330-20-7	NA	NA	2.0E-1	1.0E-1	1	0

<sup>a</sup> kg-day/mg = kilogram-day per milligram

<sup>b</sup> µg/m<sup>3</sup> = microgram per cubic meter

<sup>c</sup> mg/kg-day = milligram per kilogram-day

<sup>d</sup> mg/m<sup>3</sup> = milligram per cubic meter

## **Appendix E: Models and Equations**

*This page intentionally left blank for correct double-sided printing.*

## TABLE OF CONTENTS

---

<b>1</b>	<b>Target Levels for Non-Residential and Construction Worker Exposures .....</b>	<b>1</b>
1.1	Indoor Inhalation of Vapor Emissions .....	1
1.2	Outdoor Inhalation of Vapors and Particulates from Surficial Soil.....	2
1.3	Direct Ingestion of Surficial Soil .....	3
1.4	Dermal Contact with Surficial Soil.....	4
1.5	Combined Direct Contact Soil Pathway: Ingestion, Inhalation of Vapors and Particulates, and Dermal Contact.....	5
1.6	Subsurface Soil Concentrations Protective of Indoor Vapor Inhalation.....	6
1.7	Ground Water Concentrations Protective of Indoor Vapor Inhalation.....	7
1.8	Direct Ingestion of Ground Water .....	8
1.9	Johnson and Ettinger Infinite Source Model .....	9
1.10	Johnson and Ettinger Finite Source Model.....	11
<b>2</b>	<b>Target Levels for Residential Exposures .....</b>	<b>12</b>
2.1	Indoor Inhalation of Vapor Emissions .....	12
2.2	Outdoor Inhalation of Vapors and Particulates from Surficial Soil.....	13
2.3	Direct Ingestion of Surficial Soil .....	14
2.4	Dermal Contact with Surficial Soil.....	15
2.5	Combined Direct Contact Soil Pathway: Ingestion, Inhalation of Vapors and Particulates, and Dermal Contact.....	16
2.6	Subsurface Soil Concentrations Protective of Indoor Vapor Inhalation.....	17
2.7	Ground Water Concentrations Protective of Indoor Vapor Inhalation.....	18
2.8	Direct Ingestion of Ground Water .....	19
<b>3</b>	<b>Target Levels for Ground Water Resource Protection .....</b>	<b>20</b>
3.1	Domenico Model: Dilution Attenuation Factor (DAF) in the Saturated Zone..	20
3.2	Soil to Ground Water Leaching Factor .....	21
3.3	Soil Saturation Limit.....	22
3.4	Soil and Ground Water Concentration for Ground Water Protection.....	23
<b>4</b>	<b>Volatilization Factor, Particulate Emission Factor, and Effective Diffusion Coefficients .....</b>	<b>24</b>
4.1	Volatilization Factor from Surface Soil to Outdoor (ambient) Air.....	24
4.2	Particulate Emission Factor .....	25
4.3	Effective Diffusion Coefficients .....	25
4.3.1	Effective Diffusion Coefficient in Soil .....	25
4.3.2	Effective Diffusion Coefficient between Ground Water and Surface Soil.	26
4.3.3	Effective Diffusion Coefficient In Capillary Fringe Soil .....	26
4.3.4	Effective Diffusion Coefficient In Foundation/Wall Cracks .....	27
4.4	Water Content in Soil in the Capillary Fringe .....	27
	<b>References.....</b>	<b>28</b>

*This page intentionally left blank for correct double-sided printing.*

## 1 Target Levels for Non-Residential and Construction Worker Exposures

### 1.1 Indoor Inhalation of Vapor Emissions

#### Carcinogenic effects

$$RBTL_{ai} = \frac{TR \times AT_c \times 365}{ED \times EF \times ET_i \times IUR \times 1000}$$

#### Noncarcinogenic effects

$$RBTL_{ai} = \frac{THQ \times AT_{nc} \times 365}{ED \times EF \times ET_i \times \left( \frac{1}{RfC} \right)}$$

Where:

- $RBTL_{ai}$  = Risk-based target level for indoor air inhalation [ $\text{mg}/\text{m}^3$ ]
- $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- $THQ$  = Target hazard quotient for individual constituents [-]
- $AT_c$  = Averaging time for carcinogens [years]
- $AT_{nc}$  = Averaging time for noncarcinogens [years]
- $ED$  = Exposure duration [years]
- $EF$  = Exposure frequency [days/year]
- $ET_i$  = Exposure time for indoor inhalation [hours/day]
- $RfC$  = Chemical-specific inhalation reference concentration [ $\text{mg}/\text{m}^3$ ]
- $IUR$  = Chemical-specific inhalation unit risk [ $(\mu\text{g}/\text{m}^3)^{-1}$ ]
- 365 = Conversion factor [days/year]

Source: EPA 2009, modified from equations 6 and 11

## 1.2 Outdoor Inhalation of Vapors and Particulates from Surficial Soil

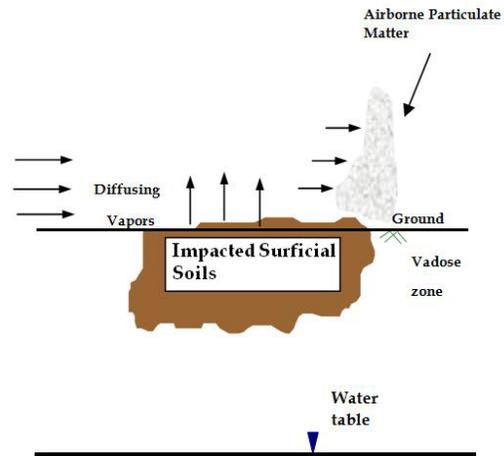
### Carcinogenic effects

$$RBTL_{ss} = \frac{TR \times AT_c \times 365}{ED \times EF_d \times ET \times IUR \times \left( \frac{1}{VF} + \frac{1}{PEF} \right) \times 1000}$$

### Noncarcinogenic effects

$$RBTL_{ss} = \frac{THQ \times AT_{nc} \times 365}{ED \times EF_d \times ET \times \left( \frac{1}{RfC} \right) \times \left( \frac{1}{VF} + \frac{1}{PEF} \right)}$$

Source: EPA 2011



Where:

- $RBTL_{ss}$  = Risk-based target level for outdoor inhalation of vapors and particulates from surficial soil [mg/kg dry weight]
- $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- $THQ$  = Target hazard quotient for individual constituents [-]
- $VF$  = Surficial soil to ambient air volatilization factor [(m<sup>3</sup>-air)/(kg-soil)]
- $PEF$  = Particulate emission factor [(m<sup>3</sup>-air)/(kg-soil)]
- $AT_c$  = Averaging time for carcinogens [years]
- $AT_{nc}$  = Averaging time for noncarcinogens [years]
- $ED$  = Exposure duration [years]
- $EF_d$  = Exposure frequency for direct contact pathway [days/year]
- $ET$  = Exposure time [hours/day]
- $RfC$  = Chemical-specific inhalation reference concentration [mg/m<sup>3</sup>]
- $IUR$  = Chemical-specific inhalation unit risk [(μg/m<sup>3</sup>)<sup>-1</sup>]
- 365 = Conversion factor [days/year]

### 1.3 Direct Ingestion of Surficial Soil

#### Carcinogenic effects

$$RBTL_s = \frac{TR \times BW \times AT_c \times 365}{SF_o \times EF_d \times ED \times IR_s \times RAF_o \times 10^{-6}}$$

#### Noncarcinogenic effects

$$RBTL_s = \frac{THQ \times BW \times AT_{nc} \times 365}{EF_d \times ED \times \left( \frac{1}{RAF_o \times RfD_o} \right) IR_s \times 10^{-6}}$$

Where:

- $RBTL_s$  = Risk-based target level for the ingestion of soil [mg/kg-wet soil]
- $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- $THQ$  = Target hazard quotient for individual constituents [-]
- $BW$  = Body weight [kg]
- $AT_c$  = Averaging time for carcinogens [years]
- $AT_{nc}$  = Averaging time for noncarcinogens [years]
- $ED$  = Exposure duration [years]
- $EF_d$  = Exposure frequency [days/year]
- $IR_s$  = Soil ingestion rate [mg/day]
- $RAF_o$  = Oral relative absorption factor [-]
- $RfD_o$  = Chemical-specific oral reference dose [mg/(kg-day)]
- $SF_o$  = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]<sup>-1</sup>
- 365 = Conversion factor [days/year]
- 10<sup>-6</sup> = Conversion factor [kg/mg]

Source: EPA 1996, p. 19

### 1.4 Dermal Contact with Surficial Soil

#### Carcinogenic effects

$$RBTL_{DC} = \frac{TR \times BW \times AT_c \times 365}{SF_o \times SA \times M \times RAF_d \times ED \times EF_d \times 10^{-6}}$$

#### Noncarcinogenic effects

$$RBTL_{DC} = \frac{THQ \times BW \times AT_{nc} \times 365}{SA \times M \times \left( \frac{1}{RfD_o \times RAF_d} \right) \times ED \times EF_d \times 10^{-6}}$$

Where:

- $RBTL_{DC}$  = Risk-based target level for dermal contact with soil [mg/kg-wet soil]  
 $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]  
 $THQ$  = Target hazard quotient for individual constituents [-]  
 $BW$  = Body weight [kg]  
 $AT_c$  = Averaging time for carcinogens [years]  
 $AT_{nc}$  = Averaging time for noncarcinogens [years]  
 $ED$  = Exposure duration [years]  
 $EF_d$  = Exposure frequency for direct contact pathway [days/year]  
 $RAF_d$  = Dermal relative absorption factor [-]  
 $SA$  = Skin surface area [cm<sup>2</sup>/day]  
 $M$  = Soil to skin adherence factor [mg/cm<sup>2</sup>]  
 $RfD_o$  = Chemical-specific oral reference dose [mg/(kg-day)]  
 $SF_o$  = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]<sup>-1</sup>  
 365 = Conversion factor [days/year]  
 10<sup>-6</sup> = Conversion factor [kg/mg]

Source: Modified from EPA 1989, p. 6-41; See also EPA 2007, Appendix D, p. D-6

### 1.5 Combined Direct Contact Soil Pathway: Ingestion, Inhalation of Vapors and Particulates, and Dermal Contact

#### Carcinogenic effects

$$RBTL_{ss-combined} = \frac{TR \times BW \times AT_c \times 365}{ED \times EF_d \times SF_o \times 10^{-6} [(IR_s \times RAF_o) + (SA \times M \times RAF_d)]} + \frac{TR \times AT_c \times 365}{ED \times EF_d \times ET \times IUR \times \left( \frac{1}{VF} + \frac{1}{PEF} \right) \times 1000}$$

#### Noncarcinogenic effects

$$RBTL_{ss-combined} = \frac{THQ \times BW \times AT_{nc} \times 365}{ED \times EF_d \times 10^{-6} \times \frac{1}{RfD_o} [(IR_s \times RAF_o) + (SA \times M \times RAF_d)]} + \frac{THQ \times AT_{nc} \times 365}{ED \times EF_d \times ET \times \frac{1}{RfC} \left( \frac{1}{VF} + \frac{1}{PEF} \right)}$$

Note: All parameters are defined under the individual pathway equations above (sections 1.2–1.4).

### 1.6 Subsurface Soil Concentrations Protective of Indoor Vapor Inhalation

$$RBTL_{si} = \frac{RBTL_{ai} * EF}{\alpha}$$

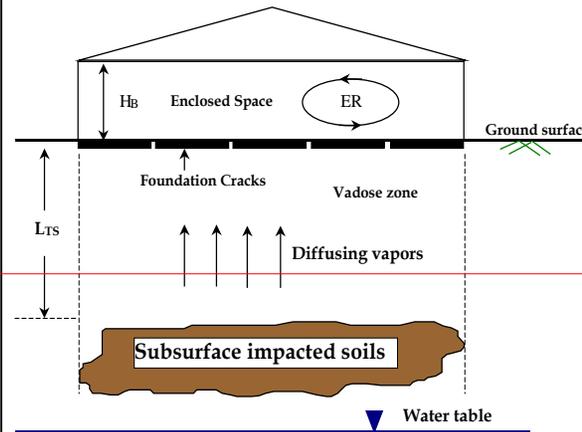
Where:

- $RBTL_{si}$  = Risk-based target level for indoor inhalation of vapors from subsurface soils [mg/kg-dry soil]
- $RBTL_{ai}$  = Risk-based target level for indoor inhalation of air [mg/m<sup>3</sup>-air]
- $\alpha$  = Attenuation factor from subsurface soil to indoor (enclosed space) air derived from the Johnson-Ettinger model [1]
- $EF$  = Equilibrium factor to convert vapor target level to total soil target level

$$= \frac{\theta_{ws} + (K_D \rho_s) + (H \theta_{as})}{(H \rho_s)} * 0.001$$

Where:

- $\rho_s$  = Dry soil bulk density [g-soil/cm<sup>3</sup>-soil]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]
- $\theta_{as}$  = Volumetric air content in the vadose zone soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in vadose zone soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>-soil]
- $K_D$  =  $f_{oc} \times K_{oc}$  = Chemical-specific soil-water sorption coefficient [cm<sup>3</sup>-H<sub>2</sub>O/g-soil]



**Comment [MAB1]:** ??? and previous comment - We might have missed this in another appendix, but where is this value given?

### 1.7 Ground Water Concentrations Protective of Indoor Vapor Inhalation

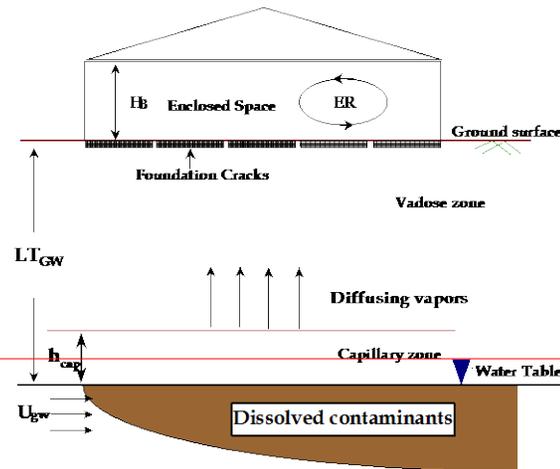
$$RBTL_{wi} = \frac{RBTL_{ai} * EF}{\alpha}$$

Where:

- $RBTL_{wi}$  = Risk-based target level for indoor inhalation of vapors from ground water [mg/L-H<sub>2</sub>O]
- $RBTL_{ai}$  = Risk-based target level for indoor inhalation of air (mg/m<sup>3</sup>-air)
- $\alpha$  = Attenuation factor from ground water to indoor (enclosed space) air derived from the Johnson-Ettinger model [-]
- EF = Equilibrium factor to convert vapor target level to water target level  
= (1/H)\*0.001m<sup>3</sup>/L

Where:

H = Henry's Law Constant [-]



Comment [MAB2]: Same as previous comment

## 1.8 Direct Ingestion of Ground Water

### Carcinogenic effects

$$RBTL_w = \frac{TR \times BW \times AT_c \times 365}{IR_w \times ED \times EF \times SF_o}$$

### Noncarcinogenic effects

$$RBTL_w = \frac{THQ \times BW \times AT_{nc} \times 365}{IR_w \times \left( \frac{1}{RfD_o} \right) \times ED \times EF}$$

Where:

- $RBTL_w$  = Risk-based target level for ingestion of ground water [mg/L-H<sub>2</sub>O]
- $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- $THQ$  = Target hazard quotient for individual constituents [-]
- $BW$  = Body weight [kg]
- $AT_c$  = Averaging time for carcinogens [years]
- $AT_{nc}$  = Averaging time for noncarcinogens [years]
- $IR_w$  = Water ingestion rate [L/day]
- $ED$  = Exposure duration [years]
- $EF$  = Exposure frequency [days/year]
- $RfD_o$  = Chemical-specific oral reference dose [mg/(kg-day)]
- $SF_o$  = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]<sup>-1</sup>
- 365 = Conversion factor [days/year]

Source: Modified from EPA 1989, p. 6-35

### 1.9 Johnson and Ettinger Infinite Source Model

The model predicts the vapor concentration inside a building from the measured soil-vapor, soil, or ground water concentration.

$$C_{building} = \alpha \times C_{source}$$

Where:

$$C_{source} = \frac{H \times C_{soil} \times \rho_s}{\theta_{ws} + K_d \times \rho_s + H \times \theta_{as}}$$

OR

$$C_{source} = H \times C_w$$

OR

$C_{source}$  = Measured soil-vapor concentration [mg/L]

- $C_{building}$  = Steady-state vapor-phase concentration in the building [mg/L]
- $\alpha$  = Attenuation coefficient in the vapor phase [-]
- $C_{source}$  = Vapor-phase concentration at the source [mg/L]
- $C_{soil}$  = Concentration in soil [mg/kg]
- $C_w$  = Concentration in ground water [mg/L]
- $H$  = Chemical-specific Henry's Law constant (L-H<sub>2</sub>O)/(L-air)
- $\rho_s$  = Dry soil bulk density [g-soil/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in vadose zone soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>-soil]
- $K_d$  =  $f_{oc} \times K_{oc}$   
= Chemical-specific soil-water sorption coefficient [cm<sup>3</sup>-H<sub>2</sub>O/g-soil]
- $\theta_{as}$  = Volumetric air content in vadose zone soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]

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

Source: EPA 2003

- $D_T^{eff}$  = Total overall effective diffusion coefficient [cm<sup>2</sup>/s]
- $D_{crack}^{eff}$  = Effective diffusion coefficient through cracks [cm<sup>2</sup>/s]
- $A_B$  = Area of the enclosed space below grade [cm<sup>2</sup>]
- $Q_{building}$  = Building ventilation rate [cm<sup>3</sup>/s]
- $L_T$  = Source-building separation [cm]
- $Q_{soil}$  = Volumetric flow rate of soil gas into the enclosed space [cm<sup>3</sup>/s]
- $L_{crack}$  = Enclosed space foundation or slab thickness [cm]
- $A_{crack}$  = Total area of cracks [cm<sup>2</sup>]

**1.9 Johnson and Ettinger Infinite Source Model (continued)**

Where:

$$Q_{building} = L_B W_B H_B ER$$

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

For vapor release from soil:

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

For vapor release from ground water:

$$D_T^{eff} = D_s^{eff} \quad D_{crack}^{eff} = D_s^{eff}$$

$$D_T^{eff} = D_{ws}^{eff} = \frac{L_T}{\frac{h_{cap}}{D_{cap}^{eff}} + \frac{(L_T - h_{cap})}{D_s^{eff}}} \quad h_{cap} = \frac{0.75}{D}$$

$Q_{building}$	=	Building ventilation rate [cm <sup>3</sup> /s]
$L_B$	=	Length of building [cm]
$W_B$	=	Width of building [cm]
$H_B$	=	Height of building [cm]
$ER$	=	Air exchange rate [1/s]
$Q_{soil}$	=	Volumetric flow rate of soil gas into the enclosed space [cm <sup>3</sup> /s]
$\pi$	=	3.14159
$\Delta P$	=	Pressure differential between the soil surface and the enclosed space [g/cm-s <sup>2</sup> ]
$k_v$	=	Soil vapor permeability [cm <sup>2</sup> ]
$X_{crack}$	=	Floor-wall seam perimeter [cm]
$\mu$	=	Viscosity of air [g/cm-s]
$Z_{crack}$	=	Crack depth below grade [cm]
$r_{crack}$	=	Equivalent crack radius [cm]
$D_T^{eff}$	=	Total overall effective diffusion coefficient [cm <sup>2</sup> /s]
$L_T$	=	Source-building separation [cm]
$L_i$	=	Thickness of soil layer $i$ [cm]
$D_i^{eff}$	=	Effective diffusion coefficient in soil layer $i$ [cm <sup>2</sup> /s]
$n$	=	Number of soil layers [-]
$D_s^{eff}$	=	Effective diffusion coefficient in soil [cm <sup>2</sup> /s]
$D_{ws}^{eff}$	=	Effective diffusion coefficient in capillary fringe [cm <sup>2</sup> /s]
$h_{cap}$	=	Thickness of capillary fringe zone [cm]
$D_{cap}^{eff}$	=	Effective diffusion coefficient in the capillary fringe soil [cm <sup>2</sup> /s]
$D_{crack}^{eff}$	=	Effective diffusion coefficient in the foundation/wall cracks [cm <sup>2</sup> /s]
$D$	=	Mean particle diameter [cm]

### 1.10 Johnson and Ettinger Finite Source Model

The model predicts the vapor concentration inside a building from the measured soil concentration when the thickness of soil contamination is known.

$$C_{building} = \alpha \times C_{source}$$

Where:

$$C_{source} = \frac{H \times C_{soil} \times \rho_s}{\theta_{ws} + K_d \times \rho_s + H \times \theta_{as}}$$

$$\alpha = \frac{\rho_s C_{soil} \Delta H_c A_B \left( \frac{L_T^0}{\Delta H_c} \right) \left[ \left( \beta^2 + 2 \psi \tau \right)^{1/2} - \beta \right]}{Q_{building} C_{source} \tau}$$

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

$$\psi = \frac{D_T^{eff} C_{source}}{\left( L_T^0 \right)^2 \rho_s C_{soil}}$$

$$\tau_D = \frac{\left[ \frac{\Delta H_c}{L_T^0} + \beta \right]^2 - \beta^2}{2 \psi}$$

Source: EPA 2003

- $C_{building}$  = Steady-state vapor-phase concentration in the building [mg/L]
- $\alpha$  = Attenuation coefficient in the vapor phase [-]
- $C_{source}$  = Vapor-phase concentration at the source [mg/L]
- $C_{soil}$  = Original concentration in soil [mg/kg]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]
- $\rho_s$  = Dry soil bulk density [g-soil/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in vadose zone soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>-soil]
- $K_d$  =  $f_{oc} \times K_{oc}$   
= Chemical-specific soil-water sorption coefficient [cm<sup>3</sup>-H<sub>2</sub>O/g-soil]
- $\theta_{as}$  = Volumetric air content in vadose zone soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $\Delta H_c$  = Initial thickness of contamination [cm]
- $\tau_D$  = Time for source depletion [seconds]
- $\tau$  = Exposure interval [seconds]
- $D_T^{eff}$  = Total overall effective diffusion coefficient [cm<sup>2</sup>/s]
- $D_{crack}^{eff}$  = Effective diffusion coefficient through cracks [cm<sup>2</sup>/s]
- $A_B$  = Area of the enclosed space below grade [cm<sup>2</sup>]
- $Q_{building}$  = Building ventilation rate [cm<sup>3</sup>/s]
- $L_T^0$  = Source-building separation at time = 0 [cm]
- $Q_{soil}$  = Volumetric flow rate of soil gas into the enclosed space [cm<sup>3</sup>/s]
- $A_{crack}$  = Total area of cracks [cm<sup>2</sup>]
- $L_{crack}$  = Enclosed space foundation or slab thickness [cm]

## 2 Target Levels for Residential Exposures

### 2.1 Indoor Inhalation of Vapor Emissions

#### Carcinogenic effects

$$RBTL_{ai-res} = \frac{TR \times AT_c \times 365}{EF_r \times ED_r \times ET_{ra} \times IUR}$$

#### Noncarcinogenic effects

$$RBTL_{ai-res} = \frac{THQ \times AT_{nc} \times 365}{EF_r \times ED_r \times ET_{ra} \times \left(\frac{1}{RfC}\right)}$$

Where:

- $RBTL_{ai-res}$  = Residential risk-based target level in indoor air [ $\text{mg}/\text{m}^3$ ]  
 $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]  
 $THQ$  = Target hazard quotient for individual constituents [-]  
 $AT_c$  = Averaging time for carcinogens [years]  
 $AT_{nc}$  = Averaging time for noncarcinogens [years]  
 $ED_r$  = Exposure duration for resident [years]  
 $EF_r$  = Residential exposure frequency [days/year]  
 $ET_{ra}$  = Indoor residential exposure time [hours/day]  
 $RfC$  = Chemical-specific inhalation reference concentration [ $\text{mg}/\text{m}^3$ ]  
 $IUR$  = Chemical-specific inhalation unit risk [ $\mu\text{g}/\text{m}^3$ ]<sup>-1</sup>  
 365 = Conversion factor [days/year]

Source: EPA 2009, modified from equations 6 and 11

## 2.2 Outdoor Inhalation of Vapors and Particulates from Surficial Soil

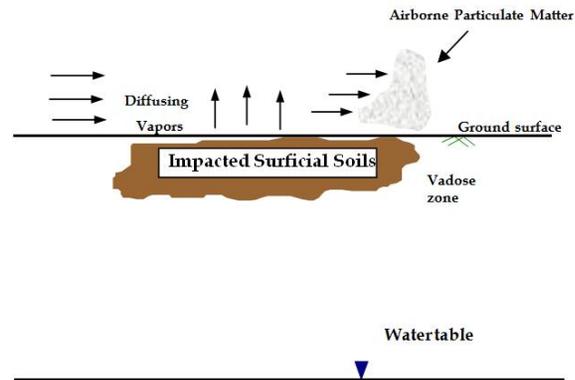
### Carcinogenic effects

$$RBTL_{SS} = \frac{TR \times AT_c \times 365}{ED_r \times EF_{res} \times ET_{o-r} \times IUR \times \left( \frac{1}{VF} + \frac{1}{PEF} \right) \times 1000}$$

### Noncarcinogenic effects

$$RBTL_{SS} = \frac{THQ \times AT_{nc} \times 365}{ED_c \times EF_{res} \times ET_{o-r} \times \left( \frac{1}{RfC} \right) \times \left( \frac{1}{VF} + \frac{1}{PEF} \right)}$$

Source: EPA 1996



Where:

- $RBTL_{SS}$  = Risk-based target level in surficial soil [mg/kg]
- $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- $THQ$  = Target hazard quotient for individual constituents [-]
- $VF$  = Surficial soil to ambient air volatilization factor [(m<sup>3</sup>-air)/(kg-soil)]
- $PEF$  = Particulate emission factor [(m<sup>3</sup>-air)/(kg-soil)]
- $AT_c$  = Averaging time for carcinogens [years]
- $AT_{nc}$  = Averaging time for noncarcinogens [years]
- $ED_c$  = Exposure duration for child [years]
- $ED_r$  = Residential exposure duration [years]
- $EF_{res}$  = Residential exposure frequency for direct contact pathway [days/year]
- $ET_{o-r}$  = Residential outdoor exposure time [hours/day]
- $RfC$  = Chemical-specific reference concentration [mg/(m<sup>3</sup>)]
- $IUR$  = Chemical-specific inhalation unit risk [ $\mu\text{g}/\text{m}^3$ ]<sup>-1</sup>
- 365 = Conversion factor [days/year]

### 2.3 Direct Ingestion of Surficial Soil

Carcinogenic effects

$$RBTL_{S-adj} = \frac{TR \times AT_c \times 365}{SF_o \times IR_{s-aa} \times RAF_o \times 10^{-6}}$$

Where:

$$IR_{s-aa} = \frac{ED_c \times EF_{res} \times IR_{s-c}}{BW_c} + \frac{(ED_{res} - ED_c) \times EF_{res} \times IR_{s-a}}{BW_a}$$

Noncarcinogenic effects

$$RBTL_S = \frac{THQ \times AT_{nc} \times 365 \times BW_c}{IR_{s-c} \times \left( \frac{1}{RfD_o \times RAF_o} \right) \times 10^{-6} \times EF_{res} \times ED_c}$$

Source: EPA 1996, p. 20

Where:

- $RBTL_{S-adj}$  = Age-adjusted risk-based target level for ingestion of soil for carcinogenic effects [mg/kg soil]
- $RBTL_S$  = Risk-based target level for ingestion of soil for noncarcinogenic effects [mg/kg-soil]
- $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- $THQ$  = Target hazard quotient for individual constituents [-]
- $AT_c$  = Averaging time for carcinogens [years]
- $AT_{nc}$  = Averaging time for noncarcinogens [years]
- $RAF_o$  = Oral relative absorption factor [-]
- $RfD_o$  = Chemical-specific oral reference dose [mg/(kg-day)]
- $SF_o$  = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]<sup>-1</sup>
- $IR_{s-aa}$  = Age-adjusted soil ingestion rate [mg/kg]
- $IR_{s-c}$  = Resident child soil ingestion rate [mg/day]
- $IR_{s-a}$  = Resident adult soil ingestion rate [mg/day]
- $BW_c$  = Resident child body weight [kg]
- $BW_a$  = Resident adult body weight [kg]
- $ED_c$  = Resident child exposure duration [year]
- $ED_a$  = Resident adult exposure duration [year]
- $ED_{res}$  = Resident exposure duration [year]
- $EF_{res}$  = Exposure frequency for a resident for direct contact pathway [days/year]
- 365 = Conversion factor [days/year]
- $10^{-6}$  = Conversion factor [kg/mg]

Comment [MAB3]: ? Previous comment - Missing BWc now RfDo?

## 2.4 Dermal Contact with Surficial Soil

### Carcinogenic effects

$$RBTL_{DC-adj} = \frac{TR \times AT_c \times 365}{SF_o \times SA_{aa} \times RAF_d \times 10^{-6}}$$

Where:

$$SA_{aa} = \frac{ED_c \times EF_{res} \times M_c \times SA_c}{BW_c} + \frac{ED_a \times EF_{res} \times M_a \times SA_a}{BW_a}$$

### Noncarcinogenic effects

$$RBTL_{DC} = \frac{THQ \times AT_{nc} \times 365 \times BW_c}{EF_{dc} \times ED_c \times M_c \times SA_c \times \left( \frac{1}{RfD_o \times RAF_d} \right) \times 10^{-6}}$$

Source: EPA 2007, Appendix D, p. D-6

Where:

- $RBTL_{DC-adj}$  = Age-adjusted risk-based target level for carcinogenic effects of dermal contact with soil [mg/kg soil]
- $RBTL_{DC}$  = Risk-based target level for noncarcinogenic effects of dermal contact with soil [mg/kg soil]
- $TR$  = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- $THQ$  = Target hazard quotient for individual constituents [-]
- $AT_c$  = Averaging time for carcinogens [years]
- $AT_{nc}$  = Averaging time for noncarcinogens [years]
- $EF_{res}$  = Exposure frequency for a resident for direct contact pathway [days/year]
- $RAF_d$  = Chemical-specific dermal relative absorption factor [-]
- $M_c$  = Resident child soil-to-skin adherence factor [mg/cm<sup>2</sup>]
- $M_a$  = Resident adult soil-to-skin adherence factor [mg/cm<sup>2</sup>]
- $RfD_o$  = Chemical-specific oral reference dose [mg/(kg-day)]
- $SF_o$  = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]<sup>-1</sup>
- $SA_{aa}$  = Age-adjusted skin surface area [mg/ kg]
- $BW_c$  = Resident child body weight [kg]
- $BW_a$  = Resident adult body weight [kg]
- $ED_c$  = Resident child exposure duration [year]
- $ED_a$  = Resident adult exposure duration [year]
- $SA_c$  = Resident child skin surface area [cm<sup>2</sup>/day]
- $SA_a$  = Resident adult skin surface area [cm<sup>2</sup>/day]
- 365 = Conversion factor [days/year]
- 10<sup>-6</sup> = Conversion factor [kg/mg]

**Comment [MAB4]:** Previous comment Missing BWc now missing RfDo

## 2.5 Combined Direct Contact Soil Pathway: Ingestion, Inhalation of Vapors and Particulates, and Dermal Contact

### Carcinogenic effects

$$RBTL_{ss-combined} = \frac{TR \times AT_c \times 365}{SF_o \times 10^{-6} \times [(IR_{s-aa} \times RAF_o) + (SA_{aa} \times RAF_d)]} + \frac{TR \times AT_c \times 365}{ED_r \times EF_{res} \times ET_{o-r} \times IUR \times \left( \frac{1}{VF} + \frac{1}{PEF} \right) \times 1000}$$

### Noncarcinogenic effects

$$RBTL_{ss-combined} = \frac{THQ \times AT_{nc} \times 365}{\frac{1}{RfD_o} \times 10^{-6} \times \left[ \left( \left( \frac{ED_c + EF_{res} + IR_{s-c}}{BW_c} \right) \times RAF_o \right) + \left( \left( \frac{ED_c + EF_{res} + M_c + SA_c}{BW_c} \right) \times RAF_d \right) \right]} + \frac{THQ \times AT_{nc} \times 365}{ED_r \times EF_{res} \times ET_{o-r} \times \left( \frac{1}{RfC} \right) \times \left( \frac{1}{VF} + \frac{1}{PEF} \right)}$$

Note: All parameters are defined under the individual pathway equations above (sections 2.2–2.4).

## 2.6 Subsurface Soil Concentrations Protective of Indoor Vapor Inhalation

$$RBTL_{si} = \frac{RBTL_{ai}}{\alpha} * EF$$

Where:

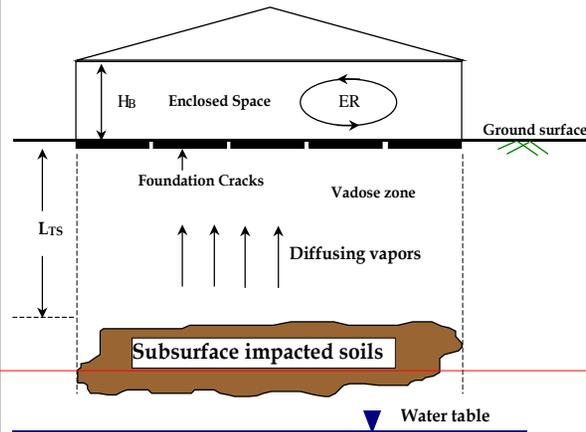
- $RBTL_{si}$  = Risk-based target level for indoor inhalation of vapors from subsurface soils [mg/kg-dry soil]
- $RBTL_{ai}$  = Risk-based target level for indoor inhalation of air [mg/m<sup>3</sup>-air]
- $\alpha$  = Attenuation factor from subsurface soil to indoor (enclosed space) air derived from the Johnson-Ettinger model [-]
- $EF$  = Equilibrium factor to convert vapor target level to total soil target level

$$= \frac{\theta_{ws} + (K_D \rho_s) + (H \theta_{as})}{(H \rho_s)} * 0.001$$

Where:

- $\rho_s$  = Dry soil bulk density [g-soil/cm<sup>3</sup>-soil]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]
- $\theta_{as}$  = Volumetric air content in the vadose zone soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in vadose zone soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>-soil]
- $K_D$  =  $f_{oc} \times K_{oc}$  = Chemical-specific soil-water sorption coefficient [cm<sup>3</sup>-H<sub>2</sub>O/g-soil]

Source: Modified from EPA 2003



Comment [MAB5]: ? Previous comment - We might have missed this in another appendix, but where is this value given?

## 2.7 Ground Water Concentrations Protective of Indoor Vapor Inhalation

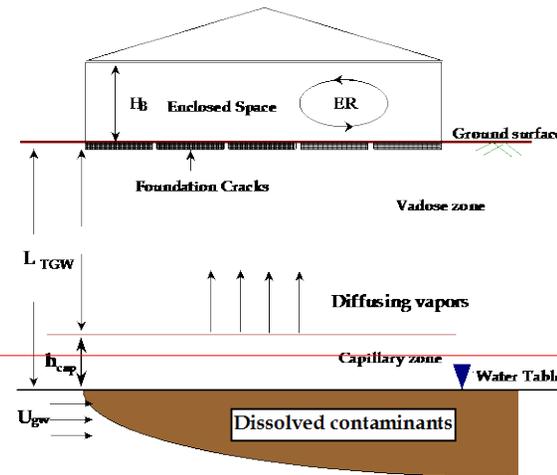
$$RBTL_{wi} = \frac{RBTL_{ai} * EF}{\alpha}$$

Where:

- $RBTL_{wi}$  = Risk-based target level for indoor inhalation of vapors from ground water [mg/L-H<sub>2</sub>O]
- $RBTL_{ai}$  = Risk-based target level for indoor inhalation of air (mg/m<sup>3</sup>-air)
- $\alpha$  = Attenuation factor from ground water to indoor (enclosed space) air derived from the Johnson-Ettinger model [-]
- EF = Equilibrium factor to convert vapor target level to water target level  
= (1/H)\*0.001m<sup>3</sup>/L

Where:

$$H = \text{Henry's Constant [-]}$$



Comment [MAB6]: Same as previous comment

Source: Modified from EPA 2003

## 2.8 Direct Ingestion of Ground Water

<p><u>Carcinogenic effects</u></p> $RBTL_{w-adj} = \frac{TR \times AT_c \times 365}{IR_{w-aa} \times SF_o}$ <p>Where:</p> $IR_{w-aa} = \frac{ED_c \times EF_{res} \times IR_{w-c}}{BW_c} + \frac{ED_a \times EF_{res} \times IR_{w-a}}{BW_a}$ <p><u>Noncarcinogenic effects</u></p> $RBTL_w = \frac{THQ \times AT_{nc} \times 365 \times RfD_o \times BW_a}{IR_{w-a} \times EF_{res} \times ED_a}$ <p>Source: Modified from EPA 1989, p. 6-35</p>	<p>Where:</p> <p><math>RBTL_{w-adj}</math> = Age-adjusted risk-based target level for ingestion of ground water [mg/L-H<sub>2</sub>O]</p> <p><math>RBTL_w</math> = Risk-based target level for ingestion of ground water [mg/L-H<sub>2</sub>O]</p> <p><math>TR</math> = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]</p> <p><math>THQ</math> = Target hazard quotient for individual constituents [-]</p> <p><math>AT_c</math> = Averaging time for carcinogens [years]</p> <p><math>AT_{nc}</math> = Averaging time for noncarcinogens [years]</p> <p><math>RfD_o</math> = Chemical-specific oral reference dose [mg/(kg-day)]</p> <p><math>SF_o</math> = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]<sup>-1</sup></p> <p><math>IR_{w-aa}</math> = Age-adjusted ground water ingestion rate [L/kg]</p> <p><math>IR_{w-c}</math> = Resident child ground water ingestion rate [L/day]</p> <p><math>IR_{w-a}</math> = Resident adult ground water ingestion rate [L/day]</p> <p><math>BW_c</math> = Resident child body weight [kg]</p> <p><math>BW_a</math> = Resident adult body weight [kg]</p> <p><math>ED_c</math> = Resident child exposure duration [year]</p> <p><math>ED_a</math> = Resident adult exposure duration [year]</p> <p><math>EF_r</math> = Exposure frequency for a resident [days/year]</p> <p>365 = Conversion factor [days/year]</p>
---	---

### 3 Target Levels for Ground Water Resource Protection

#### 3.1 Domenico Model: Dilution Attenuation Factor (DAF) in the Saturated Zone

Domenico model for multi-dimensional transport with decay and infinite source:

$$\frac{C(x, y, z, t)}{C_o} = (1/8) \exp \left[ \frac{x}{2\alpha_x} \left[ 1 - \sqrt{1 + \frac{4k\alpha_x}{v}} \right] \right] \times \operatorname{erfc} \left[ \frac{(x - vt) \sqrt{1 + \frac{4k\alpha_x}{v}}}{2\sqrt{\alpha_x \times v \times t}} \right] \times \left[ \operatorname{erf} \left[ \frac{\left( y + \frac{W_{gw}}{2} \right)}{2\sqrt{\alpha_y x}} \right] - \operatorname{erf} \left[ \frac{\left( y - \frac{W_{gw}}{2} \right)}{2\sqrt{\alpha_y x}} \right] \right] \times \left[ \operatorname{erf} \left[ \frac{(z + \delta_{gw})}{2\sqrt{\alpha_z x}} \right] - \operatorname{erf} \left[ \frac{(z - \delta_{gw})}{2\sqrt{\alpha_z x}} \right] \right]$$

Where:

- $C$  = Dissolved-phase concentration [mg/L]
- $C_o$  = Dissolved-phase concentration at the source (at  $x = y = z = 0$ ) [mg/L]
- $v$  = Retarded seepage velocity [m/sec]
- $k$  = Overall first order bio-decay rate [1/day]
- $\alpha_x$  = Longitudinal dispersivity [m] ( $\alpha_x = x/10$ )
- $\alpha_y$  = Lateral dispersivity [m] ( $\alpha_y = x/30$ )
- $\alpha_z$  = Vertical dispersivity [m] ( $\alpha_z = x/200$ )
- $x, y, z$  = Spatial coordinates [m]
- $t$  = Time [day]
- $x$  = Distance along the centerline to point of exposure from the downgradient edge of dissolved-plume, source zone, or source well [m]
- $W_{gw}$  = Ground water mixing zone width [m]
- $\delta_{gw}$  = Ground water mixing zone thickness [m]
- DAF =  $C_o/C$

Source: Domenico 1990, Eqn. 17.21

At the centerline, for steady-state (after a long time) with decay the concentration can be obtained by setting  $y = 0$ ,  $z = 0$ , and  $x \ll v \times t$  as:

$$\frac{C(x)}{C_o} = \exp \left[ \frac{x}{2\alpha_x} \left[ 1 - \sqrt{1 + \frac{4k\alpha_x}{v}} \right] \right] \times \operatorname{erf} \left[ \frac{W_{gw}}{4\sqrt{\alpha_y x}} \right] \times \operatorname{erf} \left[ \frac{\delta_{gw}}{2\sqrt{\alpha_z x}} \right]$$

At the centerline, for steady-state the concentration without decay can be obtained by setting  $y = 0$ ,  $z = 0$ ,  $x \ll v \times t$ , and  $k = 0$  as:

$$\frac{C(x)}{C_o} = \operatorname{erf} \left[ \frac{W_{gw}}{4\sqrt{\alpha_y x}} \right] \times \operatorname{erf} \left[ \frac{\delta_{gw}}{2\sqrt{\alpha_z x}} \right]$$

Retarded seepage velocity  $v$  is given by the equation:

$$v = \frac{U_{gw}}{R \times \theta_r}$$

Where:

- $U_{gw}$  = ground water Darcy velocity [m/s]
- $R$  = retardation factor in the saturated zone [-]
- $\theta_r$  = Total soil porosity in the saturated zone

### 3.2 Soil to Ground Water Leaching Factor

$$LF_{SW} = \frac{1}{DAF_{Summers} \times K_{Water-soil}}$$

$$DAF_{Summers} = 1 + \frac{U_{gw} \times \delta_{gw}}{I \times W_{gw}} \quad (\text{The Summers Model})$$

$$K_{Water-soil} = \frac{\theta_{ws} + K_d \rho_s + H \times \theta_{as}}{\rho_s}$$

Where:

- $LF_{SW}$  = Soil to ground water leaching factor [mg/L-H<sub>2</sub>O)/mg/kg-soil]
- $DAF_{Summers}$  = Dilution attenuation factor in the mixing zone [-]
- $K_{Water-soil}$  = Water-soil partitioning coefficient [(mg/kg-soil)/(mg/L-H<sub>2</sub>O)]
- $\rho_s$  = Dry soil bulk density [g-soil/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in vadose zone soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>- soil]
- $K_d$  =  $f_{oc} \times K_{oc}$   
= Chemical-specific soil-water sorption coefficient [cm<sup>3</sup>-H<sub>2</sub>O/g-soil]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]
- $\theta_{as}$  = Volumetric air content in the vadose zone soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $U_{gw}$  = Ground water Darcy velocity [cm/yr]
- $\delta_{gw}$  = Ground water mixing zone thickness [cm]
- $I$  = Infiltration rate of water through soil [cm/year]
- $W_{gw}$  = Ground water mixing zone length [cm]

Source: EPA 1996

### 3.3 Soil Saturation Limit

$$C_s^{sat} = \frac{S}{\rho_s} \times [H \times \theta_{as} + \theta_{ws} + K_d \rho_s]$$

Where:

- $C_s^{SAT}$  = Soil concentration at which dissolved pore water and vapor phases become saturated [(mg/kg-soil)]
- $S$  = Pure component solubility in water [mg/L-H<sub>2</sub>O]
- $\rho_s$  = Dry soil bulk density [g-soil/cm<sup>3</sup>-soil]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]
- $\theta_{as}$  = Volumetric air content in the vadose zone soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in vadose zone soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>- soil]
- $K_d$  =  $f_{oc} \times K_{oc}$
- = Chemical-specific soil-water sorption coefficient [cm<sup>3</sup>-H<sub>2</sub>O/g-soil]

Source: ASTM 1995

### 3.4 Soil and Ground Water Concentration for Ground Water Protection

$$\text{Allowable soil concentration at the source} = \text{Target groundwater concentration at the POE} \times \frac{DAF_{POE} \times DAF_{unsat}}{LF_{sw}}$$

$$\text{Allowable groundwater concentration at the source} = \text{Target groundwater concentration at the POE} \times DAF_{POE}$$

$$\text{Allowable groundwater concentration at the POC} = \text{Target groundwater concentration at the POE} \times \frac{DAF_{POE}}{DAF_{POC}}$$

Where:

- $POE$  = Point of exposure
- $POC$  = Point of compliance
- $DAF_{POE}$  = Dilution Attenuation Factor (in the saturated zone) between the point of exposure and the source
- $DAF_{POC}$  = Dilution Attenuation Factor (in the saturated zone) between the point of compliance and the source
- $DAF_{unsat}$  = Dilution Attenuation Factor (in the vadose zone) between water table and soil source
- $LF_{sw}$  = Dry soil leaching factor

Additional relationships used in the calculation of allowable soil and ground water concentration with chemical degradation:

$$\text{First order decay rate} = \frac{0.693}{\text{Half - Life}}$$

$$\text{Retardation Factor for Organics in saturated zone} = 1 + \left( \frac{\rho_{ss} \times K_{ds}}{\theta_{TS}} \right)$$

Where:

- $\rho_{ss}$  = Dry soil bulk density of the saturated zone soil [g-soil/cm<sup>3</sup>-soil]
- $K_{ds}$  = Chemical-specific soil-water distribution coefficient in the saturated zone [mL/g]
- =  $K_{oc} \times f_{ocs}$
- $K_{oc}$  = Organic carbon distribution coefficient in the saturated zone [mL/g]
- $f_{ocs}$  = Fractional organic carbon content in the saturated zone [-]
- $\theta_{TS}$  = Total soil porosity in the saturated zone [cm<sup>3</sup>/cm<sup>3</sup>-soil]

## 4 Volatilization Factor, Particulate Emission Factor, and Effective Diffusion Coefficients

### 4.1 Volatilization Factor from Surface Soil to Outdoor (ambient) Air

$$VF = Q/C \times \frac{(3.14 \times D_A \times \tau)^{1/2}}{(2 \times \rho_s \times D_A)} \times 10^{-4}$$

Where:

$$D_A = \frac{(\theta_{as}^{10/3} \times D^a \times H + \theta_{ws}^{10/3} \times D^w)}{\rho_s \times K_d + \theta_{ws} + \theta_{as} \times H}$$

Where:

- $VF$  = Volatilization factor from surface soil to outdoor (ambient) air [(m<sup>3</sup>-air)/(kg-soil)]
- $Q/C$  = Inverse of the mean concentration at the center of square source [cm<sup>2</sup>/s]
- $D_A$  = Apparent diffusivity [cm<sup>2</sup>/s]
- $\tau$  = Averaging time for vapor flux [s]
- $\rho_s$  = Dry soil bulk density [g-soil/cm<sup>3</sup>-soil]
- $K_d$  = Chemical-specific solid-water sorption coefficient [cm<sup>3</sup>-H<sub>2</sub>O/g-soil]
- $D^a$  = Chemical-specific diffusion coefficient in air [cm<sup>2</sup>/s]
- $D^w$  = Chemical-specific diffusion coefficient in water [cm<sup>2</sup>/s]
- $\theta_T$  = Total soil porosity in the impacted zone [cm<sup>3</sup>/cm<sup>3</sup>-soil]
- $\theta_{as}$  = Volumetric air content in the vadose zone soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in the capillary fringe soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>-soil]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]
- $10^{-4}$  = Conversion factor [m<sup>2</sup>/cm<sup>2</sup>]

Source: EPA 1996

## 4.2 Particulate Emission Factor

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

Where:

- $PEF$  = Particulate emission factor [(m<sup>3</sup>-air)/(kg-soil)]
- $Q/C$  = Inverse of the mean concentration at the center of square source [(g/m<sup>2</sup>-s)/(kg/m<sup>3</sup>)]
- $V$  = Fraction of vegetative cover [-]
- $U_m$  = Mean annual wind speed [m/s]
- $U_t$  = Equivalent threshold value of wind speed at 7 m [m/s]
- $F(x)$  = Function dependent on  $U_m/U_t$ , derived using Cowherd et al. 1985 [-]
- 0.036 = Empirical constant [m<sup>2</sup>-hr/g]

Source: EPA 1996

## 4.3 Effective Diffusion Coefficients

### 4.3.1 Effective Diffusion Coefficient in Soil

$$D_s^{eff} = D^a \times \frac{\theta_{as}^{3.33}}{\theta_T^{2.0}} + D^w \times \frac{1}{H} \times \frac{\theta_{ws}^{3.33}}{\theta_T^{2.0}}$$

Where:

- $D_s^{eff}$  = Effective diffusion coefficient in soil based on vapor-phase concentration [cm<sup>2</sup>/s]
- $D^a$  = Chemical-specific diffusion coefficient in air [cm<sup>2</sup>/s]
- $D^w$  = Chemical-specific diffusion coefficient in water [cm<sup>2</sup>/s]
- $\theta_{as}$  = Volumetric air content in capillary fringe soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $\theta_{ws}$  = Volumetric water content in capillary fringe soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>-soil]
- $\theta_T$  = Total soil porosity in the impacted zone [cm<sup>3</sup>/cm<sup>3</sup>-soil]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]

### 4.3.2 Effective Diffusion Coefficient between Ground Water and Surface Soil

$$D_{ws}^{eff} = L_{TGW} \times \left[ \frac{h_{cap}}{D_{cap}^{eff}} + \frac{(L_{TGW} - h_{cap})}{D_s^{eff}} \right]^{-1}$$

Where:

- $D_{ws}^{eff}$  = Effective diffusion coefficient between ground water and surface soil [cm<sup>2</sup>/s]
- $h_{cap}$  = Thickness of capillary fringe [cm]
- $D_{cap}^{eff}$  = Effective diffusion coefficient through capillary fringe [cm<sup>2</sup>/s]
- $D_s^{eff}$  = Effective diffusion coefficient in soil based on vapor-phase concentration [cm<sup>2</sup>/s]
- $L_{TGW}$  = Source-building separation [cm]

### 4.3.3 Effective Diffusion Coefficient In Capillary Fringe Soil

$$D_{cap}^{eff} = D^a \times \frac{\theta_{acap}^{3.33}}{\theta_T^{2.0}} + D^w \times \frac{1}{H} \times \frac{\theta_{wcap}^{3.33}}{\theta_T^{2.0}}$$

Where:

- $D_{cap}^{eff}$  = Effective diffusion coefficient for the capillary fringe [cm<sup>2</sup>/s]
- $D^a$  = Chemical-specific diffusion coefficient in air [cm<sup>2</sup>/s]
- $D^w$  = Chemical-specific diffusion coefficient in water [cm<sup>2</sup>/s]
- $\theta_{acap}$  = Volumetric air content in capillary fringe soils [cm<sup>3</sup>-air/cm<sup>3</sup>-soil]
- $\theta_{wcap}$  = Volumetric water content in capillary fringe soils [cm<sup>3</sup>-H<sub>2</sub>O/cm<sup>3</sup>-soil]
- $\theta_T$  = Total soil porosity [cm<sup>3</sup>/cm<sup>3</sup>-soil]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]

Source: ASTM 1995

#### 4.3.4 Effective Diffusion Coefficient In Foundation/Wall Cracks

$$D_{crack}^{eff} = D^a \times \frac{\theta_{acrack}^{3.33}}{\theta_T^{2.0}} + D^w \times \frac{1}{H} \times \frac{\theta_{wcrack}^{3.33}}{\theta_T^{2.0}}$$

Where:

- $D_{crack}^{eff}$  = Effective diffusion coefficient through foundation cracks [ $\text{cm}^2/\text{s}$ ]
- $D^a$  = Chemical-specific diffusion coefficient in air [ $\text{cm}^2/\text{s}$ ]
- $D^w$  = Chemical-specific diffusion coefficient in water [ $\text{cm}^2/\text{s}$ ]
- $\theta_{acrack}$  = Volumetric air content in foundation/wall cracks [ $\text{cm}^3\text{-air}/\text{cm}^3\text{-total volume}$ ]
- $\theta_{wcrack}$  = Volumetric water content in foundation/wall cracks [ $\text{cm}^3\text{-H}_2\text{O}/\text{cm}^3\text{-total volume}$ ]
- $\theta_T$  = Total soil porosity [ $\text{cm}^3/\text{cm}^3\text{-soil}$ ]
- $H$  = Chemical-specific Henry's Law constant [(L-H<sub>2</sub>O)/(L-air)]

#### 4.4 Water Content in Soil in the Capillary Fringe

$$\theta_{wcap} = \theta_r + \frac{\theta_{Tcap} - \theta_r}{\left[1 + (\alpha h)^N\right]^M}$$

Where:

- $\theta_{wcap}$  = Water content in the capillary fringe zone soil [ $\text{cm}^3\text{-water}/\text{cm}^3\text{-soil}$ ]
- $\theta_r$  = Residual soil water content [ $\text{cm}^3\text{-water}/\text{cm}^3\text{-soil}$ ]
- $\theta_{Tcap}$  = Total porosity of soil in the capillary fringe zone [ $\text{cm}^3\text{-voids}/\text{cm}^3\text{-soil}$ ]
- $\alpha$  = Point of inflection in the water retention curve where  $d\theta_w/dh$  is maximal [1/cm]
- $h$  = Air-entry pressure head [cm]
- =  $1/\alpha$  and assumed to be positive
- $N$  = Van Genuchten curve shape parameter [-]
- $M$  =  $1 - (1/N)$

## References

- ASTM (American Society for Testing and Materials). 1995. Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites E1739-95.
- Cowherd, C., G.E. Muleski, P.J. Englehart, and D.A. Gilbert. 1985. *Rapid Assessment of Exposure to Particulate Emissions from Surface Contamination Sites*. Midwest Research Institute.
- Domenico, P.A., and F.W. Schwartz. 1990. *Physical and Chemical Hydrogeology*. New York: John Wiley and Sons, 824 p.
- EPA (U.S. Environmental Protection Agency). 1989. *Risk Assessment Guidance for Superfund*, Vol. I., Part A.
- EPA (U.S. Environmental Protection Agency). 1996. *Soil Screening Guidance: Technical Background Document*.
- EPA (U.S. Environmental Protection Agency). 2003. *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings*. EPA, Office of Solid Waste and Emergency Response.
- EPA (U.S. Environmental Protection Agency). 2007. *Risk Assessment Guidance for Superfund*, Vol. I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment). EPA, Office of Solid Waste and Emergency Response. 9285.7-02EP.
- EPA (U.S. Environmental Protection Agency). 2009. *Risk Assessment Guidance for Superfund*, Vol. I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment). EPA, Office of Solid Waste and Emergency Response. 9285.7-82.
- EPA (U.S. Environmental Protection Agency). 2010. *Regional Screening Levels for Chemical Contaminants at Superfund Sites*, Users Guide and Equations. Accessed May 2011. Available at: [http://www.epa.gov/reg3hwmd/risk/human/rb-concentration\\_table/equations.htm](http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/equations.htm).

## Appendix F: Methodology and Example Calculation for Remedial Action Target Levels

Comment [MAB1]: No comments at this time

*This page intentionally left blank for correct double-sided printing.*

## Introduction

For each receptor, the cumulative risk for carcinogenic effects and hazard index (HI) for noncarcinogenic effects at a site for all petroleum chemicals of interest (COIs) and complete routes of exposures (ROE) (except ingestion of water) should not exceed  $1 \times 10^{-5}$  and 1, respectively. This appendix describes the default methodology used by the Idaho Department of Environmental Quality (DEQ) to apportion risk and derive remedial action target level (RATL) concentrations for petroleum COIs in various media at sites where the risk or hazard is estimated to exceed the acceptable target risk level or acceptable HI.

## Developing Target Levels: Method

The default method for developing target levels can be summarized by the following steps:

**Step 1:** Based on complete or potentially complete routes of exposure identified earlier and estimated representative concentrations, calculate the corresponding risk ( $Risk_{i,j}^{rep}$ ) and hazard quotient ( $HQ_{i,j}^{rep}$ ) for each chemical ( $i$ ) for each complete pathway ( $j$ ).

Results can be used to generate a matrix of risk and hazard quotient (HQ) values as shown in Table 1 below.

**Table 1. Example matrix for calculation of remedial action target levels**

Petroleum Chemical of Interest	Pathway 1		Pathway 2		Pathway 3		Cumulative		Number of Pathways	
	Risk	HQ	Risk	HQ	Risk	HQ	Risk	HI	Carcinogenic	Noncarcinogenic
C1	X	N/A	X	N/A	—	N/A	SUM	SUM	2	0
C2	N/A	X	N/A	X	N/A	X	SUM	SUM	0	3
C3	N/A	X	—	X	N/A	X	SUM	SUM	0	3
C4	X	N/A	X	N/A	X	N/A	SUM	SUM	3	0
C5	X	X	N/A	X	N/A	X	SUM	SUM	1	3
Cumulative							Risk <sub>site</sub> = SUM(SUM)	HI <sub>site</sub> = SUM(SUM)	6	9

Note: X indicates pathway complete

N/A indicates not applicable because there is no relevant toxicity data or physical-chemical property.

A dash (—) indicates the value was not calculated because there was no entry under representative concentrations. This could mean that the chemical is not a petroleum chemical of interest for the pathway being evaluated based on release history or based on site characterization data.

**Step 2:** Calculate cumulative risk (site risk) and site HI.

$$Risk_{site} = \sum_{i=1}^{n_c} \sum_{j=1}^{m_i} Risk_{i,j}$$

$$HI_{site} = \sum_{i=1}^{n_{nc}} \sum_{j=1}^{m_i} HQ_{i,j}$$

Where:

$Risk_{i,j}$  = risk from exposure to chemical  $i$  through pathway  $j$

$HQ_{i,j}$  = hazard quotient for exposure to chemical  $i$  through pathway  $j$

$m_i$  = number of complete pathways for chemical  $i$  (the suffix to  $m$  indicates that the number of complete pathways can be different for different chemicals)

$n_c$  = number of carcinogenic chemicals at the site

$n_{nc}$  = number of noncarcinogenic chemicals at the site

If the cumulative risk and HI for all the receptors at the site are below the acceptable levels, the site does not require the development of RATL. Site closure may be appropriate if other required regulatory issues have been resolved.

**Step 3:** Determine the number of chemical-pathway combinations (for carcinogens and noncarcinogens separately) at the site.

For the number of chemical-pathway combinations for carcinogens,

$$N_c = \sum_{i=1}^{n_c} \sum_{j=1}^{m_i} p_{i,j}$$

For the number of chemical-pathway combinations for non-carcinogens,

$$N_{nc} = \sum_{i=1}^{n_{nc}} \sum_{j=1}^{m_i} p_{i,j}$$

Where:

$p_{i,j}$  = complete pathway for chemical  $i$  and pathway  $j$

$m_i$  = number of complete pathways for chemical  $i$  (the suffix to  $m$  indicates that the number of complete pathways can be different for different chemicals)

$n_c$  = number of carcinogenic chemicals at the site

$n_{nc}$  = number of noncarcinogenic chemicals at the site

Note that some chemicals show both carcinogenic and noncarcinogenic toxicity and should be counted in both categories. For example, chemical C5 in the example above (Table 1) has 3 complete pathways for the noncarcinogenic effects and 1 pathway for the carcinogenic effects.

**Step 4:** Based on equal apportioning of target cumulative risk and HI, compute allocated risk and HQ contribution by chemical  $i$  through pathway  $j$  using the following equations:

$$Risk_{i,j}^{allocated} = \frac{1 \times 10^{-5}}{N_c}$$

$$HQ_{i,j}^{allocated} = \frac{1}{N_c}$$

**Step 5:** Estimate the risk reduction factor (RRF) in risk or HQ required so the contribution by chemical  $i$  acting through pathway  $j$  is equal to the allocated risk or allocated HQ.

Calculate the RRF for chemical  $i$  acting through pathway  $j$  with the following equation:

$$RRF_{i,j} = \frac{Risk_{i,j}^{rep}}{Risk_{i,j}^{allocated}}$$

Calculate the hazard quotient reduction factor (HQRF) for chemical  $i$  acting through pathway  $j$  with the following equation:

$$HQRF_{i,j} = \frac{HQ_{i,j}^{rep}}{HQ_{i,j}^{allocated}}$$

**Step 6:** Calculate the target level (i.e., allowable concentration) for chemical  $i$  acting through pathway  $j$ .

For carcinogens,

$$C_{i,j}^{allowable} = \frac{C_{i,j}^{rep}}{RRF_{i,j}}$$

For noncarcinogens,

$$C_{i,j}^{allowable} = \frac{C_{i,j}^{rep}}{HQRF_{i,j}}$$

If a chemical has  $C_{i,j}^{allowable}$  based on carcinogenic and noncarcinogenic toxicity, the applicable RATL for that chemical should be the lower of the two allowable concentrations.

## Developing Target Levels: Example

The following is an example of the target level calculations described above. Table 2 presents fictitious representative concentrations for each of five chemicals and three pathways (two soil and one ground water).

**Table 2. Fictitious representative concentrations used in target level calculation example**

Petroleum Chemical of Interest	Pathway 1 (milligrams/kilogram)	Pathway 2 (milligrams/kilograms)	Pathway 3 (milligrams/liter)
C1	1	2	—
C2	2	4	2
C3	3	6	3
C4	4	8	4
C5	5	10	5

**Step 1:** Use these representative concentrations to calculate risk and HQ for each chemical and pathway the chemical acts through. The resulting matrix of risk and HQ values are shown in Table 3.

**Table 3. Example of risk/chemical-of-interest/pathway matrix for target level calculation**

Petroleum Chemical of Interest	Pathway 1		Pathway 2		Pathway 3		Cumulative		Number of Pathways	
	Risk	HQ	Risk	HQ	Risk	HQ	Risk	HI	Carcinogenic	Noncarcinogenic
C1	1E-5	N/A	2E-5	N/A	N/A	N/A	3E-5	N/A	2	0
C2	N/A	1	N/A	3	N/A	1	N/A	5	0	3
C3	N/A	1	—	1	N/A	3	N/A	5	0	3
C4	1E-5	N/A	1E-5	N/A	1E-5	N/A	3E-5	N/A	3	0
C5	2E-5	1	N/A	1	N/A	1	2E-5	3	1	3
Cumulative							Risk <sub>site</sub> = 8E-5	HI <sub>site</sub> = 13	6	9

**Note:** **N/A** indicates not applicable because there is no relevant toxicity data or physical-chemical property. **A dash (—)** indicates the value was not calculated because there was no entry under representative concentrations. This could mean that the chemical is not a petroleum chemical of interest for the pathway being evaluated based on release history or based on site characterization data.

**Step 2:** Calculate the cumulative site risk and HI for all chemicals and pathways for a given receptor. (In this case, the site risk and HI are  $7 \times 10^{-5}$  and 13, respectively.)

**Step 3:** Determine the number of chemical-pathway combinations (for carcinogens and noncarcinogens separately) at the site. In this example, the number of chemical-pathway combinations for carcinogens is 6, and the number of chemical-pathway combinations for noncarcinogens is 9.

**Step 4:** Based on equal apportioning of the target cumulative risk and HI, calculate the allocated risk and HQ contribution by chemical  $i$  through pathway  $j$ .

$$Risk_{i,j}^{allocated} = \frac{1 \times 10^{-5}}{6} = 1.67 \times 10^{-6}$$

$$HQ_{i,j}^{allocated} = \frac{1}{9} = 0.111$$

**Step 5:** Estimate the RRF in risk or HQ required so that the contribution by a given chemical acting through a particular pathway is equal to the allocated risk or allocated HQ.

The RRF for chemical  $i$  acting through pathway  $j$  is found with the following equation:

$$RRF_{i,j} = \frac{Risk_{i,j}^{rep}}{Risk_{i,j}^{allocated}}$$

The HQ reduction factor for chemical  $i$  acting through pathway  $j$  is calculated with the following equation:

$$HQRF_{i,j} = \frac{HQ_{i,j}^{rep}}{HQ_{i,j}^{allocated}}$$

The calculations of the RFs for the example are presented in Table 4. At actual sites, the reduction factors are rarely as uniform as they are in the example.

**Table 4. Reduction factor example for target level calculations**

Petroleum Chemical of Interest	Pathway 1		Pathway 2		Pathway 3	
	RRF	HQRF	RRF	HQRF	RRF	HQRF
C1	1E-5/1.67E-6 = 5.99	N/A	2E-5/1.67E-6 = 11.98	N/A	—	N/A
C2	N/A	1/0.111 = 9.0	N/A	3/0.111 = 27.0	N/A	1/0.111 = 9.0
C3	N/A	1/0.111 = 9.0	—	1/0.111 = 9.0	N/A	3/0.111 = 27.0
C4	1E-5/1.67E-6 = 5.99	N/A	1E-5/1.67E-6 = 5.99	N/A	1E-5/1.67E-6 = 5.99	N/A
C5	2E-5/1.67E-6 = 11.98	1/0.111 = 9.0	N/A	1/0.111 = 9.0	N/A	1/0.111 = 9.0

*Note:* **N/A** indicates not applicable because there is no relevant toxicity data or physical-chemical property. **A dash (—)** indicates the value was not calculated because there was no entry under representative concentrations. This could mean that the chemical is not a petroleum chemical of interest for the pathway being evaluated based on release history or based on site characterization data.

**Step 6:** Calculate the target level for a chemical acting through a given pathway.

For carcinogens,

$$C_{i,j}^{allowable} = \frac{C_{i,j}^{rep}}{RRF_{i,j}};$$

and for non-carcinogens,

$$C_{i,j}^{allowable} = \frac{C_{i,j}^{rep}}{HQRF_{i,j}}$$

The resulting RATL calculations, carcinogenic and/or noncarcinogenic, for the example are presented in Table 5. The RATL concentrations are presented in bold.

**Table 5. Example remedial action target level (RATL) concentrations for target level calculations**

Petroleum Chemical of Interest	Pathway 1 (milligrams/kilogram)		Pathway 2 (milligrams/kilogram)		Pathway 3 (milligrams/liter)	
	RATL <sub>c</sub>	RATL <sub>nc</sub>	RATL <sub>c</sub>	RATL <sub>nc</sub>	RATL <sub>c</sub>	RATL <sub>nc</sub>
C1	1/5.99 = <b>0.17</b>	N/A	2/11.98 = 0.17	N/A	—	N/A
C2	N/A	2/9.0 = 0.222	N/A	4/27.0 = <b>0.148</b>	N/A	2/9.0 = <b>0.222</b>
C3	N/A	3/9.0 = <b>0.333</b>	—	6/9.0 = 0.667	N/A	3/27.0 = <b>0.111</b>
C4	4/5.99 = <b>0.67</b>	N/A	8/5.99 = 1.34	N/A	4/5.99 = <b>0.67</b>	N/A
C5	5/11.98 = <b>0.42</b>	5/9.0 = 0.555	N/A	10/9.0 = 1.11	N/A	5/9.0 = <b>0.555</b>

Note: **N/A** indicates not applicable because there is no relevant toxicity data or physical-chemical property.  
**A dash (—)** indicates the value was not calculated because there was no entry under representative concentrations. This could mean that the chemical is not a petroleum chemical of interest for the pathway being evaluated based on release history or based on site characterization data.

In this example, for chemical C5 and pathway P1, both carcinogenic and noncarcinogenic RATLs are calculated. The lower of the two, 0.42 milligrams/kilogram (the carcinogenic RATL), would be used.

**Appendix G: Evaluation of the Vapor Intrusion Pathway**

*This page intentionally left blank for correct double-sided printing.*

---

**TABLE OF CONTENTS**

---

1	Background .....	1
2	Evaluation Process for the Vapor Intrusion Pathway .....	1
2.1	Screening Evaluation.....	4
2.2	Refined Exclusion Criteria .....	6
2.3	Site Specific Evaluation .....	8
3	Protocol for the Measurement of Soil Vapor Levels .....	11
3.1	Soil Gas Measurement Techniques and Analysis .....	12
3.2	Sampling Locations.....	16
3.3	Sampling Depths .....	16
3.4	Sample Numbers .....	17
3.5	QA/QC Procedures.....	18
4	Indoor Air Sampling .....	18
5	Suggested References .....	20

---

**LIST OF FIGURES**

---

Figure 1.	Conceptual model of the vapor intrusion pathway (source: API 2005) .....	1
Figure 2.	Flowchart for evaluation of the vapor intrusion pathway .....	3
Figure 3.	Schematic of single permanent soil vapor probe installation (adapted from Cal/EPA 2010).....	13
Figure 4.	Schematic of nested multidepth soil vapor probe installation (source: Hartman 2010).....	14
Figure 5.	Schematic of subslab soil vapor probe installation (source: EPA 2006).....	15

---

**LIST OF TABLES**

---

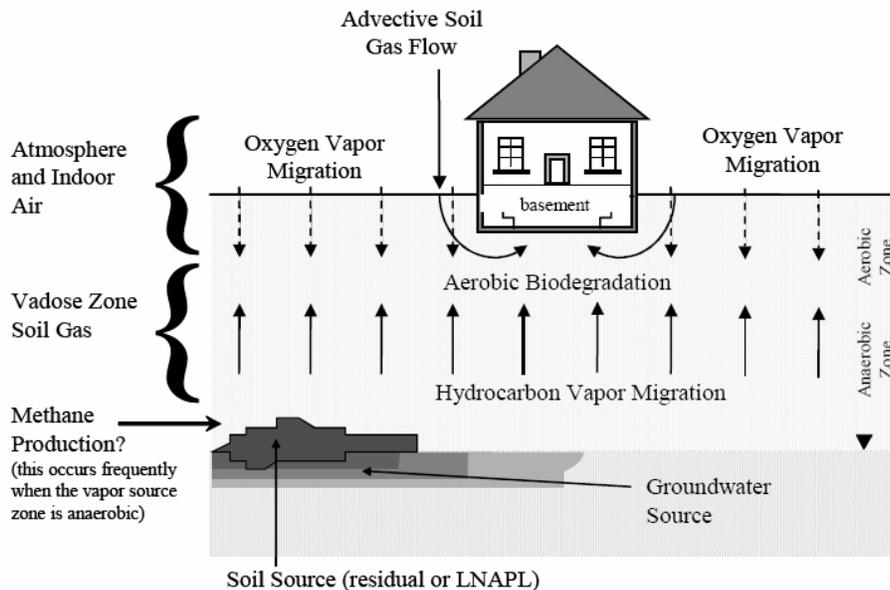
Table 1.	Screening level concentrations for soil, ground water, and soil vapor .....	5
----------	---	---

*This page intentionally left blank for correct double-sided printing.*

## 1 Background

A potentially complete exposure pathway at petroleum release sites is vapor intrusion (VI). The VI pathway involves exposure via inhalation of vapors emitted from impacted soil or ground water, which are subsequently transported to indoor spaces. Figure 1 shows the general conceptual model that is assumed for the VI pathway at petroleum release sites.

This appendix describes a VI pathway-specific evaluation process and provides general guidance on soil vapor and indoor air sampling and data interpretation for use within the risk-based corrective action process. The focus of this appendix is on indoor inhalation only since experience suggests that outdoor inhalation from subsurface contamination rarely results in unacceptable risk. It is assumed that any imminent threats to human health via explosive levels of vapors have been mitigated prior to this evaluation. The state of the science regarding VI evaluation at petroleum release sites is rapidly evolving, and this guidance will be modified in the future to reflect this evolution.



**Figure 1. Conceptual model of the vapor intrusion pathway (source: API 2005)**

Note: LNAPL = light non-aqueous phase liquid

## 2 Evaluation Process for the Vapor Intrusion Pathway

Evaluating the VI pathway is an iterative process that is dependent on the following activities:

- Developing and validating a sound site conceptual model

- Collecting appropriate characterization data
- Evaluating the data to determine whether the pathway is complete or, if incomplete, may be excluded from further consideration
- Calculating risk if the pathway is complete

Figure 2 is a flowchart of a step-by-step approach to evaluating the VI pathway. While the flowchart outlines a stepwise process, it also provides several places where—depending on the type, site-specificity, and quality of characterization data collected—a determination that the VI pathway is incomplete can be made, thus completing the evaluation. The criteria applied to make this determination vary with the type and quality of available data. These criteria are described in more detail below.

Only petroleum chemicals of interest (COIs) at the site that are volatile should be considered during evaluation of the VI pathway. Nonvolatile chemicals are commonly considered those chemicals with a Henry's Law constant of less than or equal to  $1 \times 10^{-5}$  atm-m<sup>3</sup>/mol and a molecular weight exceeding 200 (EPA 2011). Of the COIs typically considered at petroleum release sites, those that meet this nonvolatility criteria include the polynuclear aromatic hydrocarbons (PAH) benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, fluoranthene, and pyrene.

Using soil and ground water data, many of the remaining PAH chemicals that are considered volatile will often be eliminated from further consideration during the initial screening evaluation described below.

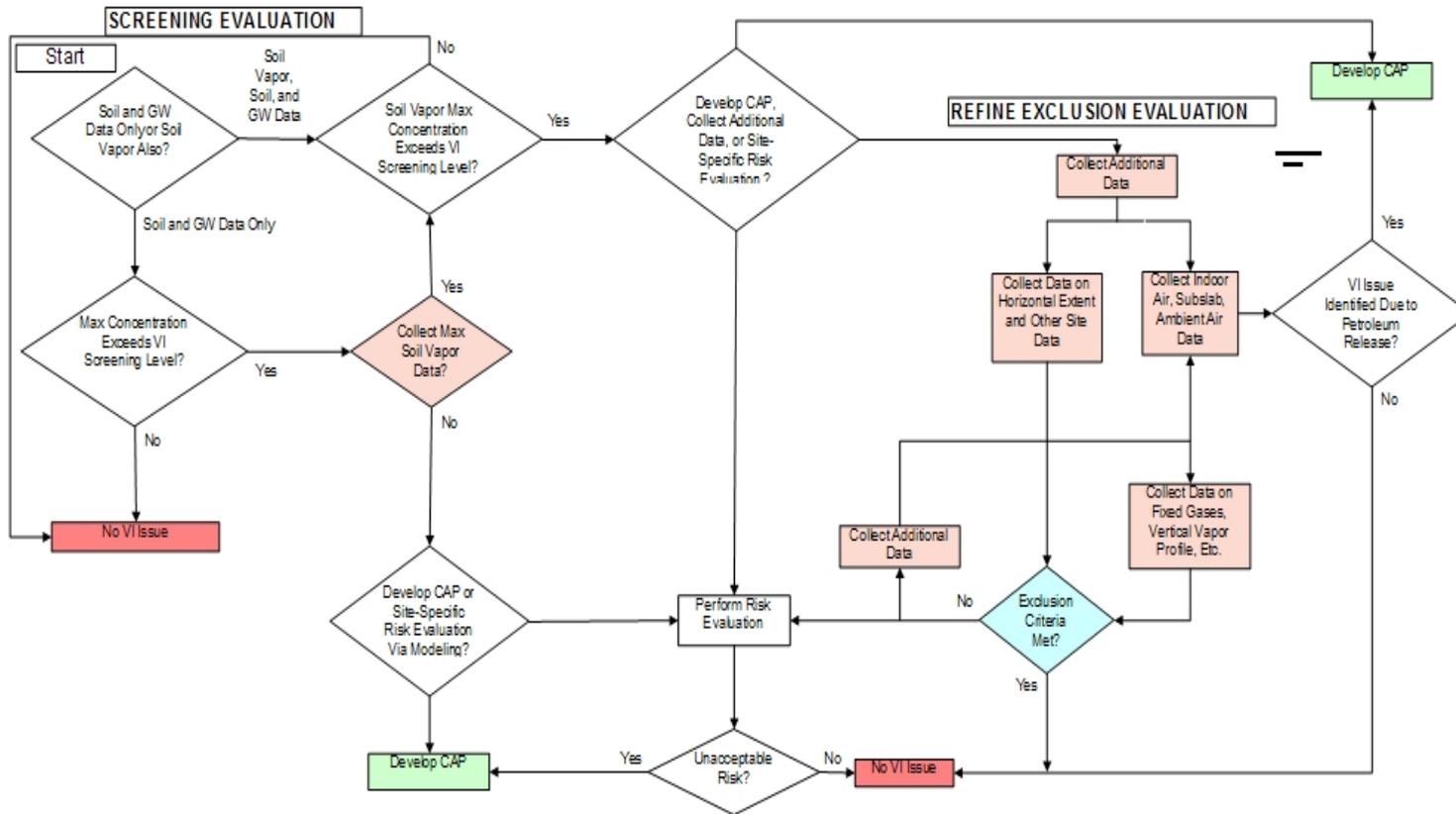


Figure 2. Flowchart for evaluation of the vapor intrusion pathway

## 2.1 Screening Evaluation

The screening evaluation uses soil, ground water, or soil vapor chemical data for the petroleum COIs that are collected to be representative of the highest concentrations associated with the petroleum release source areas. These data are typically collected early in the site characterization process. The concentrations are compared to associated media-specific and pathway-specific screening levels. These screening levels, presented in Table 1, are based on an assumption of unrestricted land use at the site and close proximity of the contamination to potential receptors. The screening levels do not take into account site-specific information such as the spatial relationship of the contamination to potential receptors, current and assumed future land use, building characteristics, or potential attenuation of petroleum release chemicals via biodegradation.

Screening level evaluation outcomes depend on what data is available:

If **only** maximum soil and/or ground water data are available, the following evaluation outcomes are possible:

1. No screening levels are exceeded. **NO VI ISSUE** exists.
2. Concentrations only exceed the screening levels for non-VI pathways. **NO VI ISSUE** exists.
3. Concentrations only exceed the screening levels for VI pathways.
4. Concentrations exceed the screening levels for both VI and non-VI pathways.

In the case of outcomes 3 and 4, VI is a potentially complete pathway. Next step options include the following:

1. Collect maximum concentration soil vapor data appropriate for comparison to soil vapor screening levels; or
2. Develop a corrective action plan to reach screening levels or otherwise mitigate VI risk; or
3. Collect additional data to conduct a site-specific risk evaluation (see section 2.3 below). The site-specific evaluation could result either in exclusion of the VI pathway as a complete pathway or inclusion and an evaluation of the level of risk.

If maximum soil, ground water, and vapor data are **all** available, several scenarios with respect to the VI pathway are possible:

- Soil and/or ground water data exceed VI screening levels but soil vapor does not. The soil vapor data is given preference (assuming it was representative of maximum concentrations), the VI pathway is considered incomplete, and there is **NO VI ISSUE**. Further consideration of other complete or potentially complete pathways of concern still should be carried out.
- Soil, ground water, and soil vapor data all exceed VI pathway screening levels. Options include developing a corrective action plan (CAP), collecting additional site characterization data to refine the evaluation regarding the existence of a VI issue, or performing a site-specific risk evaluation.
- Soil, ground water, and soil vapor data do not exceed VI pathway screening levels. **NO VI ISSUE** exists.

**Table 1. Screening level concentrations for soil, ground water, and soil vapor**

Chemical	Soil (milligrams/kilogram)			Ground Water (milligrams/liter)		Deep Soil Vapor (micrograms/cubic meter) (>3–5 feet below ground surface)	
	Vapor Intrusion	Direct Contact	Ground Water Protection	Vapor Intrusion	Ingestion	Unrestricted Use	Non-Residential
						Vapor Intrusion	Vapor Intrusion
Benzene	0.08	8.3	<b>0.025</b>	0.044	<b>0.005</b>	31	160
Toluene	1300	62000	<b>6.6</b>	340	<b>1</b>	520000	2200000
Ethylbenzene	<b>0.25</b>	39	7.4	<b>0.05</b>	0.700	97	490
Xylenes	<b>27</b>	8500	<b>91</b>	<b>8.7</b>	10	10000	44000
Naphthalene	<b>0.12</b>	44	9.2	<b>0.07</b>	0.73	7	36
MTBE	2.4	340	<b>0.08</b>	6.8	<b>0.04</b>	940	4700
1,2-Dichloroethane	0.02	3.7	<b>0.013</b>	0.03	<b>0.005</b>	9	47
Ethylene Dibromide	0.001	0.27	<b>0.00014</b>	0.004	<b>0.00005</b>	0.4	2
Acenaphthene	NA	37000	<b>200</b>	NA	<b>2.2</b>	NA	NA
Anthracene	NA	190000	<b>3200</b>	NA	<b>11</b>	NA	NA
Benz(a)anthracene	NA	0.19	<b>0.09</b>	NA	<b>0.00003</b>	NA	NA
Benzo(a)pyrene	NA	<b>0.02</b>	2.1	NA	<b>0.0002</b>	NA	NA
Benzo(b)fluoranthene	NA	<b>0.19</b>	0.31	NA	<b>0.00003</b>	NA	NA
Benzo(k)fluoranthene	NA	<b>1.9</b>	3.1	NA	<b>0.0003</b>	NA	NA
Chrysene	NA	19	<b>9.5</b>	NA	<b>0.003</b>	NA	NA
Fluoranthene	NA	25000	<b>1400</b>	NA	<b>1.5</b>	NA	NA
Fluorene	NA	25000	<b>240</b>	NA	<b>1.5</b>	NA	NA
Pyrene	NA	19000	<b>1100</b>	NA	<b>1.1</b>	NA	NA

Note: Values in bold are current petroleum risk evaluation manual screening concentrations. Screening values for deep soil vapor are equivalent to U.S. Environmental Protection Agency regional screening levels (EPA 2010b) for residential and industrial ambient air multiplied by an attenuation factor of 100. Chemicals with NA for vapor intrusion either do not meet the EPA regional screening level volatility criteria or do not have an ambient air value available.

**Comment [MAB1]:** This table has changed since the January 2011 review. Why? Our PQL discussion will likely affect this table

## 2.2 Refined Exclusion Criteria

If the potential for a VI issue exists after the screening evaluation and additional site characterization data will be collected, the following types of information are most valuable in refining the evaluation:

- Physical site data—Includes the nature and extent of surface and subsurface features (natural or man-made) in relation to vapor sources, which may enhance or impede the flow of chemical vapors or oxygen needed for biodegradation.
- Soil properties data—Site-specific information on soil properties to calculate site-specific soil gas screening levels.
- Soils/ground water/vapor/non-aqueous phase liquid (NAPL) data—Characterize the horizontal and vertical extent of vapor sources.
- Structure data—Includes building construction (slab on grade, basement, or crawl space), building condition, HVAC system design and operation, and location of occupied spaces in relation to contamination distribution.
- Current and future land use—Knowledge and assumptions about current and future use of both existing structures and the delineated vapor sources on the property or adjacent properties or structures potentially impacted by the release.

If the above information demonstrates compliance with each criterion in items a–g below, a VI issue does not exist:

- a) No fractured rock or subsurface geology, which provides the potential for enhanced vapor transport, is present between delineated vapor sources and existing structures within 50 feet of the ground surface.
- b) No reasonably identifiable preferential pathways, such as utility trenches backfilled with highly permeable material or sumps connected to existing structures, exist between delineated vapor sources and the existing structures.
- c) No low permeability layers exist (either at the surface or in the subsurface) connected to existing structures between the delineated vapor sources and the structures that allow enhanced transport of vapors without degradation.
- d) No exceedance of vapor intrusion pathway screening levels in ground water, soil, or soil gas within 50 feet of existing structures; if ground water or soil concentrations exceed screening levels but appropriate soil vapor data is available, as explained in section 2.1, the soil vapor data is given preference.
- e) Delineated ground water plume sources are determined to be stable or unlikely to expand within 50 feet of an existing enclosed structure.
- f) No NAPL vapor sources exist within 100 feet of existing structures.
- g) Current and reasonably likely future land use (including the configuration and use of existing structures) at the site are assumed to be unchanged, and no development is planned within 50 feet of delineated vapor sources.

Critical distances specified by the American Society of Testing and Materials (ASTM) in their 2010 *Standard Guide for Vapor Encroachment Screening on Property Involved in Real Estate Transactions* (ASTM 2010) can be modified based on the environmental professional's evaluation of relevant factors.

**Comment [MAB2]:** Need to better define structure to mean occupied and not include things like sheds, barns, etc.

These factors include, but are not limited to, the following:

- Completeness of source delineation
- Amount of oxygen in the soil
- Physical setting of the structure and site
- Other chemical contaminants that may impact oxygen availability for biodegradation

The distance criteria specified in items a–g above may be adjusted based on these types of site-specific factors when supported with adequate documentation.

If the more detailed exclusion evaluation described above results in a determination that a VI issue likely exists because one or more of the criteria are not met, additional data collection to further refine the analysis of those criteria may be appropriate. This additional step commonly involves the collection of additional soil vapor data. Several of the criteria listed above have the potential to enhance the transport of soil vapor (e.g., fractured rock, preferential pathways, low permeability layers). Vapor samples may be taken from targeted locations at the site in order to resolve these issues. For example, fractured rock may be overlain by a thin layer (<10 feet) of soil. If appropriate soil vapor samples taken near the soil-rock interface result in acceptable concentrations, the potential impact of the shallow presence of the fractured rock may be discounted. A similar situation may occur with impacted shallow ground water (<50 feet below ground surface) that may be resolved with more detailed soil vapor assessment. Collection of multi-depth vertical soil vapor samples may demonstrate adequate attenuation of contamination.

At sites where the current and reasonably likely future land use is nonresidential, the screening levels for deep soil vapor for commercial land use provided in Table 1 may be applied. The Idaho Department of Environmental Quality (DEQ) will require an environmental covenant, or other land use restriction, for any site where an assumption is made that the likely future land use is ~~commercial/industrial~~ nonresidential. DEQ may require restrictions on land use within undeveloped delineated vapor source areas depending on vapor concentrations and assumed future land use in these areas.

For delineated vapor source areas without buildings that have demonstrated no current VI risk to existing structures but whose future land use condition with respect to buildings and land use is uncertain, the collection of detailed soil vapor data may show that **NO VI ISSUE** exists. The data and analysis used to make this determination are as follows:

- Data collection should concentrate on vertical and horizontal profiles of vapor chemical concentrations and fixed gases (oxygen, carbon dioxide, methane); determination of soil type; and soil organic carbon at critical locations in the delineated vapor source areas. The goals of this data collection are two-fold: 1) to establish that adequate attenuation of vapors is occurring and will continue to occur and 2) to prevent unacceptable exposure to hypothetical future receptors.

The data should be graphically displayed to demonstrate that the absence or reduced concentrations of petroleum hydrocarbons in shallow soil gas is supported by evidence of the aerobic conditions (e.g., high concentrations of oxygen and low or non-detectable concentrations of volatile COIs) needed for degradation. The presence of the anaerobic zone (e.g., high levels of methane and/or carbon dioxide) correlates to higher

concentrations of volatile COIs where degradation is not occurring and should also be displayed, if possible (API 2005).

If site-specific data show that biodegradation is attenuating soil gas concentrations to vapor screening levels as detailed in items a–c below, then **NO VI ISSUE** exists in this area and no further sampling is required:

- a. Total concentrations of petroleum COIs in ground water are below 1,000 micrograms per liter ( $\mu\text{g/L}$ ).
- b. Concentrations of oxygen in the unsaturated zone above an anaerobic zone are sufficient in concentration ( $\geq 10\%$ ) throughout an adequate thickness (5 to 10 feet) of clean soil (vapor concentrations less than screening levels) to continue to support biodegradation.
- c. Depth to ground water does not vary annually in a manner that would result in an inadequate thickness of clean soil.

Formatted: Highlight

This data and analysis may also be used to demonstrate that vapor sources are attenuated to screening levels by biodegradation in close proximity to existing structures.

If it is concluded that a VI issue may still exist following this level of site characterization, these options are available:

- Develop a risk management strategy to address the VI pathway through a comprehensive CAP for the site. The plan may include, as appropriate, implementation of activity and use limitations through an environmental covenant.
- Further evaluate the VI pathway by collecting and evaluating subslab vapor and ambient air data prior to performing a site-specific risk reevaluation per section 2.3. This data collection includes chemical concentration data for each structure of concern, an inventory of potential indoor and outdoor sources of the petroleum COIs, and an assessment of background concentrations. See section 2.3 for details regarding the interpretation of this data.
- Perform a site-specific risk evaluation per section 2.3.

Formatted: Highlight

## 2.3 Site Specific Evaluation

A site-specific VI pathway evaluation may include one or more of the following tasks:

- Collection of additional site characterization data (such as subslab vapor, indoor air, and ambient air data)
- Development of a refined site conceptual model (SCM) for VI
- Completion of a risk evaluation

Formatted: Highlight

The elements of an SCM are discussed in detail in section 4.1 of the body of the risk evaluation manual. These elements include descriptions of current and future land use and receptors; site conditions (surface, subsurface, and structural) that facilitate the transport of vapors to indoor air; and chemical concentrations for appropriate petroleum COIs.

Upon completion of the SCM, the risk evaluation for VI can be completed in several ways depending on available data per the following:

### VI Evaluation Using Soil/Ground Water Data

These types of site chemical data can be used with fate and transport models to estimate the risks associated with VI, realizing the limitations of both the data and models. Using this data presents certain limitations: 1) equilibrium partitioning theory, used to convert soil and ground water concentrations into vapor concentrations, is typically found to overestimate vapor concentrations compared to field-measured vapor data and 2) the primary model currently available that can use soil and ground water data, the Johnson and Ettinger model (Johnson and Ettinger 1991), is incorporated into the Idaho petroleum risk evaluation manual software. This model does not accommodate the effects of biodegradation of petroleum chemicals and therefore is limited in its predictive ability for these types of chemicals. The model also does not accommodate analysis of structures with crawl spaces or unfinished basements.

Comment [MAB3]: Is it possible to update this?

### VI Evaluation Using Soil Vapor and Subslab Vapor Data

Soil vapor and subslab vapor data can be used in several ways when evaluating VI risk and offer several advantages to using soil and ground water data:

- Since soil vapor and subslab vapor data are direct measures of vapor concentrations, the uncertainty associated with equilibrium partitioning-based vapor concentration calculations is avoided. In addition, if collected appropriately, these data can reflect the effect of biodegradation.
- The data can be incorporated into the Johnson and Ettinger model as well as other models specific to the VI pathway, such as the BioVapor model (API 2010), in order to predict indoor air chemical concentrations and risk. When the Johnson and Ettinger modeling option is used with soil, ground water, or soil vapor data, it is recommended that the model default values for key parameters be retained with the exception that site-specific soil properties can be used.
- Subslab vapor data can be collected for existing structures and compared to screening levels based on the application of an attenuation factor of 0.1 to U.S. Environmental Protection Agency (EPA) regional screening levels for ambient air.
- Subslab vapor data can be used along with indoor air and ambient air data (if an unacceptable risk is identified in indoor air) to develop site-specific attenuation factors and soil vapor cleanup criteria.
- Deep vapor data (3–5 feet below ground surface) can be used to evaluate the potential VI risk in areas where future development of the site may be desired or expected. This data can also be compared with screening levels to delineate areas that may be candidates for activity and use limitations through the use of an environmental covenant.
- Along with data on oxygen, carbon dioxide, and methane in soil vapor, another line of evidence for biodegradation of the petroleum vapors can be established.

### VI Evaluation Using Indoor Air Data

Collection of these data provides the best opportunity for developing multiple lines of evidence in determining if VI presents a building-specific risk. Collection of indoor air data should, at a minimum, be accompanied with concurrently collected outside ambient air, an inventory of potential indoor chemical sources, and information on building construction and heating/cooling

system design and operation. In many cases, collection of subslab and subsurface soil vapor data can help determine if subsurface petroleum releases are contributing to VI risk. Specifically, deeper subsurface soil vapor data collected under the building may establish that chemical concentrations detected in the subslab originate, in whole or in part, from indoor air rather than from subsurface contamination.

Accessory measurements—such as indoor/subslab pressure differentials and analysis of vapors for fixed gases—will assist in data interpretation. The selection of ambient air sampling locations should attempt to take into account factors such as dominant wind direction, building characteristics, and the potential contributions from fueling/dispensing operations (at actively operating fueling facilities). In some cases, sampling at multiple ambient air locations may be advisable.

Multiple outcomes of possible risk are possible based on the results of the site-specific sampling program described above and comparison of measured indoor air (IA), ambient air (AA), and risk-based allowable indoor air (AIA) concentrations:

- 1) If  $IA < AA < AIA$ , the risk is **acceptable** and there is no indication of contribution from indoor/subsurface sources.
- 2) If  $AA < IA < AIA$ , the risk is **acceptable**, but there may be some potential indoor or subsurface sources.
- 3) If  $IA < AIA < AA$  (the occurrence of this scenario is rare), the risk is **acceptable** and the likelihood of any indoor/subsurface contribution is low.
- 4) If  $AIA < IA < AA$  (also a relatively unusual occurrence), ambient sources appear to be the primary contributor to elevated indoor air concentrations with an unknown contribution from indoor/subsurface sources. The results of the indoor inventory and soil vapor concentrations may help evaluate the relative magnitude or contribution of each of these other two sources but it is unlikely that they contribute significantly to indoor air risk. The risk may be considered **acceptable** if subsurface sources are determined to be minor contributors to total risk. Additional indoor and ambient air sampling may be needed to confirm this relationship.
- 5) If  $AIA < AA < IA$ , there is an **unacceptable** risk, primarily from indoor/subsurface sources but with ambient air contributions. When ambient air concentrations are greater than risk-based concentrations, the ambient concentrations may be utilized as the cleanup criteria.

Also, ambient concentrations (if considered representative) may be subtracted from indoor air concentrations to estimate the remaining risk due to indoor/subsurface sources. If this remaining risk is still significant, further evaluations can be conducted to distribute the respective contributions from indoor versus subsurface sources.

Elevated ambient air concentrations may need to be confirmed with additional sampling. If subslab vapor data are available, a comparison to ambient air concentrations may provide some indication as to the relative contribution of these two sources to indoor air risk.

- 6) If  $AA < AIA < IA$ , there is an **unacceptable** risk and it is primarily from indoor/subsurface sources. If the indoor inventory does not indicate significant potential indoor sources or if identified sources were removed prior to sampling, the dominant source of vapors is more likely to be subsurface in origin.

The conclusions in scenarios 5 and 6 above are supported when data from subslab and deeper soil gas samples show that the source to indoor air is due to subsurface releases. For example, if subslab soil vapor concentrations are greater than indoor air and if soil vapor is of a chemical composition similar to indoor air samples, the conclusion that the source to indoor air is from the subsurface is supported. In addition, if the attenuation ratios of individual petroleum COIs between subslab and deeper soil vapor concentrations and indoor air concentrations increase with depth, the conclusion that the primary source is the subsurface is supported.<sup>1</sup>

In contrast, in some instances the above data may show that the source to indoor air is not from the subsurface. Results showing that deeper soil vapor concentrations (if they are taken above a known source) are lower than subslab or indoor air concentrations indicate that the source to indoor air is not the subsurface and that subslab soil gas may be impacted by indoor air.

Further, a comparison of petroleum COIs and concentrations in the indoor air, subslab, and deeper vapor samples may show that the chemicals in the subslab samples are impacted by indoor air and the source is not the subsurface release.

### 3 Protocol for the Measurement of Soil Vapor Levels

The goals of soil vapor sample collection and analysis are two-fold: 1) to obtain spatially and temporally representative values that can be used to assist in a determination of whether a VI issue exists at a site and 2) to estimate risk to the receptors.

The reliability of soil vapor concentrations at a site may be impacted by a number of factors, including:

- 1) Atmospheric conditions (e.g., temperature, pressure, precipitation)
- 2) Soil conditions (e.g., porosity, moisture content, vapor permeability, stratigraphy)
- 3) Site and structure characteristics (e.g., location, amount, and type of paved surfaces; type of building construction; HVAC design and operation)
- 4) Source characteristics
- 5) Age of the release
- 6) Capacity of the soil to attenuate or biodegrade the petroleum COIs

To the extent that these factors exhibit spatial and temporal variations, soil vapor concentrations can be variable and thereby less reliable. Thus, a single soil gas sampling event ~~is often~~ may not be adequate to characterize potential VI pathways. A single sampling event can be appropriate if

---

<sup>1</sup> Tracer compounds in vapor and air, such as radon, can also be used to calculate attenuation ratios, particularly between subslab vapor (where biodegradation can be considered negligible) and indoor air.

the SCM is well understood and complete, the proposed sampling is considered representative of that SCM, and it can be demonstrated to DEQ that the factors described above have been accounted for and are not influencing measured concentrations.

When collecting vapor samples at a site, the number and timing of measurement events must be sufficient to account for the factors (out of those 6 listed above) expected to contribute the greatest amount to vapor concentration variability. For example, at sites where ground water depths are shallow with significant seasonal water table fluctuations (>5 feet), measurements should be made when the water table is both high and low. If initial sampling takes place during periods of high soil moisture, such as after a significant precipitation event, it may be desirable to repeat the sampling when drier soil conditions exist. Atmospheric conditions of increasing high pressure, associated with the arrival of weather fronts, can result in net movement of air and vapor downward, potentially reducing vapor concentrations if sampling occurs during these times. This tendency may necessitate additional sampling during periods of greater atmospheric stability. Subslab vapor sampling can be impacted by pressure gradients created by atmospheric and structural conditions, which should be accounted for.

DEQ recommends but does not require that the owner/operator develop a work plan describing how representative soil gas data will be collected at the site for use in site characterization and risk evaluation and submit it for review and approval by DEQ prior to collecting the data. The work plan should include the following elements:

- Soil gas measurement techniques and methods of analysis
- Sampling locations
- Sampling depths
- Sampling numbers
- QA/QC procedures

Each of these elements is discussed below.

### **3.1 Soil Gas Measurement Techniques and Analysis**

Soil vapor can be collected and analyzed in a number of ways. Presently, DEQ recommends using permanently installed active soil gas probes for most applications where the data will be used for risk assessment.

Depending on the SCM and the goals of the investigation, active soil gas probes can consist of single installations located inside (i.e., a subslab vapor probe) or outside a structure, or they can be nested multiple probe installations. A typical outdoor permanent single probe installation is presented in Figure 3 and a nested multiple probe installation in Figure 4. Subslab probe installation is illustrated in Figure 5 and described by EPA (2006) and Hartman (2010).

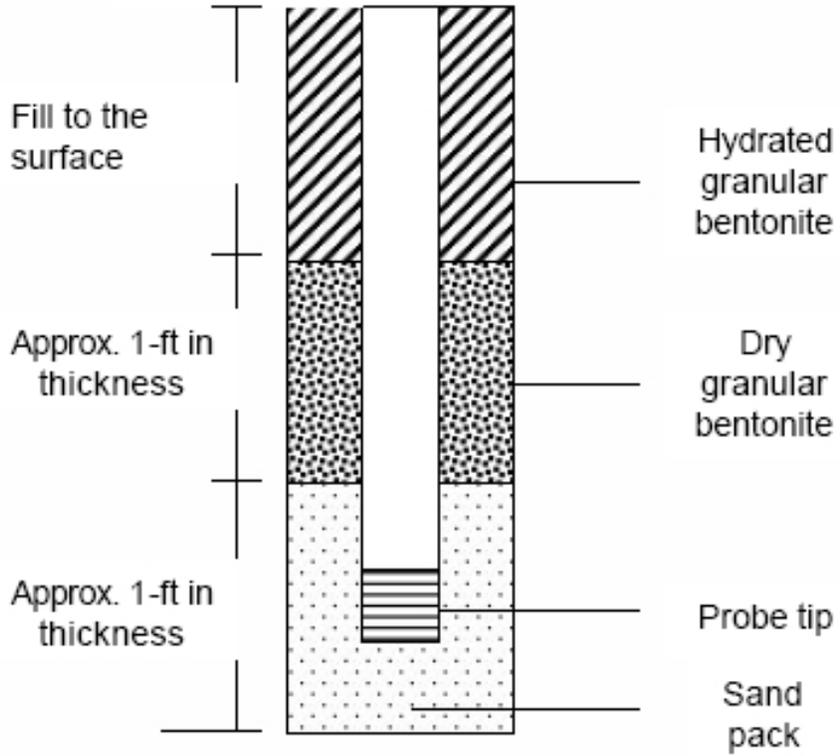


Figure 3. Schematic of single permanent soil vapor probe installation (adapted from Cal/EPA 2010)

# Multi-Depth Nested Well

## Soil Vapor Nested Well

Our vapor implants are inexpensive, unintrusive and offer repeated analysis at multiple depths

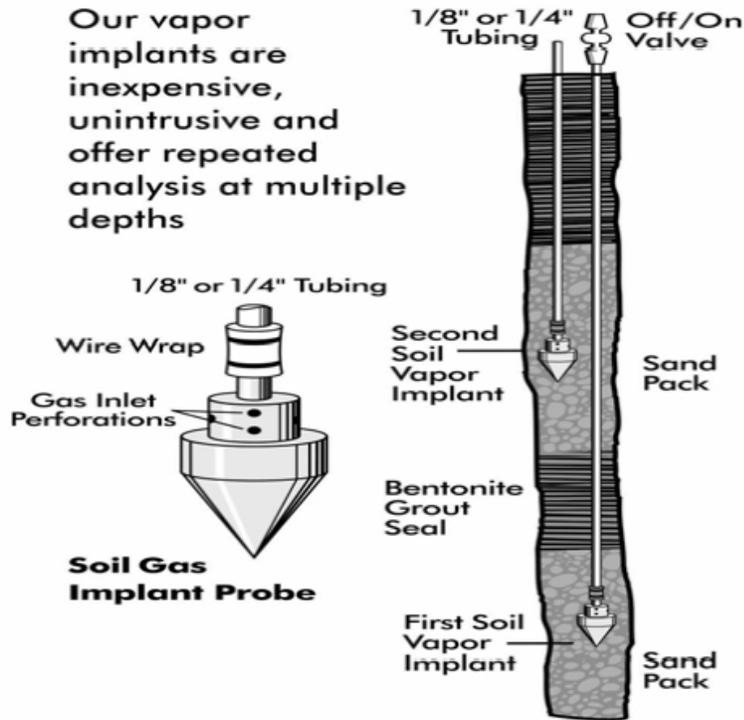
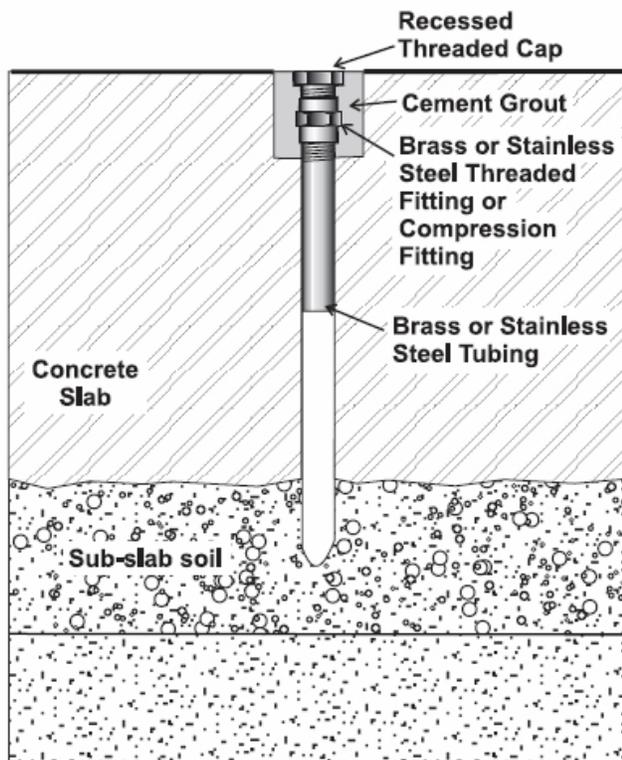


Figure 4. Schematic of nested multiddepth soil vapor probe installation (source: Hartman 2010)



**Figure 5. Schematic of subslab soil vapor probe installation (source: EPA 2006)**

As discussed above, it may be necessary to collect soil vapor samples from soil probes at multiple times in order to address data variability. Hence, probe installations should be treated similarly to a ground water monitoring well in terms of construction and expected longevity. Guidance on installing and using soil vapor monitoring probes is provided in the *ASTM Standard Guide for Soil Gas Monitoring in the Vadose Zone* (ASTM 2006), the California Environmental Protection Agency's advisory for active soil gas investigations (Cal/EPA 2010), and *Soil Vapor Sampling Methods for Vapor Intrusion Assessments* (Hartman 2010).

Soil vapor samples can be collected in a Tedlar bag, evacuated Summa canister, or granulated carbon depending on the analytical method used. The typical analytical methods used for the collection of soil vapor samples are EPA methods TO-15 and TO-17 (EPA 1999). Method TO-17 is most appropriate where lower detection limits for compounds such as naphthalene are needed, such as for indoor air or subslab vapors. Prior to collecting the sample, the probes and tubing should be thoroughly purged to ensure that the sample sent for analysis is truly representative of the formation being sampled. Leak testing of soil probe installations is also recommended.

DEQ recommends analysis of the vapor samples for fixed gases such as oxygen, methane, and carbon dioxide at the time that chemical concentrations are measured. These measurements may be used to demonstrate the occurrence of biodegradation.

### 3.2 Sampling Locations

The following criteria, which constitute the major elements of a SCM, should be considered when selecting the number, type, and potential locations for soil vapor measurements:

- The size, magnitude, and location of the release area, soil and ground water contamination, and free phase product
- The location of existing buildings on site and off site in relation to vapor source areas
- The location of potential future on-site and off-site buildings
- The location of paved and unpaved surfaces
- The location of potential preferential pathways for vapor migration such as utility trenches, sumps, low permeability layers, or fractured subsurface geology

Probes should be located to adequately characterize the vapor pathway between the source and the structure. DEQ recommends collecting samples as close as possible around the footprint of an existing structure and within the footprint of potential future structures. When contamination extends under an existing structure, sampling points within the structure may be necessary. These samples may consist of soil vapor probes below the concrete slab of an existing floor or within the earthen material of a crawl space or unfinished basement or ambient air sampling.

In all cases, at least one soil vapor probe shall be located in the source areas (i.e., the most impacted soil area and above the most impacted ground water area). Sampling at off-site locations may be necessary if soil or ground water contamination associated with the release is known or suspected to have migrated off site.

With the exception of vapor source area sampling or areas potentially slated for future development, sample probes should not be located in unpaved areas or areas subject to impacts from water infiltration or surface volatilization. If samples are to be collected from unpaved areas, they should be taken at depths greater than 5 feet, where site conditions permit.

Proposed locations of soil vapor borings on a site map and the rationale for the location may be included in a work plan submitted to DEQ for review.

### 3.3 Sampling Depths

The depth at which soil vapor samples are collected is a site-specific determination primarily dependant on the goals of the investigation, whether a structure is present, and, if present, the type of structure. For risk assessment purposes, sample depth should correspond to the characteristics of impacted or potentially impacted structures. Subslab vapor probes should be installed as close to the base of the foundation slabs as possible. When feasible, deeper probes are appropriate when attempting a detailed investigation of a subsurface source to indoor air; deeper probes can be installed below the slab.

Ideally, structures with basements with earthen floors or crawl spaces (vented or unvented) should be investigated with ambient air samples collected from within the space itself. If this is not possible, vapor samples can be collected from soil probes installed in the earthen floor. These probes should be constructed and installed such that the effects of surficial drying are minimized, the samples are representative of subsurface conditions, and the potential for short-circuiting of vapor flow is minimized. The use of deeper soil probe installations (greater than 3 but no more than 5 feet) in these instances can help avoid these issues.

Individual probes outside a slab-on-grade building footprint should be installed as close as possible to the base of foundation footings, typically 3 to 5 feet below ground surface. Structures with basements will require greater depth of installation. In no case should probes be located shallower than the foundation depth. Where it is feasible to do so and where it fits with the SCM, deeper probe installations (greater than 5 feet below ground surface) are preferred when installing probes in areas that are unpaved.

Nested soil gas probes located at multiple depths (Figure 4) can aid in the characterization of soil, ground water, or LNAPL source areas; structures with basements; and soil layering effects on vapor concentrations and in documenting the presence of biodegradation. For structures with basements, soil gas multiple depth probes should be located below and adjacent to the basement wall. In ground water source areas, DEQ does not recommend locating probes or collecting samples within the capillary fringe.

### 3.4 Sample Numbers

The number of sample locations needed is a site-specific determination that is a function of the size and location of vapor source areas in relation to existing structures; the number, size, and construction of existing potentially impacted structures; and the goals of the investigation. For existing buildings with soil or ground water contamination below them, if only outside probes are used, DEQ recommends a minimum of 4 probes, one on each side of the building. For subslab probe installations for typical building sizes (up to 2,000 square feet), a minimum of 3 probes is recommended, ideally spaced throughout the footprint of the structure and taking into account the spatial location of the vapor source. [Site conditions will ultimately determine the ideal number and locations of sample points.](#) The rationale of this sampling scheme is to attempt to account for the spatial variability in soil gas chemical and oxygen concentrations observed across similarly sized structures (Luo et al. 2009).

Larger commercial spaces will likely require greater numbers of probes. If indoor air sampling is also being conducted and it is feasible to collect deeper soil vapor samples under the building, this data may assist in interpreting potential sources of any detected chemicals in indoor air.

One or more probes should be located in each vapor source area. The number of depth intervals at a given sampling location for nested probe installations will be dependent on factors such as the total soil thickness being investigated, the depth to soil, ground water or LNAPL sources, and the degree of soil layering or heterogeneity present. If the goal is to demonstrate the occurrence of biodegradation with multidepth probes, then enough points should be installed at a given location to be able to clearly show the location of the transition to clean soil/well-oxygenated conditions.

### 3.5 QA/QC Procedures

In addition to the common QA/QC procedures that are employed during any environmental sampling event (e.g., collection of appropriate QA samples and decontamination), particular attention should be paid to the following items during the collection of soil vapor samples:

- Leak testing of soil probe installations during sampling
- Selection of appropriate sampling equipment
- Purging and monitoring prior to sampling
- Selection of appropriate analytical methods

## 4 Indoor Air Sampling

The intent of this section is not to provide exhaustive details on indoor air sampling protocols, but rather to outline a desired approach and identify issues that must be considered and addressed when developing a work plan for these types of data collection efforts. DEQ recommends but does not require that a work plan be submitted for review prior to implementation of any indoor air sampling investigation.

Sampling details are well presented in other guidance documents. Notable examples are those documents developed by the EPA (1992), New Jersey Department of Environmental Protection (NJDEP 2005, see section 6.6 for indoor and ambient air sampling procedures), and the Massachusetts Department of Environmental Protection (MDEP 2002). Indoor air sampling typically uses active sampling methods such as air pumps or evacuated canisters with flow controllers. Passive diffusive samplers, such as the Radiello or Ultra, currently being developed and tested may provide data quality comparable to active methods (Sigma-Aldrich 2010; SKC, Inc. 2011, see description of the application of Ultra diffusive samplers to vapor intrusion measurements; EPA 2010b) for both ambient and indoor air sampling.

The ultimate goal of the data collection is to document whether or not indoor air concentrations exceed indoor air screening levels for petroleum COIs resulting from a specific release. To achieve this goal, the contribution of other sources of the petroleum COIs, either from ambient, outdoor sources or from sources within the building itself, must be eliminated. Therefore, an integral part of any indoor air sampling campaign will be collecting representative, contemporaneous outdoor air and soil gas data (typically in the form of subslab and deep soil vapor data).

The influence of seasonal and diurnal meteorological changes on indoor air concentrations may necessitate conducting multiple sampling events. In general, a minimum of two events timed so as to account for the effect of these variables is necessary. If the goal is to identify “worst case” indoor air concentrations, then sampling should take place under those circumstances that will maximize indoor air concentrations. In many cases, this goal will entail sampling during winter or early spring because of the influences of building depressurization, reduced building ventilation, and frozen ground. Impacts from ground water sources may require sampling during periods of high water levels (for dissolved phase petroleum COIs) or low water levels (if separate phase product is suspected). If the goal is to characterize “average” conditions, multiple events conducted at a variety of critical time periods may be needed.

A single sampling event may be appropriate if the SCM is well understood and complete, the proposed sampling is considered representative of that SCM, and it can be demonstrated that the important influences on indoor air concentrations (such as those described above) have been accounted for and are not likely to influence measured concentrations.

Other important considerations when developing an indoor air sampling work plan include the following:

- Sampling duration—The typical sampling duration for both ambient and indoor air is 24 hours. Sampling for shorter time periods (e.g., 8 hours) may be justified if the goal of the sampling is to document “worst case” conditions or where 24-hour sampling is not practical.
- Target detection limits—The target detection limits for indoor and ambient air samples should be the EPA ambient air screening levels for residential and industrial receptors (EPA 2010b). The appropriate analytical methods (TO-15 and TO-17) and sample volumes needed to achieve these detection limits should be selected and described in the work plan.
- Building construction and HVAC operation—How the structure of interest is constructed (slab-on-grade, basement, crawlspace); the activity patterns of building occupants; and the design and operation of any HVAC system used in the structure should be understood when determining the number and location of indoor air samples.
- Indoor sources—Prior to sampling, an inventory of potential indoor sources of the target petroleum COIs should be compiled. If possible, identified indoor sources should be removed prior to sampling. Building survey forms and checklists are available from a number of sources (NJDEP 2005; ODEQ 2010, see Appendix E for building survey form for indoor air sampling).
- Other on-site sources—Sampling locations for ambient air should generally be upwind (taking into account seasonal changes in dominant wind direction) of the structure of interest. If potential on-site outdoor point sources of the petroleum COIs are identified that are not in a dominant upwind direction and cannot be removed, additional ambient air samples should be considered to account for their potential influence on indoor air quality.
- Data analysis—Data interpretation is discussed in section 2.3 of this appendix.

## 5 Suggested References

- API (American Petroleum Institute). 2005. Collecting and Interpreting Soil Gas Samples from the Vadose Zone: A Practical Strategy for Assessing the Subsurface Vapor-to-Indoor Air Migration Pathway at Petroleum Hydrocarbon Sites. Publication Number 4741. Available at <http://www.api.org/ehs/groundwater/lnapl/upload/4741final111805.pdf>.
- API (American Petroleum Institute). 2010. BioVapor: A 1-D Vapor Intrusion Model with Oxygen-Limited Aerobic Biodegradation. Users Manual. Available at: [http://www.api.org/ehs/groundwater/vapor/upload/BioVapor\\_Users\\_Guide\\_2010\\_01\\_08.pdf](http://www.api.org/ehs/groundwater/vapor/upload/BioVapor_Users_Guide_2010_01_08.pdf).
- ASTM (American Society for Testing and Materials). 2006. Standard Guide for Soil Gas Monitoring in the Vadose Zone. West Conshohocken, PA: ASTM. Designation D5314-92(2006).
- ASTM (American Society for Testing and Materials). 2010. Standard Guide for Vapor Encroachment Screening on Property Involved in Real Estate Transactions. West Conshohocken, PA: ASTM. Designation E2600-10(2010).
- Cal/EPA (California Environmental Protection Agency). 2010. Advisory—Active Soil Gas Investigation (draft). Sacramento, CA: Cal/EPA. Available at [http://www.dtsc.ca.gov/SiteCleanup/Vapor\\_Intrusion.cfm](http://www.dtsc.ca.gov/SiteCleanup/Vapor_Intrusion.cfm).
- EPA (U.S. Environmental Protection Agency). EPA Vapor Intrusion Database website. Available at <http://iavi.rti.org/index.cfm>.
- EPA (U.S. Environmental Protection Agency). 1992. Assessing Potential Indoor Air Impacts for Superfund Sites. Air/Superfund National Technical Guidance Study Series. Office of Air Quality. EPA-451/R-92-002.
- EPA (U.S. Environmental Protection Agency). 1996. Soil Screening Guidance: Technical Background Document. Washington DC: Office of Solid Waste and Emergency Response. EPA/540/R-95-128.
- EPA (U.S. Environmental Protection Agency). 1999. Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air. Washington DC: Office of Research and Development. EPA/625/R-96/010b.
- EPA (U.S. Environmental Protection Agency). 2006. Assessment of Vapor Intrusion in Homes Near the Raymark Superfund Site Using Basement and Sub-Slab Air Samples. Cincinnati, OH: Office of Research and Development, National Risk Management Research Laboratory. EPA/600/R-05/147. Available at <http://www.epa.gov/nrmrl/pubs/600R05147/600R05147.pdf>.

- EPA (U.S. Environmental Protection Agency). 2010a. Petroleum Vapor Intrusion Information Paper. How is Petroleum Vapor Intrusion Different From Chlorinated Solvent Vapor Intrusion? Draft. Petroleum Vapor Intrusion Workgroup. June 2010.
- EPA (U.S. Environmental Protection Agency). 2010b. EPA Region 9's "RARE" Opportunity to Improve Vapor Intrusion Indoor Air Investigations. Presented at EPA Update on Vapor Intrusion Workshop, AEHS Annual Conference, San Diego, California, March 16, 2010. Available at [http://iavi.rti.org/attachments/WorkshopsAndConferences/09\\_Lee\\_AEHS\\_VI%20R9%20Study\\_3-11-10.pdf](http://iavi.rti.org/attachments/WorkshopsAndConferences/09_Lee_AEHS_VI%20R9%20Study_3-11-10.pdf).
- EPA (U.S. Environmental Protection Agency). 2011. Regional Screening Levels for Chemical Contaminants at Superfund Sites. Available at [http://www.epa.gov/reg3hwmd/risk/human/rb-concentration\\_table/index.htm](http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm).
- Hartman, B. 2010. Soil Vapor Sampling Methods for Vapor Intrusion Assessments. Presented at Neilsen Field School, Tampa, Florida. January 2010. Available at <http://www.handpmg.com/documents/neilsen-school-1-2010.pdf>
- ITRC (Interstate Technology and Regulatory Council). 2007. Vapor Intrusion Pathway: A Practical Guideline. ITRC Vapor Intrusion Team. Available at <http://www.itrcweb.org/Documents/VI-1.pdf>.
- Johnson, P.C., and R.A. Ettinger. 1991. Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors Into Buildings. *Environmental Science and Technology* 25:1445–1452.
- Luo, H., P. Dahlen, P.C. Johnson, T. Peargin, and T. Creamer. 2009. Spatial Variability of Soil Gas Concentrations near and beneath a Building Overlying Shallow Petroleum Hydrocarbon-Impacted Soils. *Ground Water Monitoring and Remediation* 29(1):81–91.
- MDEP (Massachusetts Department of Environmental Protection). 2002. Indoor Air Sampling and Evaluation Guide. Boston, MA: MDEP, Office of Research and Standards. WSC Policy #02-430. Available at <http://www.mass.gov/dep/cleanup/laws/02-430.pdf>.
- NJDEP (New Jersey Department of Environmental Protection). 2005. Vapor Intrusion Guidance. Trenton, NJ: NJDEP. Available at [http://www.state.nj.us/dep/srp/guidance/vaporintrusion/vig\\_main.pdf](http://www.state.nj.us/dep/srp/guidance/vaporintrusion/vig_main.pdf).
- ODEQ (Oregon Department of Environmental Quality). 2010. Guidance for Assessing and Remediating Vapor Intrusion in Buildings. Portland, OR: ODEQ, Environmental Cleanup Program. Available at <http://www.deq.state.or.us/lq/pubs/docs/cu/VaporIntrusionGuidance.pdf>.
- Sigma-Aldrich. 2010. Radiello Diffusive Sampling System. Available at <http://www.sigmaaldrich.com/analytical-chromatography/air-monitoring/radiello.html>.
- SKC, Inc. 2011. ULTRA passive sampler downloads. Available at <http://www.skcinc.com/prod/590-100.asp#downloads>.

*This page intentionally left blank for correct double-sided printing.*

## **Appendix H: Application of Natural Attenuation**

*This page intentionally left blank for correct double-sided printing.*

## TABLE OF CONTENTS

---

Introduction.....	1
PART I: The Science of Natural Attenuation.....	1
1 The Concept of Natural Attenuation.....	1
2 Overview of Natural Attenuation Processes.....	2
2.1 Advection.....	3
2.2 Molecular Diffusion.....	4
2.3 Mechanical Dispersion.....	4
2.4 Hydrodynamic Dispersion.....	5
2.5 Sorption.....	5
2.6 Volatilization.....	5
2.7 Biodegradation.....	5
2.8 Overall Effect of Natural Attenuation Processes.....	6
2.8.1 Expanding Plume.....	7
2.8.2 Stable Plume.....	7
2.8.3 Shrinking Plume.....	7
2.8.4 Lifecycle of a Plume.....	7
3 Biodegradation of Petroleum Hydrocarbons.....	8
3.1 Composition and Amount of Hydrocarbons.....	9
3.2 Available Electron Acceptors.....	9
3.3 Quantity and Quality of Nutrients.....	10
3.4 Characteristics of Microorganisms.....	11
3.5 Indicators of Natural Attenuation of Hydrocarbon Plumes.....	11
3.5.1 Primary Line of Evidence.....	11
3.5.2 Secondary Line of Evidence.....	11
3.5.3 Tertiary (Optional) Line of Evidence.....	12
PART II: Process for the Implementation of Remediation by Natural Attenuation.....	14
4 Risk Management Plan for Remediation by Natural Attenuation.....	15
5 Source Characterization and Control.....	15
6 Plume Characterization.....	16
7 Reasonable Time Frame Determination.....	17
8 Monitoring to Demonstrate the Effectiveness of Remediation by Natural Attenuation.....	18
9 Contingency Measures.....	19
PART III: Techniques Available to Demonstrate Natural Attenuation.....	20
10 Techniques to Demonstrate the Occurrence of Natural Attenuation.....	20
10.1 Graphical Techniques.....	20

10.2	Statistical Evaluations .....	22
11	Techniques to Estimate the Site-specific Rate of Natural Attenuation.....	22
11.1	Mass Balance Analysis.....	23
11.2	Well Concentration-versus-Time Plot.....	23
11.3	Well Concentration-versus-Distance Plot .....	24
11.4	Evaluation of Plume Behavior with a Recalcitrant Tracer .....	25
12	Techniques to Quantify the Future Behavior of the Plume .....	25
	References.....	27

**LIST OF TABLES**

---

Table 1.	Expected pattern of natural attenuation indicators (secondary line of evidence) .....	12
----------	---	----

**LIST OF FIGURES**

---

Figure 1.	Schematic of a hydrocarbon release .....	3
Figure 2.	Concentration profile as a function of distance (ideal behavior and data from an actual site).....	6
Figure 3.	Expected pattern of natural attenuation indicators (secondary line of evidence) .....	10
Figure 4.	Concentration-versus-time plot of benzene.....	21

## Introduction

This appendix presents general guidance on the applicability and implementation of remediation by natural attenuation (RNA) at petroleum release sites in Idaho. Its primary focus is on attenuation of ground water contamination. Attenuation of petroleum hydrocarbons has also been documented in other media such as soil and soil vapor. Attenuation in soil vapor is addressed in Appendix G, which discusses evaluation of the vapor intrusion pathway. This appendix is divided into three parts:

- Part I presents a brief overview of the science of natural attenuation (NA)
- Part II presents the regulatory requirements for implementing NA as a remedial option
- Part III discusses the techniques available to support, quantify, and implement NA as a remedial option

This document should be used in conjunction with the *Idaho Risk Evaluation Manual for Petroleum Releases* (REM) and publicly available literature when implementing RNA. Additional information is available in the references provided at the end of this document.

## PART I: The Science of Natural Attenuation

Part I presents an overview of the science of NA, including the following topics:

- A brief overview of the processes that constitute NA (section 2)
- A description of how biodegradation operates in attenuating petroleum hydrocarbons (section 3)
- A description of the indicators of NA of hydrocarbon plumes (section 3.5)

### 1 The Concept of Natural Attenuation

The term natural attenuation refers to the reduction in concentration or mass of chemicals in a media due to the effects of various environmental fate and transport processes. NA occurs without human intervention. Although NA is applicable to a reduction in concentration in any medium (e.g., air, surface water, ground water), in this appendix it refers to the reduction in concentration of a dissolved ground water contaminant plume. For a ground water plume, environmental fate and transport processes include physical processes (advection, dispersion, dilution, sorption, and volatilization); chemical processes (hydrolysis, oxidation, and reduction); and biodegradation processes (aerobic and anaerobic). Physical processes are nondestructive in that they redistribute the chemicals in the environment without affecting the total mass of the individual chemical. Chemical transformation processes and biodegradation result in the transformation of the parent chemical into other chemicals referred to as daughter products.

The only human action involved in RNA is monitoring to demonstrate that concentration reduction is occurring at a reasonable rate. Depending on site-specific conditions, RNA may be used as a stand-alone corrective action strategy or in combination with other engineered remediation alternatives.

This guidance focuses on using NA on sites contaminated with petroleum products. NA has also been used at sites with other classes of contaminants, such as metals, explosives, and pesticides (USACE 1999; SNL 1997). The same concepts for evaluation, requirements for site characterization, and demonstrations as to effectiveness are required regardless of the class of contaminant. A general approach to the evaluation of the bioremediation aspects of NA for a range of biotreatable compounds is described in ITRC 2002.

## 2 Overview of Natural Attenuation Processes

Although each contaminated site is unique, for this discussion it is useful to consider a generic site where a petroleum spill has occurred. The soil immediately below and around the point of release becomes contaminated, and the contaminant front moves downward. The downward movement of the contaminant front continues until one of the following three conditions occurs:

- The soil sorption capacity exceeds the amount of contaminant available.
- An impermeable barrier is encountered and the contaminant spreads horizontally.
- The contaminant reaches the water table and, if it is a light non-aqueous phase liquid (LNAPL), spreads horizontally.

The term LNAPL relates to the density of the released contaminant. LNAPLs are chemicals that are liquid at ambient temperature but lighter than water. For example, the density of toluene is 0.866 grams per cubic centimeter (g/cc) compared to a density of 1 g/cc for water.

After the contaminant movement has stopped, the soil through which it traveled is contaminated with residual chemicals that act as a contaminant source for the ground water plume. Figure 1 shows a schematic of a LNAPL moving through the soil to the ground water.

When rainwater infiltrates through the residual contaminated soils, it dissolves and leaches out the soluble components. For petroleum hydrocarbons, the toxic soluble chemicals include, but are not limited to, benzene, toluene, ethylbenzene, and xylene (BTEX); the soluble additives methyl tertiary butyl ether (MTBE) and ethylene dibromide; and smaller fractions of other less-soluble constituents. After undergoing NA processes in the unsaturated zone, these dissolved chemicals reach the water table, mix with ground water, and move with the ground water to form a dissolved plume. At sites where the spill is of a sufficient quantity to reach the water table and form an LNAPL layer on the water table, soluble constituents from the LNAPL gradually dissolve in ground water and form a dissolved ground water plume.

Additionally, vapors of volatile hydrocarbons (chemicals with a Henry's Law constant greater than  $1 \times 10^{-5}$ ) will spread outwards from the contaminated soil and dissolve in soil moisture and ground water.

As the dissolved plume moves through the unsaturated and the saturated zones, its concentration decreases due to the combined influence of several NA processes. Each of these processes is briefly discussed below.

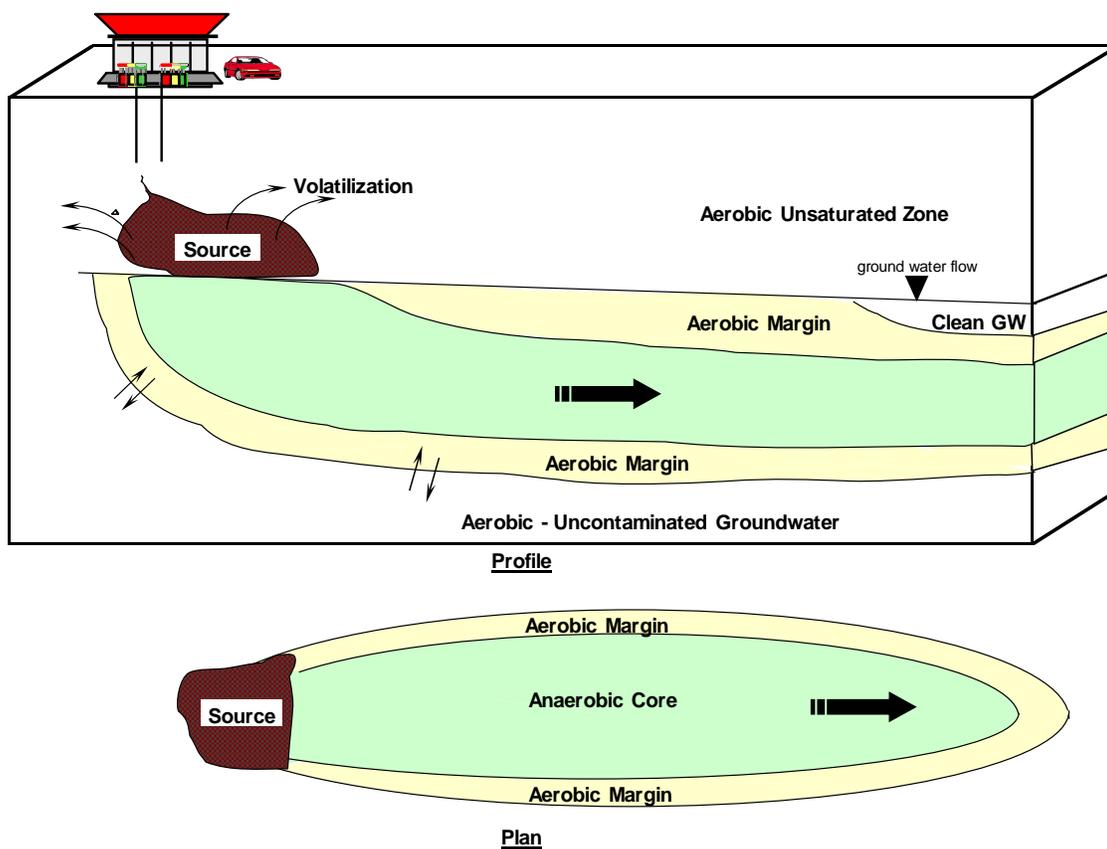


Figure 1. Schematic of a hydrocarbon release

## 2.1 Advection

Advection refers to the bulk movement or flow of water caused by differences in density, temperature, or pressure. In most aquifers, flow occurs predominantly due to hydraulic gradients, which may be natural—resulting in regional ground water movement—or man-made, caused by pumping or artificial recharge. In saturated zones, hydraulic gradients may exist in horizontal and vertical directions, resulting in complex three-dimensional flow patterns. However, at most sites there exists a predominant flow direction that results in the migration of most mass.

As water moves in the saturated zone, it carries with it the dissolved constituents. The process results in the migration of dissolved constituents in the saturated zone without a change in concentration and is termed advection.

Parameters required to estimate the volume of water moving through a saturated zone include the Darcy velocity and the cross-sectional flow area. Darcy velocity is estimated using hydraulic conductivity and hydraulic gradient.

Hydraulic conductivity may be estimated using a variety of methods, including slug tests, pump tests, grain size distribution, and literature values corresponding to the site stratigraphy. For most saturated zones, hydraulic conductivity varies in the horizontal and vertical directions.

Site-specific values of hydraulic gradients are estimated based on water-level measurements in monitoring wells, or piezometers. When estimating horizontal hydraulic gradients, it is important to compare data from wells screened in the same saturated zone. Wells screened in different zones or at different depths (e.g., cluster wells) can be used to estimate the vertical hydraulic gradient between the zones. Site-specific hydraulic gradients may exhibit seasonal and spatial variations (in magnitude and direction) due to a variety of factors such as pumping, seasonal flow in surface water bodies, and seasonal variations in rainfall.

Another related parameter used to estimate the travel time of a chemical due to advection is the seepage velocity, which requires an estimate of the porosity of the media. Typically, literature values corresponding to the aquifer type (e.g., sand or silt) are used to estimate porosity.

## **2.2 Molecular Diffusion**

Molecular diffusion refers to the transport of chemical mass from a zone of higher concentration to a zone of lower concentration due to the movement of molecules. The effect of diffusion is to spread the chemical mass over a large area and hence reduce the overall concentration. Thus, diffusion results in a reduction in concentration by dilution. In most ground water systems where there is advection, the attenuation in concentration or the chemical mass transport due to diffusion is small and often negligible. However, in no-flow or low-flow situations, diffusion can be an important attenuation mechanism.

Molecular diffusion is quantified using Fick's Law, and the parameter required to quantify diffusion is the effective diffusion coefficient of the chemical (Freeze and Cherry 1979).

## **2.3 Mechanical Dispersion**

Mechanical dispersion refers to the spreading of the contaminant plume that occurs due to variations in the flow velocity. In the saturated zone, velocity variations occur due to a variety of factors, including inter-pore and intra-pore velocity variations and the tortuosity of the porous media. The net effect of mechanical dispersion is that the chemical spreads both horizontally and vertically, thus reducing the overall concentration in the plume. Thus, like diffusion, dispersion is a dilution process.

The transport of mass due to mechanical dispersion is quantified using Fick's Law. The key parameters are the dispersivity coefficients in the three cardinal ( $x$ ,  $y$ , and  $z$ ) directions. Dispersivity values have been measured using tracers at several research sites, based on which empirical dispersivity relationships have been developed (EPRI 1985; Xu and Eckstein 1995). For most site-specific applications of fate and transport models, these empirical relationships are used. Higher dispersivity values result in larger plumes, which result in increased dilution and lower concentrations.

## **2.4 Hydrodynamic Dispersion**

The term hydrodynamic dispersion refers to the sum of molecular diffusion and mechanical dispersion. In most ground water systems where there is advection, hydrodynamic dispersion is approximately equal to mechanical dispersion, since the effect of molecular diffusion is negligible.

## **2.5 Sorption**

Sorption refers to the transfer or distribution of mass between the liquid and solid phases. Sorption has the overall effect of reducing the mobility of the chemical, which increases its residence time in the subsurface and hence the amount of microbial degradation. This distribution is quantified by the soil water partition coefficient. For organic chemicals, the partition coefficient depends on the chemical-specific normalized organic carbon partition coefficient and the organic carbon content in the soil. The partition coefficient is used to estimate the retardation factor for the chemical, which is a measure of the "stickiness" of the chemical to the formation. Parameters required to estimate the retardation factor include porosity, organic carbon content of soil, bulk density of soil, and chemical-specific normalized organic partition coefficient.

## **2.6 Volatilization**

Volatilization refers to the transfer of chemical from the LNAPL or dissolved phase to the vapor phase. Vapors can migrate by diffusion alone (in the absence of a pressure gradient) and by diffusion and advection if a pressure gradient exists in the formation. Chemicals volatilizing from the dissolved plume occupy the pores in the unsaturated zone and migrate outwards due to the combined influences of molecular diffusion and vapor-phase advection if pressure gradients exist. Thus, volatilization can result in a net loss of chemical from the dissolved phase or from the LNAPL.

The chemical-specific factors controlling volatilization from a dilute solution and LNAPL are the Henry's Law constant and saturated vapor pressure, respectively. These factors are sensitive to the temperature of the media where volatilization occurs.

## **2.7 Biodegradation**

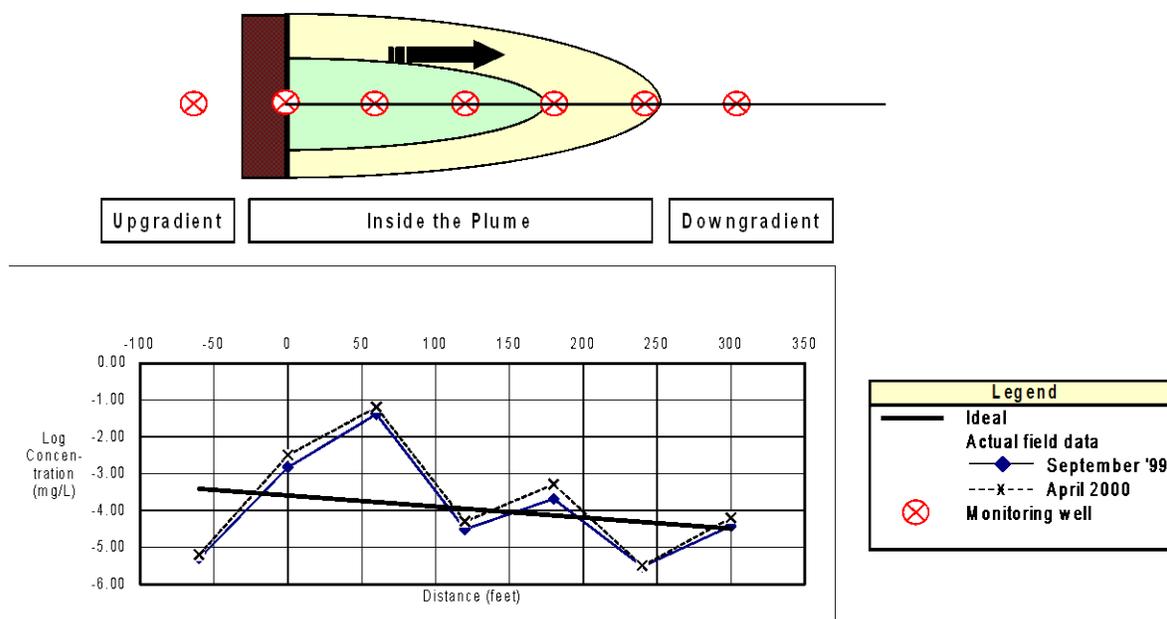
Biodegradation refers to the destruction of chemicals by indigenous microorganisms present in the aquifer. For petroleum hydrocarbons, biodegradation is the primary

destruction mechanism. Due to the significance of biodegradation within the overall process of NA, biodegradation is discussed at length in section 3. In certain situations, additional compounds (e.g., ozone, oxygen, peroxide); nutrients; or microorganisms may be added to the contaminant plume to enhance the rate of biodegradation.

## 2.8 Overall Effect of Natural Attenuation Processes

As explained above, the process of NA refers to a combination of advection, molecular diffusion, dispersion, sorption, volatilization, chemical reactions, and biodegradation.

The combined effect of these processes is to spread or reduce the chemical mass in the dissolved plume. Thus, the concentration of the chemical decreases as distance from the source increases. Figure 2 shows the concentration profiles in actual monitoring wells down-gradient of a source and the expected concentrations under ideal conditions. Although such patterns have been observed at several sites, fluctuations in water levels, flow direction, and climatic conditions often result in nonideal behavior. Additional complications occur due to errors in data collection, analytical measurements, and the existence of multiple sources (in space and time) at a site.



**Figure 2. Concentration profile as a function of distance (ideal behavior and data from an actual site)**

Depending on the overall rate of NA and the on-going contribution of chemicals to the ground water plume from the residual soil source, ground water plumes may be classified as expanding, stable, or shrinking. These concepts are discussed below.

### **2.8.1 Expanding Plume**

An expanding plume is characterized by increasing concentrations within the plume and/or an outward movement of the plume that increases the size of the plume. An expanding plume occurs when the chemical mass loading to the plume from leaching or dissolution of residual LNAPL exceeds the mass loss due to NA processes.

In an expanding plume, NA processes continue to occur but at a rate too slow to prevent the increase in concentrations or the size of the plume.

### **2.8.2 Stable Plume**

A stable plume is characterized by stable concentrations within the plume and at the periphery of the plume (i.e., the concentrations do not show a decreasing or increasing trend). For a plume to be stable in size or concentration, the rate of chemical mass addition to the plume from the source is equal to the rate of chemical mass loss by NA processes. The source may be the chemicals leaching from adsorbed and residual concentrations in the capillary/water table fluctuation zone or in the vadose zone or the dissolution of chemicals from the LNAPL source.

### **2.8.3 Shrinking Plume**

A shrinking plume is characterized by decreasing ground water concentrations within the plume, decreasing concentrations at the periphery of the plume, or a decrease in the area of the plume. For a shrinking plume, the addition of chemical mass from the source is less than the mass lost due to NA processes. Thus, unless site-specific conditions change that result in an increase in chemical mass addition to the plume or a decrease in the rate of NA, the plume will eventually disappear.

### **2.8.4 Lifecycle of a Plume**

Initially, when a chemical reaches the ground water and a plume forms, it is an expanding plume. The plume continues to expand as long as the addition of chemical mass from the source exceeds mass loss by NA processes. As the plume expands and occupies an ever-increasing portion of the aquifer, the loss of mass by NA processes increases. Thus, a point is reached when the mass addition equals mass lost, and the plume becomes stable. Because of the phenomenon of NA, most BTEX plumes resulting from service station spills become stable at lengths less than 500 feet, as demonstrated by numerous plume studies (Buscheck et al. 1996; Rice et al. 1995). At most sites, the chemical source is finite; in time, the mass loading from the source to the dissolved plume decreases. Meanwhile, the rate of mass loss due to NA processes increases or stays the same, so eventually the plume begins to shrink.

Under ideal conditions, all dissolved chemical plumes would follow the above lifecycle; however, real plumes may not follow this pattern due to a number of confounding factors, including the following:

- Variations in ground water velocities that affect the rate of NA

- Fluctuations in the water table that affect the source mass loading due to the release of chemicals trapped in the capillary fringe
- Variations in climatic conditions that affect the rate of NA
- Variations in rainfall and infiltration that affect mass loading to ground water
- Additions to the plume from new releases and spills from operating facilities

Because of the above complications, it is important to collect and evaluate all the site data and look at multiple lines of evidence to understand the plume behavior and predict its future behavior (see section 3.5).

### **3 Biodegradation of Petroleum Hydrocarbons**

This section discusses the biodegradation of dissolved petroleum hydrocarbons and identifies the various indicators that should be measured to confirm biodegradation.

The biodegradation of hydrocarbons is the process by which naturally occurring subsurface microorganisms biodegrade contaminants. The process of biodegradation, as facilitated by microorganisms, can be represented by the general reaction:

*Hydrocarbon + Electron Acceptors + Nutrients YIELDS Carbon Dioxide + Water + Microorganisms + Waste Products*

The above biologically mediated reaction produces energy for cell growth and reproduction of the microbial population. The process of electron transfer results in the oxidation of the donor (hydrocarbon), reduction of the electron acceptor, and the production of usable energy for the organisms. Based on the principles of thermodynamics, biologically mediated reactions that yield the most energy are favored over reactions that yield less usable energy for the organisms. For hydrocarbons, biologically mediated reactions ideally occur in the following order:

1. Dissolved oxygen in the ground water is used as the electron acceptor.
2. After all oxygen has been depleted and anaerobic conditions exist within the dissolved plume, dissolved nitrate is used as the electron acceptor.
3. After the depletion of dissolved oxygen and nitrate, ferric iron is used as an electron acceptor and is reduced to ferrous iron.
4. After the depletion of oxygen, nitrate, and iron, sulfate is used by sulfate-reducing bacteria to degrade the hydrocarbons.
5. Finally, methanogenesis degrades the hydrocarbons.

While all petroleum hydrocarbons are biodegradable, the rate of biodegradation can differ significantly from site to site depending on the composition and amount of hydrocarbons; type and amount of available electron acceptors; type, number, and characteristics of the microorganisms; and quantity and quality of nutrients.

Site-specific measurements of these factors, comparison of these factors within and outside the plume, and temporal variations in these factors can be used to demonstrate the occurrence of biodegradation. Each of these factors is discussed below.

### 3.1 Composition and Amount of Hydrocarbons

Almost all petroleum hydrocarbons are biodegradable under aerobic conditions. The ease of biodegradation depends on the type of hydrocarbon. Low molecular weight hydrocarbons (e.g., C10 to C24 alkenes) and single-ring aromatics are the most easily biodegradable. As molecular weight increases, resistance to biodegradation also increases. Individual compounds degrade at different rates under aerobic and anaerobic conditions.

For most hydrocarbon-impacted sites, the primary chemicals of interest (from a risk perspective) are BTEX, MTBE, and naphthalene. Naphthalene and BTEX are readily degradable under aerobic conditions. Benzene typically degrades slower than other BTEX hydrocarbons under anaerobic conditions. The biodegradation and NA of MTBE has been a topic of current research (Moyer and Kosteki 2003; EPA 2005; API 2007). MTBE degrades under both aerobic and anaerobic conditions. However, the rates of MTBE degradation and controlling factors have not yet been firmly established.

### 3.2 Available Electron Acceptors

The biodegradation of hydrocarbons is essentially an oxidation-reduction reaction. In this reaction, the hydrocarbon donates the electron (i.e., the hydrocarbon is oxidized) and a second compound (the electron acceptor) is reduced. Of the several electron acceptors available in the subsurface environment, oxygen, because of its high energy yield, is typically used first by microorganisms. Anaerobic bacteria can use other electron acceptors, including the following:

- Nitrate ( $\text{NO}_3^-$ ) that is reduced to nitrogen ( $\text{N}_2$ )
- Manganese ( $\text{Mn}^{4+}$ ) that is reduced to water soluble  $\text{Mn}^{2+}$
- Ferric iron ( $\text{Fe}^{3+}$ ) that is reduced to water soluble  $\text{Fe}^{2+}$
- Sulfate ( $\text{SO}_4^{2-}$ ) that is reduced to sulfide ( $\text{S}^-$ )
- Carbon dioxide ( $\text{CO}_2$ ) that may be used by methanogens to yield methane ( $\text{CH}_4$ )

As the biodegradation of hydrocarbons occurs, the concentration of the electron acceptors decreases and the concentration of the products formed increases. This concept can be used to demonstrate the occurrence of biodegradation (i.e., secondary line of evidence, see section 3.5.2). Table 1 shows the expected relationship between the BTEX concentration and the electron acceptors and the products of the oxidation reduction reaction.

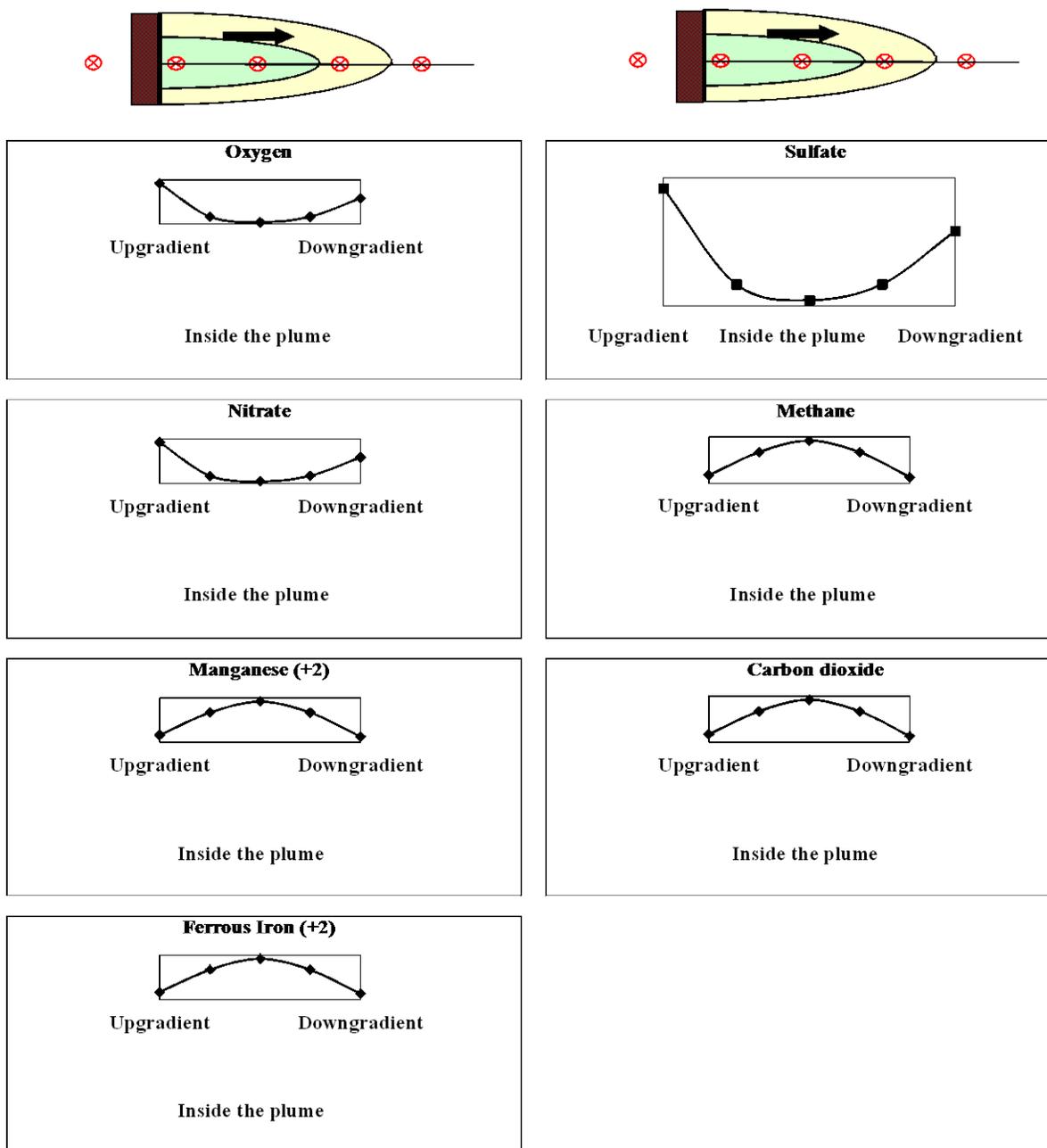


Figure 3. Expected pattern of natural attenuation indicators (secondary line of evidence)

### 3.3 Quantity and Quality of Nutrients

In addition to the electron acceptors, microorganisms also require nutrients. These nutrients are incorporated into the biomass and are necessary to form cells. The nutrients nitrogen and phosphorous are required in relatively large amounts. Small amounts of micro-nutrients—such as sulfur, manganese, and magnesium—are also required.

Certain compounds, such as nitrates and sulfates, can serve either as nutrients or electron acceptors. Nutrients are rarely a limiting factor in the subsurface biodegradation of petroleum hydrocarbons. A decrease in nutrient levels within the zone of degradation can indicate biodegradation.

### **3.4 Characteristics of Microorganisms**

The ability of microorganisms to degrade a wide variety of petroleum hydrocarbons is well documented. Hydrocarbon-degrading microorganisms are widespread in the environment, as they occur in fresh water, salt water, soil, and ground water. The number of cells per milliliter of water can also be used as an indicator of biodegradation. As hydrocarbons degrade, the cell count for hydrocarbon-degrading bacteria increases. McKee et al. (1972) found 50,000 or more hydrocarbon-degrading bacteria per milliliter of water in samples from wells containing traces of gasoline, while a noncontaminated well had only 200 microorganisms per milliliter.

### **3.5 Indicators of Natural Attenuation of Hydrocarbon Plumes**

Based on the information presented above, concentrations of several substances (hydrocarbons, electron acceptors, microorganisms, nutrients, and carbon dioxide) can be measured to demonstrate the occurrence of NA.

These measurements are typically divided into three tiers, or “lines of evidence” (i.e., primary, secondary, and tertiary lines of evidence), to demonstrate NA. Data collected under each line of evidence can be evaluated qualitatively or quantitatively.

#### **3.5.1 Primary Line of Evidence**

The purpose of the primary line of evidence of NA is to demonstrate the loss of chemical mass by evaluating measured petroleum hydrocarbon concentrations. Of all the methods available to demonstrate the occurrence of NA, this is perhaps the simplest and most useful to demonstrate site-specific reductions in risk. Site-specific application of the primary line of evidence requires an adequate number of correctly installed sampling points (monitoring wells), an adequate amount of chemical data from these points, and a thorough evaluation of these data. These issues are discussed in Parts II and III of this document.

Although the primary line of evidence can show whether the concentration of a plume is attenuating, it does not show whether the decrease is due to destructive mechanisms or merely dilution. Secondary lines of evidence are necessary to determine whether the decrease is due to biodegradation.

#### **3.5.2 Secondary Line of Evidence**

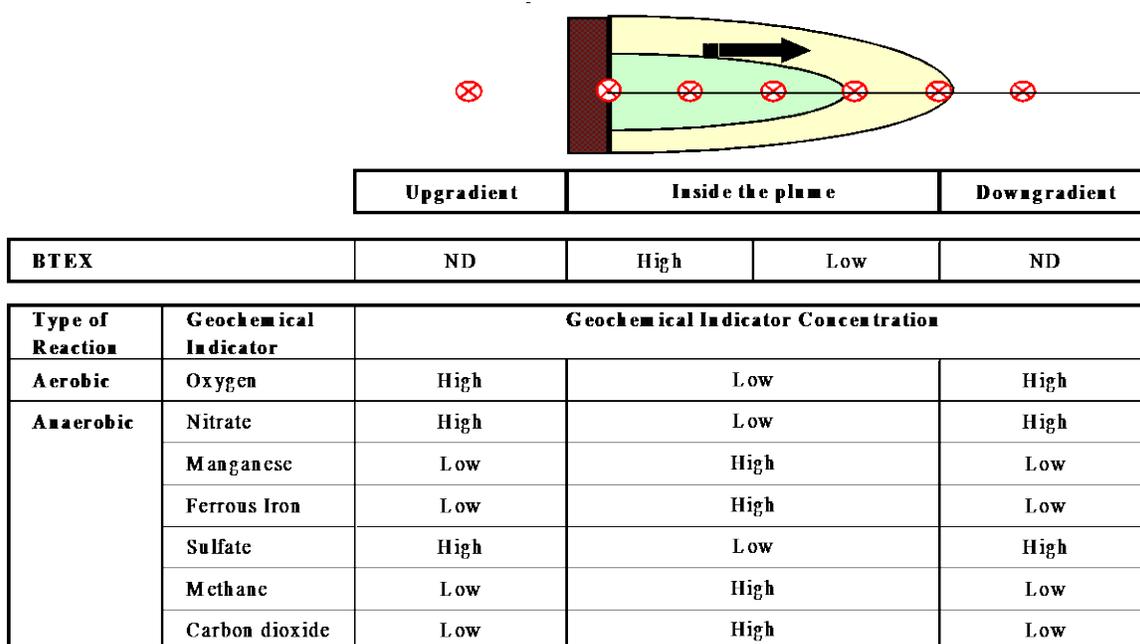
Secondary evidence of NA refers to measurements of electron acceptors and products of metabolism within the plume and their comparison with concentrations in the unimpacted area of the aquifer, where no biodegradation activity would be expected to occur.

Parameters that are typically measured in the field include dissolved oxygen, [REDOX potential](#), dissolved nitrates, manganese, ferrous iron, sulfate, and methane. These parameters should be measured at up-gradient locations, inside the plume near the source, and at down-gradient locations. Expected patterns of these parameters that are indicative of biodegradation are shown in Table 1 and Figure 3.

As microorganisms consume chemicals, there is a corresponding consumption of the compounds that serve as electron acceptors. Thus, the concentration of these compounds would decrease in the portion of the plume where biodegradation is occurring. For example, under aerobic biodegradation, the concentration of oxygen would decrease, assuming oxygen is not being added to the plume. Similarly, under anaerobic conditions, a depletion of nitrate, ferric (III) iron, and sulfate can be expected.

Biodegradation also results in an increase in the concentration of metabolic byproducts. For example, increased concentrations of nitrite and ferrous (II) iron within the plume would be indicative of biodegradation.

**Table 1. Expected pattern of natural attenuation indicators (secondary line of evidence)**



The secondary line of evidence demonstrates the occurrence of biodegradation only. It does not provide any data on the occurrence of other NA processes.

### 3.5.3 Tertiary (Optional) Line of Evidence

The tertiary (optional) line of evidence involves performing microbiological studies, such as identifying the microorganisms present in the formation and counting their cells, in an effort to demonstrate the occurrence of NA. Thus, the objectives of secondary and tertiary lines of evidence are similar. In the portion of the plume where NA is occurring, the ratio of petroleum degraders to the total number of bacteria should be higher than in

the uncontaminated portion of the plume due to the readily available petroleum energy source. Tertiary lines of evidence are seldom required at petroleum hydrocarbon impacted sites and are not discussed further.

## **PART II: Process for the Implementation of Remediation by Natural Attenuation**

Remediation by natural attenuation refers to the achievement of site-specific cleanup goals using NA. As discussed in Part I, NA consists of several processes that occur at all contaminated sites at varying rates. As with any other remedial option, the site-specific applicability of RNA must be carefully evaluated before it is selected as the remedial alternative of choice. RNA should not be considered a presumptive remedy; rather, it is one of several available strategies that should be evaluated to ensure its applicability based on site-specific conditions.

The first step in any evaluation of NA is the collection of appropriate site characterization data. In general, the data collected need to confirm the occurrence of NA, the effectiveness of RNA, and that the receptors are not exposed to unacceptable risk throughout the period when the site is being remediated by NA. The data collected should help answer the following questions and support the activities described in the questions.

- Has the full horizontal and vertical extent of the source and the plume been delineated?
- Is the plume at steady state and is it stable or shrinking in size?
- Can contaminant degradation be demonstrated and quantified?
- Can the long-term behavior of the source and the plume be modeled?
- Can the time frame to achieve remedial cleanup goals be estimated?
- What is the impact of source removal/reduction on the remedial time frame?

Once the site has been characterized to document the feasibility of NA, an evaluation as to the site-specific appropriateness of NA as the preferred remedy should be performed. RNA is applicable only at the following types of sites:

- Sites where immediate threats to human health, safety, and the environment do not exist or have been mitigated
- Sites where “active” sources, such as leaking tanks, drums, etc., have been removed
- Sites where the projected time frame to achieve remedial objectives is “reasonable,” as defined in section 7
- Sites where the plume is stable or shrinking and is not likely to impact current receptors or sensitive habitat
- Sites where active remediation has removed the bulk of the contaminants and the role of RNA is to perform the “final touchup”
- Sites where any necessary institutional controls can be reliably implemented

Upon selection of RNA as part or all of the preferred remedy, a corrective action plan will be developed to document the selection process and provide details about implementation of the remedy. The Idaho Department of Environmental Quality (DEQ) must approve this corrective action plan. At all sites, RNA will be accompanied by long-term monitoring to demonstrate that RNA is occurring at the rate anticipated when RNA

was selected as the remedial option. Monitoring will continue until the specified cleanup goals have been achieved. If the monitoring data indicate that RNA is not occurring at an acceptable rate, the remedial plan will need to be modified.

## **4 Risk Management Plan for Remediation by Natural Attenuation**

At sites where RNA is part of the preferred remedial option, the responsible party should include a discussion in the corrective action plan that addresses the following elements:

- A summary of site characterization activities that demonstrates a thorough understanding of the nature and extent of the source and the nature and extent of the impacts, provides data supporting the likely effectiveness of RNA, and discusses any source removal/control activities performed at the site
- A discussion of remedial endpoints and points of compliance, and the manner in which these were determined
- A discussion of the time frame over which the endpoints are expected to be achieved
- A demonstration that during this time frame, risks to human health and the environment are acceptable
- A discussion of monitoring locations, the rationale for monitoring location selection, and the type and frequency of data that will be collected to monitor the performance of RNA and the achievement of remedial goals
- A description of the tools to be used to evaluate/analyze the monitoring data
- A description of the institutional controls that may be required and documentation of their implementation
- A description of a contingency plan that will be implemented if the monitoring results indicate that RNA is not sufficiently effective or is not proceeding at the expected rate
- A description of the frequency and form of the reports to be submitted to DEQ during the course of implementing RNA

A brief discussion of critical components of the RNA portion of the corrective action plan is presented below.

## **5 Source Characterization and Control**

Characterizing and controlling the source are important aspects of RNA. Sufficient data should be collected during the site investigation phase to delineate the nature and extent of the source and estimate the source lifetime. The term “nature” refers to an evaluation of the chemicals of interest and a determination that the chemicals are amenable to NA. The extent refers to the physical dimensions of the source as well as a determination of the mass of residual chemicals present in the source. An estimate of the lifetime of the source can be made by calculating the mass flux out of the source area (using ground water flow characteristics and contaminant concentrations in the source area) and

comparing this to the total contaminant mass in the source area (including free phase product, soils, and ground water).

DEQ requires that all active sources (e.g., leaking pipes, tanks, spills) be stopped and any free phase product in ground water be removed, to the maximum extent practicable. It is best to reduce the source and remediate soils containing residual product that are significant sources of contamination to ground water. Such control measures will reduce the time required to achieve remedial objectives. At a minimum, sufficient source material should be removed to ensure a declining plume. The amount of active remedial activity necessary should be determined on a case-by-cases basis and clearly presented in the risk management plan.

## **6 Plume Characterization**

The goals of collecting data to characterize the plume are to demonstrate the magnitude and direction of contaminant transport and the stability status of the plume, to confirm degradation is occurring, and to estimate the contaminant degradation rate or the ability of the aquifer to assimilate the contamination.

To achieve these goals, the responsible party must construct wells to account for aquifer heterogeneity and dominant zones of contaminant transport, select appropriate monitoring locations, collect samples at an adequate frequency, and collect and evaluate the appropriate analytical data. How to determine the appropriate monitoring locations, sampling frequency, and data is discussed below.

The location and number of ground water samples collected and analyzed must be determined based on site-specific conditions.

At a minimum, sampling points should be located so as to achieve the following:

- Locate the distribution of contaminants within the plume
- Locate the plume boundaries
- Track plume movement and migration

While they do help define the extent of the plume, sampling points at nondetect locations provide little useful information for documenting plume characteristics for an NA evaluation. Most sampling points need to be located within the plume boundaries for NA evaluation purposes.

Monitoring wells should be located up-gradient of the source, within or immediately down-gradient of the source area, and within the plume aligned along the plume axis. Data should be collected from an unimpacted down-gradient well also. A down-gradient clean well can be used to help characterize the extent of the plume and may be used to protect down-gradient receptors by providing early detection of plume movement. This function is described in section 8. Wells delineating the sides of the plume assist in determining if there are significant seasonal changes in ground water flow direction.

As discussed in sections 3.5.1 and 3.5.2, data related to the primary and secondary lines of evidence should be collected. In rare cases, it may be necessary to collect data to demonstrate tertiary lines of evidence as well. Based on the data collected, a determination should be made whether the plume is expanding, stable, or shrinking. The specific analytical tools that may be used to conduct this characterization are discussed in Part III of this document.

Expanding plumes require continued monitoring. Depending on site conditions, such as the risk to current or potential future receptors and the rate at which the plume is expanding, additional assessment of the plume and/or source removal and reduction may be necessary. An expanding plume typically requires active remediation.

Plumes documented to be stable or shrinking are candidates for the use of NA. These plumes will also require continued monitoring, though perhaps at a lower frequency than expanding plumes. Depending on site conditions and the time frame of remediation, a stable plume may require residual source characterization or removal.

The frequency and duration of monitoring during the plume characterization phase should be determined on a site-specific basis and in consultation with DEQ. However, in most cases, 1–2 years of quarterly monitoring data are necessary to evaluate the degree of seasonal variations in water levels and flow directions present at a site. This information is necessary to characterize a plume as expanding, stable, or shrinking and to estimate degradation rates. As clear trends emerge in the data, the monitoring frequency may be modified. The actual duration of sampling will depend on the time it takes to demonstrate a clear trend in the concentrations.

## **7 Reasonable Time Frame Determination**

The determination as to what constitutes a reasonable time frame for RNA is a complex, site-specific determination not amenable to simple rules of thumb or quantification. In making this determination, DEQ will take into account factors that include, but are not limited to, the following:

- The time frame for RNA compared to that for other remedies being evaluated
- The time frame in which affected portions of the aquifer might be needed for various uses
- The likelihood that impacted ground water will be utilized
- The degree of uncertainty in site characterization and NA estimates
- The reliability of institutional controls over the time frames for which they may be required to function
- The ability of the responsible party to maintain the required monitoring and plume evaluation required when NA is used as a remedy

## 8 Monitoring to Demonstrate the Effectiveness of Remediation by Natural Attenuation

Due to the uncertainties associated with the site-specific implementation of RNA, long-term monitoring is necessary to demonstrate its effectiveness. Long-term monitoring is used to ensure that the behavior of the plume does not change (EPA 1999) and that predictions of plume behavior are accurate. The objectives of long-term monitoring are to demonstrate NA is continuing to occur, human health and the environment are being protected, and the plume is not expanding.

The specifics of the monitoring plan (e.g., the location, frequency, and type of samples to be collected and the analytical procedures to be used) should be determined on a site-specific basis. The primary factors that should be considered when designing a long-term monitoring program include the following:

- Distance to potential receptor exposure points
- Ground water seepage velocity and direction
- Types of contaminants
- Aquifer heterogeneity
- Three-dimensional distribution of chemicals of interest
- Areas of unique geochemical conditions
- Surface water impacts
- Effects of active remediation systems (Wiedemeier et al. 2000)

The secondary factors that should be considered include the following:

- Access issues
- Property lines
- Contaminant contributions from offsite sources (Wiedemeier et al. 2000)

Two types of wells are required for any long-term monitoring program: performance monitoring wells and contingency monitoring wells. Performance monitoring wells are used to demonstrate that NA is proceeding according to expectations; document that geochemical conditions continue to be adequate to support NA processes; identify any toxic products resulting from NA processes; determine if plume conditions remain stable or are shrinking; identify changes in ground water conditions, such as change in flow direction, recharge, etc.; and document that cleanup criteria have been met.

Contingency monitoring wells are placed beyond the predicted down-gradient boundary of the plume and up gradient from known or potential receptor exposure points. Their purpose is to provide an “early-warning” if unexpected plume expansion occurs and allow implementation of a contingent remedy if needed. Multiple contingency wells may be needed, particularly if seasonal variations in ground water flow direction are known to occur.

Sampling frequency should be based on the following factors:

- The natural variability observed in contaminant concentrations
- The distance and travel time from the source to the point of compliance

- The reduction in concentrations needed to meet target levels

## 9 Contingency Measures

The RNA corrective action plan should include a contingency plan to be implemented if the site data indicate that RNA is not occurring at the expected rate or the exposure conditions at the site have changed, resulting in an unacceptable risk to human health or the environment.

Contingency measures will prevent delays in site remediation and provide a clear roadmap for site remediation. Triggers should be established and included in the plan that would cause the responsible party to implement alternative active strategies to enhance RNA. The triggers should be as objective and quantitative as possible. Examples of triggers that would cause the responsible party to implement alternative strategies include, but are not limited to, the following:

- A consistent increase in concentrations in one or more wells
- A failure of any of the institutional conditions necessary to protect human health and the environment during the period of RNA
- A change in the exposure conditions (e.g., removal of pavement)
- Continued expansion of the plume
- Unacceptably low rates of RNA

## **PART III: Techniques Available to Demonstrate Natural Attenuation**

Several techniques are available to evaluate the data collected to demonstrate NA or to design and implement an RNA program. These techniques can be divided into three categories: techniques to demonstrate the occurrence of NA, techniques to estimate the site-specific rate of NA, and techniques to quantify the future behavior of the plume. The available techniques for each of these evaluations are presented below.

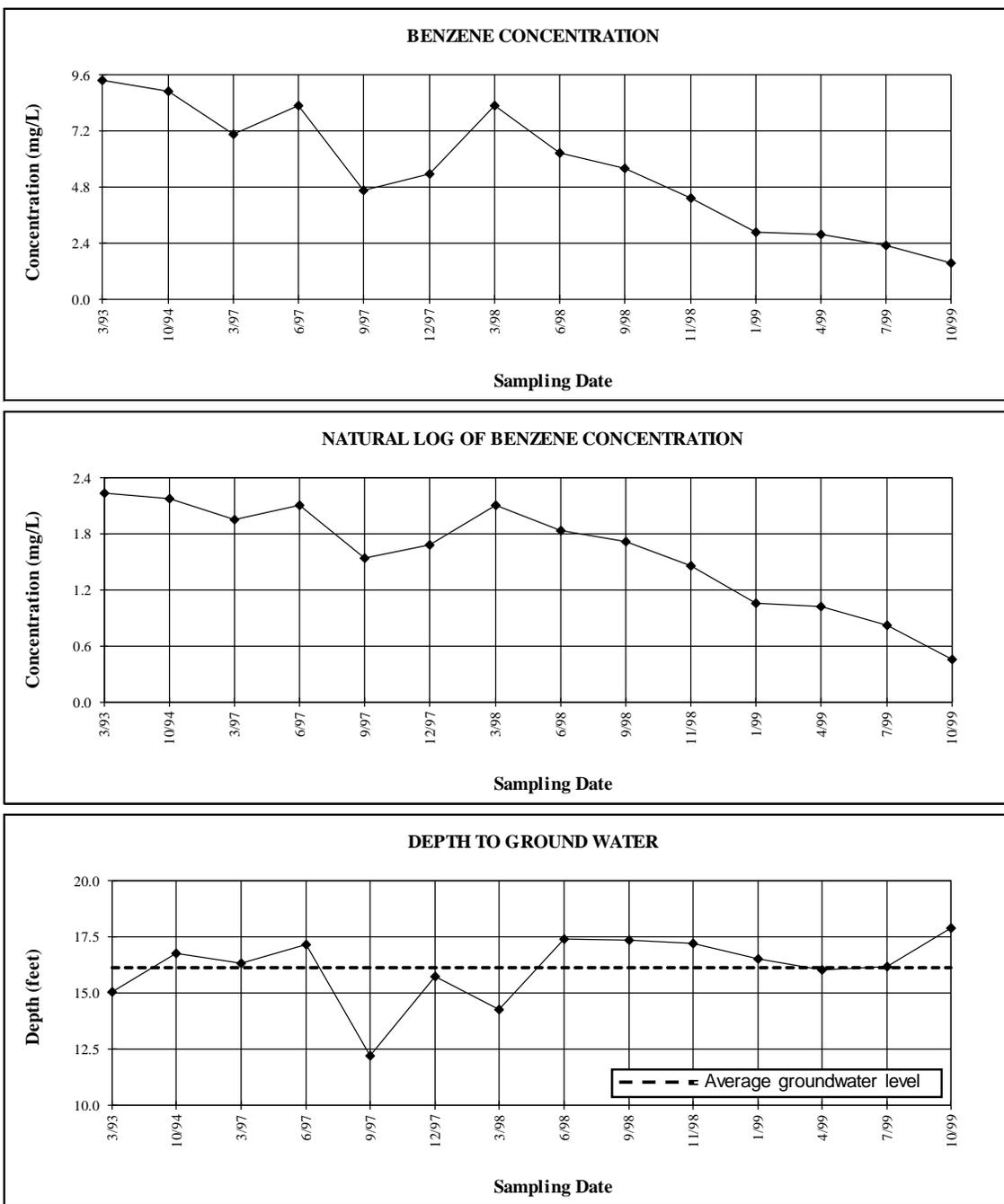
### **10 Techniques to Demonstrate the Occurrence of Natural Attenuation**

The occurrence of NA may be demonstrated by using graphical and/or statistical techniques. The specific techniques used will vary depending on site conditions and the specifics of the data. To the extent possible, multiple techniques should be used to provide added insight into the NA process.

#### **10.1 Graphical Techniques**

Chemicals-of-interest data collected from strategically located monitoring wells can be used to draw site-wide contour maps of individual constituent concentrations for each monitoring event, create concentration-versus-time plots for each well with detectable constituent levels and at least four rounds of data, and create concentration-versus-distance plots along the flow direction for several monitoring events. Depending on the variability in the concentrations, it may be better to plot the natural logarithm of concentration versus time and distance. An example plot is shown in Figure 4. When creating these plots, care should be taken to ensure that the selected scale clearly demonstrates the trend. Since the concentrations are affected by water level fluctuations, it is important to also plot water levels as a function of time.

These plots can indicate whether the concentration trend is decreasing, stable (no significant trend), increasing, or mixed. The latter refers to a situation where different wells (source wells versus periphery wells) exhibit different trends. Increasing concentrations in the source well and decreasing concentrations in the down-gradient wells may occur due to a variety of reasons. For example, the mass loading to the source may cause an increase in the source wells due to an increase in the infiltration rate, or the rate of biodegradation near the source may be reduced due to a depletion of oxygen.



**Figure 4. Concentration-versus-time plot of benzene**

Conversely, increasing concentrations in down-gradient wells and decreasing concentrations near the source may indicate that the plume is moving but the source has depleted. Conclusions related to concentration trends based on visual observations of the data must be supported by statistical analysis.

In addition to the chemical-of-interest concentrations, indicator chemical concentrations should be plotted along the plume axis (in the concentration-versus-distance plots) along with the hydrocarbon concentrations. The observed pattern of concentrations can be used

to demonstrate NA. For example, low dissolved oxygen concentrations within the plume and higher concentrations up-gradient and down-gradient of the source are indicative of biodegradation within the plume.

## 10.2 Statistical Evaluations

Statistical tools may be used to determine and quantify the concentration trend. These tests can be used to test a null hypothesis and an alternative hypothesis. A null hypothesis might be that there is no time trend in the concentrations-versus-distance or time, and the alternative hypothesis might be that there is a downward trend. Application of the statistical test would then result in accepting or rejecting the null hypothesis at a specified level of significance.

A nonparametric test, called the Mann-Kendall test, is often used to determine whether a trend exists in the data. This test is particularly useful for environmental data for several reasons:

- The test is nonparametric, which implies that the test is applicable irrespective of the underlying distribution of the data.
- The test is simple to implement.
- Concentration values below the detection limit can be used.
- The results are not affected by missing data.

The Mann-Kendall test is applicable only when there is no seasonality in the data. This is the case if the data do not show any seasonal variations or the data were collected from one season. When data indicate seasonality, the seasonal Kendall test may be used. For details on both of these tests, refer to Gilbert (1987), Gibbons (1994), or other books on statistical analysis.

DEQ strongly recommends the use of the Mann-Kendall test to determine the trend in nonseasonal data except in situations where a visual plot of data indicates without **any** ambiguity that a trend exists in the data.

If the concentration-versus-time or concentration-versus-distance data indicate a decreasing trend, a regression analysis may be used to estimate the slope of the best-fit line.

As explained in section 11.2 and 11.3, the slope of the line can be used to estimate the NA or the biodegradation rate. For additional information on regression analysis, refer to any statistics textbook.

## 11 Techniques to Estimate the Site-specific Rate of Natural Attenuation

The data collected to demonstrate the primary line of evidence of NA can be used to estimate site-specific NA rates and biodegradation rates. Since NA includes multiple processes in addition to biodegradation, the NA rate would be higher than the

biodegradation rate. The latter can be used as an input into a ground water fate and transport model, such as Domenico's model (Domenico 1987), to estimate the future migration of the plume, and to estimate a site-specific dilution attenuation factor. Three methods are available to estimate the NA rate: 1) mass balance analysis for expanding, stable, or shrinking plumes; 2) plume concentration-versus-time plots; and 3) plume concentration-versus-distance plots. Descriptions of each of these methods are presented below. An excellent discussion of the calculation and use of rate constants for use in NA evaluations is presented in EPA (2002). This section also includes a discussion of calculating biodegradation rates using recalcitrant tracers.

## 11.1 Mass Balance Analysis

This method of estimating the NA rate is based on the concept of mass balance. For a stable plume, the mass entering the ground water plume must equal the mass lost by NA. Thus, if the mass entering the plume can be estimated, it should be possible to estimate the NA rate. A detailed description of the application of mass balance analysis to estimate the NA rate of a petroleum release is described in Section X6.1 of the *Standard Guide for Remediation of Groundwater by Natural Attenuation at Petroleum Release Sites* (ASTM 2004).

## 11.2 Well Concentration-versus-Time Plot

The estimate of the overall attenuation rate for a shrinking plume can be calculated assuming a first-order decay rate and is represented mathematically by Equation 1:

$$\frac{dC}{dt} = \exp^{-kt} \quad (\text{Equation 1})$$

Where:

$C$  = concentration

$t$  = time [years]

$k$  = NA rate [1/yr]

The solution to the above differential equation results in the familiar exponential decay equation (Equation 2):

$$C(t) = C(t=0) \exp^{-kt} \quad (\text{Equation 2})$$

Where:

$C(t)$  = Concentration at any time  $t$  (mg/L)

Taking the natural logarithms of both sides of Equation 2 results in Equation 3:

$$\ln C(t) - \ln C(t=0) = -kt \quad (\text{Equation 3})$$

Thus, a plot of natural log of concentration versus time would be a straight line with a slope equal to  $k$  (the NA rate).

### 11.3 Well Concentration-versus-Distance Plot

Advective travel time can be expressed as below (Equation 4):

$$t = \frac{x}{v} \quad (\text{Equation 4})$$

Where:

$x$  = Advective travel distance (cm)

$v$  = Seepage velocity (cm/yr)

Substituting Equation 4 in Equation 2 results in Equation 5:

$$C(t) = C(t=0) \exp\left(-k \frac{x}{v}\right) \quad (\text{Equation 5})$$

Taking the natural log of both sides of the equation results in Equation 6:

$$\ln[C(t=0)] - \ln[C(t)] = -k \frac{x}{v} \quad (\text{Equation 6})$$

For a shrinking plume that follows the first-order attenuation rate presented above, a plot of log concentration versus distance would be a straight line with a slope of  $k/v$ . By multiplying the slope with the seepage velocity, the NA rate ( $k$ ) can be estimated.

Buscheck and Alcantar (1995) used the solution of the one-dimensional transport equation with biodegradation to estimate the biodegradation rate based on the slope of the log concentration-versus-distance plot. Specifically, they derived the following expression (Equation 7) for the biodegradation rate:

$$\lambda = \frac{v}{4\alpha_x} \left\{ \left[ 1 + 2\alpha_x \left( \frac{k}{v} \right) \right]^2 - 1 \right\} \quad (\text{Equation 7})$$

Where:

$\lambda$  = Biodegradation rate, assumed to occur at equal rates in the dissolved and sorbed phases

$\alpha_x$  = Longitudinal dispersivity (0.1x)

Zhang and Heathcote (2003) modified this method to account for situations with finite source size and lateral dispersion to improve the estimates of the biodegradation rate.

The following step-by-step description of the biodegradation rate estimation process can be implemented on a site-specific basis.

Step 1: Determine the ground water flow direction based on the water level measurements for each monitoring event.

- Step 2: For each monitoring event, identify the wells located along the direction of flow (i.e., along the plume center line). Since the flow direction may vary seasonally, different wells may be used for different monitoring events.
- Step 3: Tabulate the concentrations of the chemicals of interest and calculate the natural log concentrations.
- Step 4: Plot the natural log concentrations on the  $y$ -axis and the distance along the  $x$ -axis.
- Step 5: Calculate the slope of the best-fit line and the confidence in this estimate by examining the 95% confidence limits of the slope.
- Step 6: Estimate the ground water seepage velocity.
- Step 7: Multiply the slope of the best-fit line calculated in Step 5 with the seepage velocity. The result will represent the overall NA rate. This NA rate represents the reduction in concentration due to the combined influence of the various NA processes mentioned in section 2. This decay rate should not be confused with the biodegradation rate ( $\lambda$ ) that is an input to ground water models.
- Step 8: Estimate the biodegradation rate from Equation 7.

Steps 1–8 should be completed for each time period for which data are available and the results presented as a range of NA and biodegradation rates. The latter can be used as an input to the Domenico model (Domenico 1987) to estimate the dilution attenuation factor. Due to confounding factors such as seasonal variations in ground water velocity, fluctuations in water levels, and errors in sampling and analysis methods, the NA and biodegradation rates may vary significantly (by as much as a factor of 10). Therefore, it is best to present the range as well as the average rates.

## 11.4 Evaluation of Plume Behavior with a Recalcitrant Tracer

Physical, chemical, and biological processes act together to decrease contaminant concentrations away from a source. However, monitored NA requires that accurate biodegradation rates for a site be known. To estimate accurate biodegradation rates, conservative tracers can be employed. The concentrations of these tracers are not affected by biodegradation processes and so can be used to delineate between the effects of biodegradation and other NA processes such as dilution and sorption. Generally, tracers are biologically recalcitrant and have chemical properties similar to the contaminant of interest. Examples of common tracers include MTBE for petroleum hydrocarbon plumes.

## 12 Techniques to Quantify the Future Behavior of the Plume

The future behavior of the plume can be estimated by using fate and transport models. A number of analytical and numerical models are available. Commonly used analytical

models include the Domenico model (Domenico 1987) and BIOSCREEN. BIOSCREEN can be downloaded from [www.epa.gov/ada/csmos/models/bioscrn.html](http://www.epa.gov/ada/csmos/models/bioscrn.html).

These models can be used to estimate plume length, concentrations at down-gradient receptor locations, and dilution attenuation factors and can be calibrated to site-specific ground water data. The correct application of fate and transport models requires experience and specialized knowledge that is beyond the scope of this document.

## References

- API (American Petroleum Institute). 2007. *Technical Protocol for Evaluating the Natural Attenuation of MtBE*. Washington DC: API, Regulatory and Scientific Affairs Department. API Publication 4761.
- ASTM (American Society for Testing and Materials). 2004. *Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites*. Conshohocken, PA: ASTM. Standard E1943-98(04).
- Buscheck, T.E., and C.M. Alcantar. 1995. *Regression Techniques and Analytical Solutions to Demonstrate Intrinsic Bioremediation*. In R.E. Hinchee, J.T. Wilson, and D.C. Downey, eds. *Intrinsic Bioremediation*. Columbia, OH: Batelle Press. pp. 109–116.
- Buscheck, T.E., D.C. Wickland, and D.L. Kuehne. 1996. *Multiple Lines of Evidence to Demonstrate Natural Attenuation of Petroleum Hydrocarbons*. Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater. NGWA/API, Houston, TX.
- Domenico, P.A. 1987. *An Analytical Model for Multidimensional Transport of a Decaying Contaminant Species*. *Journal of Hydrology* 91:49–58.
- EPA (U.S. Environmental Protection Agency). 1999. *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action and Underground Storage Tank Sites*. Washington DC: EPA, Office of Solid Waste and Emergency Response. Directive 9200.4-17P.
- EPA (U.S. Environmental Protection Agency). 2002. *Calculation and Use of First-Order Rate Constants for Monitored Natural Attenuation Studies*. Cincinnati, OH: EPA, National Risk Management Research Laboratory. Ground Water Issue Paper, EPA/540/S-02/500.
- EPA (U.S. Environmental Protection Agency). 2005. *Monitored Natural Attenuation of MTBE as a Risk Management Option at Leaking Underground Storage Tank Sites*. Cincinnati, OH: EPA, National Risk Management Research Laboratory. EPA/600/R014/179.
- EPRI (Electric Power Research Institute). 1985. *A Review of Field-Scale Physical Solute Transport Processes in Saturated and Unsaturated Porous Media*. Palo Alto, CA: EPRI. Report EA-4190.
- Freeze, A.R., and J. A. Cherry. 1979. *Groundwater*. Englewood Cliffs, NJ: Prentice-Hall, Inc.
- Gibbons, R.D. 1994. *Statistical Methods for Groundwater Monitoring*. New York: John Wiley & Sons, Inc.

- Gilbert, R.O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. New York: Van Nostrand Reinhold Company.
- ITRC (Interstate Technology and Regulatory Council). 2002. *A Systematic Approach to In Situ Bioremediation in Groundwater Including Decision Trees on In Situ Bioremediation for Nitrates, Carbon Tetrachloride, and Perchlorate*. ITRC, In Situ Bioremediation Team.
- McKee, J.E., F.B. Lavery, and R.M. Hertel. 1972. *Gasoline in Ground Water*. J. Water Pollution Control Federation 44(2):293–302.
- Moyer, E.E., and P.T. Kosteki. 2003. *MTBE Remediation Handbook*. Amherst, MA: Amherst Scientific Publishers.
- Rice, D.W., R.D. Grose, J.C. Michaelson, B.P. Dooher, D.H. Macqueen, S.J. Cullen, W.E. Kastenber, L.G. Everett, and M.A. Marino. 1995. *California Leaking Underground Fuel Tank (LUFT) Historical Case Analysis*. Livermore, CA: Lawrence Livermore National Laboratory, Environmental Protection Department, Environmental Restoration Division.
- SNL (Sandia National Laboratories). 1997. *Natural Attenuation of Metals and Radionuclides: Report from a Workshop held by Sandia National Laboratories*. SNL. SAND97-2727. UC-800.
- USACE (U.S. Army Corps of Engineers). 1999. *Draft Protocol for Evaluating, Selecting, and Implementing Monitored Natural Attenuation at Explosives-Contaminated Sites*. Vicksburg, MS: USACE, Engineer Research and Development Center. Technical Report EL-99-10.
- Wiedemeier, T.H., M.A. Lucas, and P.E. Haas. 2000. *Designing Monitoring Programs to Effectively Evaluate the Performance of Natural Attenuation*. Brooks Air Force Base, TX: U.S. Air Force, Air Force Center for Environmental Excellence.
- Xu, M., and Y. Eckstein. 1995. *Use of the Least-Squares Method in Evaluation of the Relationship Between Dispersivity and Field Scale*. Ground Water 33(6):905–908.
- Zhang, Y., and R.C. Heathcote. 2003. *An Improved Method for Estimation of Biodegradation Rate with Field Data*. Ground Water Monitoring and Remediation 23(3):112–116.

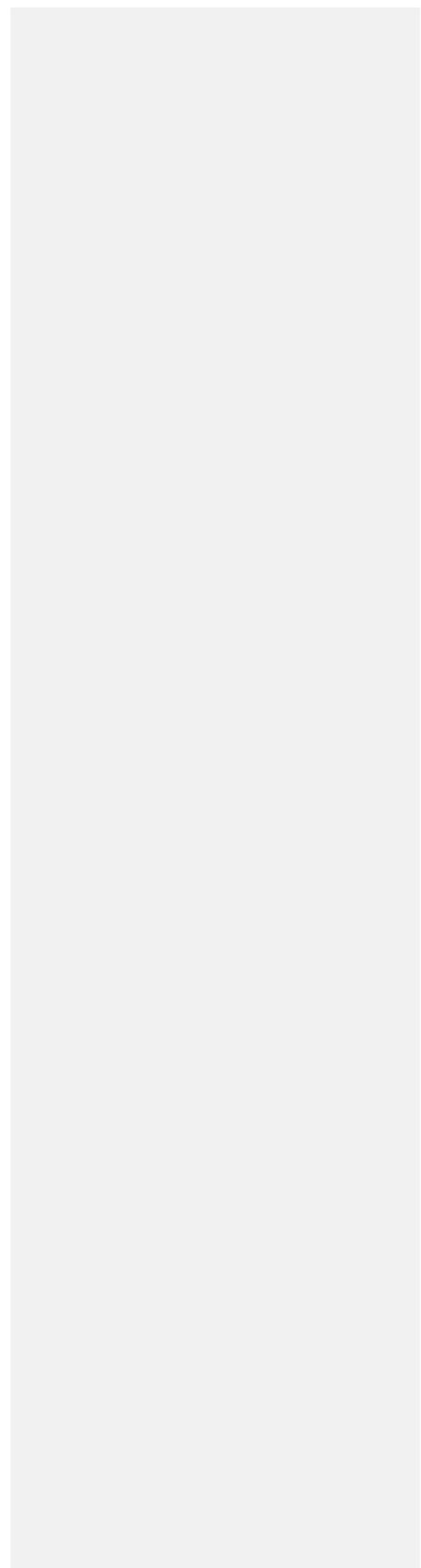
## Other Useful References

- Alaska DEC (Alaska Department of Environmental Conservation). 2000. *Guidance on the Selection of Natural Attenuation as a Cleanup Alternative for the Restoration of Soil and Groundwater at Contaminated Sites*. Juneau, AK: Alaska DEC, Division of Spill Prevention and Response. Guidance No. SPAR 2000-1.

- Bauer, S., C. Beyer, and O. Kolditz. 2006. *Assessing Measurement Uncertainty of First-Order Degradation Rates in Heterogeneous Aquifers*. Water Resources Research Vol. 42, W01420, 14 p.
- Wiedemeier, T.H., J.T. Wilson, and D.H. Kampbell. 1996. *Natural Attenuation of Chlorinated Aliphatic Hydrocarbons at Plattsburg Air Force Base, New York*. Symposium on Natural Attenuation of Chlorinated Organics in Ground Water. Dallas, TX, September 1996.
- Wiedemeier, T.H., J.T. Wilson, R.N. Miller, and J.E. Hanson. 1999. *Technical Protocol for Implementing Intrinsic Remediation for Long-Term Monitoring for Natural Remediation of Fuel Contamination Dissolved in Groundwater, Volume I*. Brooks Air Force Base, TX: U.S. Air Force, Air Force Center for Environmental Excellence.
- Wisconsin DNR (Wisconsin Department of Natural Resources). 1999. *Interim Guidance On Natural Attenuation For Petroleum Releases*. Madison, WI: Wisconsin DNR, Bureau for Remediation and Redevelopment. PUB-RR-614.

*This page intentionally left blank for correct double-sided printing.*

**Appendix I: Estimation of Exposure Point Concentrations in  
Soil and Ground Water**



*This page intentionally left blank for correct double-sided printing.*

---

**TABLE OF CONTENTS**

---

1	Background .....	1
2	Statistical Considerations for Estimating Exposure Point Concentrations .....	2
2.1	Maximum Detected Concentration .....	2
2.2	Upper Confidence Limit.....	3
2.3	Arithmetic Average .....	4
2.4	Geometric Average .....	4
2.5	Area-Weighted Average.....	4
2.6	Depth-Weighted Average.....	5
2.7	Volume-Weighted Average.....	5
3	General Considerations for Estimating Exposure Point Concentrations .....	5
3.1	Surface and Subsurface Soil Concentrations .....	5
3.2	Ground Water Concentrations.....	6
4	Calculation of Exposure Point Concentrations.....	7
4.1	Surficial Soil (0–1 Foot below Ground Surface) .....	7
4.1.1	Exposure Point Surficial Soil Concentration for the Ground Water Protection Pathway.....	8
4.1.2	Exposure Point Surficial Soil Concentrations for the Direct Contact Pathway.....	9
4.2	Subsurface Soil (Greater Than 1 Foot below Ground Surface) .....	9
4.2.1	Exposure Point Subsurface Soil Concentration for Ground Water Protection Pathway.....	10
4.2.2	Exposure Point Subsurface Soil Concentration for Vapor Intrusion Pathway .....	10
4.3	Exposure Point Concentration for Protection of a Construction Worker.....	11
4.4	Ground Water .....	11
4.4.1	Exposure Point Compliance Well Concentration for Ground Water Protection Pathway.....	12
4.4.2	Exposure Point Ground Water Concentration for Protection of Indoor Inhalation Pathway.....	12
4.5	Soil Vapor .....	13
5	Estimating Area-Weighted Exposure Point Concentrations.....	14
5.1	Step 1: Identify the Exposure Unit.....	14
5.2	Step 2: Subdivide the Exposure Unit .....	14
5.3	Step 3: Estimate Exposure Point Concentrations for Each Thiessen Polygon.....	14
5.4	Step 4: Estimate Area-Weighted Average Concentration for the Exposure Unit .....	15
6	Recommendations.....	16
	References.....	18
	Other Useful References .....	19

**LIST OF FIGURES**

---

Figure 1. Schematic of soil leaching to ground water ..... 8  
Figure 2. Thiessen polygon method..... 16

## 1 Background

Exposure point concentrations (EPC) are the **average** chemical concentrations to which receptors are exposed over a specified duration within a specified geographical area. The geographical area about which a receptor moves and contacts contaminated media during the specified exposure duration is termed an exposure unit (EU). EPCs are also often referred to as representative concentrations.

This appendix describes the concept and methodology that should be used to estimate EPCs. This guidance ~~is an attempt to provide~~ general recommendations on procedures to accurately determine EPCs. ~~It is not expected that~~ these recommendations ~~will~~ may not apply to all sites, particularly large, complex sites. Site-specific circumstances may require consultation with the Idaho Department of Environmental Quality (DEQ), the application of professional judgment, and reference to the more detailed literature cited herein. Other useful references are also included at the conclusion of this appendix.

In the site-specific application of the risk evaluation process, EPCs are used as input parameters in ~~to~~ estimating the risk to a specified receptor for each complete route of exposure identified in the site conceptual exposure model (SCM) and each petroleum chemical of interest (COI). Risk management decisions are then made based on a comparison of the estimated risk with the regulatory specified target risk. This comparison is termed a forward-mode calculation. EPCs can also be used in what are termed backward-mode calculations when they are compared with calculated target levels for each complete route of exposure and each petroleum COI. In either mode, the calculation of EPCs is critical in the outcome of the risk evaluation.

Complications in the calculation of the EPCs may arise because the concept of EPC is often mistakenly associated with a site as opposed to an exposure pathway or the source. Since there may be several complete pathways at a site, several EPCs, one for each complete pathway, should be estimated. For example, estimation of the soil EPC for the soil leaching and protection of ground water ingestion at a release site typically considers data over the entire soil profile from the source area. At the same site, soil EPC estimates for direct contact surficial soil exposure would typically consider only the upper several feet of the soil profile and would focus on the portions of the site where receptors may travel. Ground water EPCs for on-site versus off-site risk from vapor intrusion would be different because typically off-site concentrations are lower than on-site/source area concentrations.

The accurate estimation of EPCs is complicated by several factors, including the following:

- Spatial variability in the concentrations
- Temporal variability in the concentrations
- Lack of sufficient, appropriately located, site-specific concentration data
- Poor definition or uncertainty in the location, size, or other characteristics of the EU

**Comment [m1]:** This example is confusing, consider deleting. The example above gets the points across – one concentration value does not fit all exposure pathways.

The uncertainty in the EPC introduced by some of these factors can be reduced by considering them during the development of the SCM and the sampling and analysis plan.

After samples have been collected and analyzed, the results need to be appropriately evaluated to produce sound estimates of EPCs. This evaluation includes assessing the following:

- Data quantity
- Data quality (which data are acceptable for use)
- Statistical methods (which methods to use)
- Which usable data apply to a specific EU

This guidance focuses primarily on the latter two issues.

## **2 Statistical Considerations for Estimating Exposure Point Concentrations**

Numerous statistical methods can be employed to develop estimates of the exposure point (average) chemical concentration to which a receptor will be exposed. These methods include examining the maximum detected concentration, upper confidence limit (UCL) of the mean (for example the 95% UCL), arithmetic average, geometric average, area-weighted average, depth-weighted average, and volume-weighted average concentration (very rarely used). Associated with each of these methods are certain advantages, disadvantages, and constraints on their appropriate use. There is no uniformly accepted statistical methodology to estimate the EPC. Implicit in the decision to use any particular method is the need to acknowledge and account for the representativeness of the samples collected, the homogeneity of the defined EU, the statistical distribution of the data, the minimum data requirements of the statistical method used, and the uncertainty in the resultant data used to derive the estimated concentration.

From a practical perspective, several factors common to petroleum release sites may make the use of statistical methods to develop EPCs at a given site unrealistic, particularly for ground water. These factors include the following:

- Small release areas
- Dominantly subsurface releases, often at great depth
- Focus on source areas and not exposure pathways
- Limited sample numbers due to temporal/spatial constraints

### **2.1 Maximum Detected Concentration**

The use of the maximum detected chemical concentration is required for comparison to screening levels during the screening level evaluation (see Section 3, Screening Level Evaluation, in the main body of the document). Depending on the quality of the site characterization data available, the maximum detected concentration can be used as EPCs

in site-specific risk evaluations and will typically represent a conservative estimate of the average concentrations, particularly when sample numbers are low (i.e., four or less).

The effort necessary to calculate EPCs for certain complete pathways can be avoided by using the maximum media-specific concentrations when they do not exceed the target levels or when the cumulative risk, calculated using maximum concentrations, does not exceed the target risk.

## 2.2 Upper Confidence Limit

The true population mean is a unique value that can be calculated only if the entire population has been sampled (i.e., the entire contaminated media analyzed). Since the entire population is almost never sampled, the true mean is never known. Thus, at best, only an estimate of the true population mean concentration is possible.

To account for the uncertainty associated with the estimated mean concentration, a confidence interval about the true but unknown mean is often constructed. The interval estimate includes a range and an associated degree of confidence that the true unknown mean lies within this range. In risk assessment applications, instead of calculating a two-sided confidence interval, a one-sided confidence interval is most often estimated.

For the calculation of EPCs, the U.S. Environmental Protection Agency (EPA) has recommended, in most cases, using the 95% upper ~~confidence concentration~~ limit (UCL) of the mean (EPA 1992a). The upper limit for a one-sided 95% confidence interval of the mean is defined as a value that, when calculated repeatedly for randomly drawn subsets of site data, equals or exceeds the true mean 95% of the time. Alternatively, the true mean exceeds the UCL only 5% of the time. Ideally, a minimum of 8 to 10 samples is desirable to generate a 95% UCL. Although the UCL can be determined with fewer samples, doing so tends to results in the 95% UCL estimate being larger (large variances) than the arithmetic average and will sometimes exceed the maximum measured concentration. In these instances, the maximum measured concentration can be substituted for the 95% UCL or the user can decide to collect more samples to reduce the sampling variance.

Several issues commonly arise with environmental data sets that complicate the development of the confidence limit and should be evaluated through the use of an exploratory analysis prior to performing the calculation. These issues include the following:

- Determination of the distribution of the data chosen to represent the EU (normal, lognormal, or nonparametric [i.e., not conforming to a specific distribution]). This determination includes decisions as to what analysis and statistical tests to perform, how to interpret the test results, and how to treat the data once a determination is made.
- How to handle censored data and/or skewed data (typically due to non-detect [ND] values).

Depending on the nature of the underlying distribution of the data (or lack thereof), the one-sided 95% UCL can be calculated using a number of methodologies. The details regarding these methodologies are beyond the scope of this guidance.

EPA has developed technical guidance, a user's guide, and computer software (ProUCL 4.1) for calculating the UCL based on parametric (normal and lognormal distributions) and nonparametric distributions and when data sets have ND observations (EPA 2011a, 2011b). The ProUCL technical guidance (Sections 1.7.1 and 1.7.2) describes the minimum data set conditions under which the ProUCL software will perform UCL calculations. These guidelines generally involve data set sizes greater than or equal to five with more than one detected value.

For samples collected using a multi-increment sampling approach, data set sizes as small as three may be sufficient to calculate a UCL.

For simpler data sets (with few or no ND values), DEQ has developed the IdahoUCL software, which is available at <http://www.deq.idaho.gov/risk-evaluation-manual>.

**Comment [m2]:** I'm good with these added paragraphs. Suggest adding a reference here for MIS – Probably use ITRC's reference.

### 2.3 Arithmetic Average

Using the arithmetic average is similar to the UCL with the disadvantage that no estimate of the uncertainty, variability of the average, or information regarding the underlying distribution of the population is incorporated into the value generated. For a population that is normally distributed, the estimates generated using the 95% UCL versus the straight arithmetic average tend to converge as the number of samples approaches 20 to 30.

**Comment [m3]:** Ok, Please provide reference for the reader. Is this suppose to the central Limit Theorem ?

### 2.4 Geometric Average

The geometric average is sometimes used as an estimate of the mean of lognormally distributed variables. It represents the value in the original scale of the mean of the transformed variable. It is, however, a biased estimate of the mean, and statistical texts such as *Statistical Methods for Environmental Pollution Monitoring* (Gilbert 1987) caution against its use in environmental applications. *Statistical Methods for Environmental Pollution Monitoring* (Gilbert 1987) or *ProUCL 4.1 Technical Guide* (EPA 2011a) should be consulted when attempting to develop an unbiased estimate of the mean of a lognormally distributed variable. Exploratory data analysis should be conducted to confirm an assumption that the variable is lognormally distributed prior to calculating an EPC. As with the arithmetic average, no estimate of the uncertainty or variability is incorporated into the value generated by the geometric average and it may not be conservative.

**Comment [MAB4]:** Reworded; previous comment - Really? Sample size increases with additional samples but there is still a variance and if there is variance the UCL will be greater than the mean. This suggest if you take 30 samples use the mean instead of the UCL.

### 2.5 Area-Weighted Average

Where sampling locations are unevenly spaced, area-weighted averaging methods can be employed to generate an estimate of the average concentration across an area. This calculation is done by generating an area (or Thiessen polygon) associated with each

sampling location, assigning a “weight” to each data point based on the area of the polygon associated with that point, and summing the weighted data point values. One advantage of the method is that it is useful in characterizing areas where the number of sample points is low.

The method also has several disadvantages. First, the shape, and consequently the contribution of an area associated with a sample location to the “average,” is totally dependent on the spatial distribution of all data points and may not be reflective of the true distribution of contaminants at a site. Second, since each polygon is associated with one sample point, no estimate of the accuracy or error in the average value is possible. Finally, the method, unlike several other interpolation schemes, does not assume that points that are closer together are more similar than points that are farther apart. The method for calculating an area-weighted average using Thiessen polygons is discussed in section 5.

## 2.6 Depth-Weighted Average

Depth-weighted averaging methods are used to develop an average or EPC for a specific borehole where multiple samples at varying depth intervals have been obtained. In characterizing a source area with multiple boreholes, the depth-weighted averages from each borehole can be used in a 95% UCL calculation. The methodology for depth-weighted averaging is described in EPA’s *Soil Screening Guidance: User’s Guide* (EPA 1996, section 2.3).

## 2.7 Volume-Weighted Average

Volume-weighted averaging methods are a combination of area- and depth-weighted averaging techniques. They are rarely used in risk assessment evaluations.

# 3 General Considerations for Estimating Exposure Point Concentrations

Estimating EPCs requires considering several issues. Prior to performing the computations, consider the information in the following sections.

## 3.1 Surface and Subsurface Soil Concentrations

When evaluating exposure point soil concentrations consider the following:

- The spatial resolution of the data must be sufficient. While the exact number of necessary samples cannot be specified, data should be available from areas of known or likely sources, and the EU should be defined for a given pathway and receptor.
- Historical data should be examined closely prior to inclusion in the EPC estimate, particularly if the petroleum COIs are susceptible to biodegradation (such as petroleum hydrocarbons), ~~or other attenuation mechanisms, such as~~ volatilization

or leaching. If sufficient new data are collected, they may be used for risk evaluation and the old data may be disregarded. A new release requires the collection of additional data.

- If there is a “high” density of soil samples (>30) for a homogeneous EU and sample locations are approximately equally spaced, the arithmetic average may be used instead of the 95% UCL or the area-weighted average. This method is acceptable because the area-weighted average, arithmetic average, and UCL concentrations will tend to converge (EPA 1992a) if the underlying population can be assumed to be normally distributed. The >30 value mentioned above should also be considered in relation to the size of the EU and may not be appropriate for very large EUs.
- ND soil samples located at the periphery of the EU (e.g., the footprint of a building) should not be used.
- ND samples (also referred to as left-censored data) located within the EU require special treatment. The EPA has recently discouraged using replacement methods (such as half the detection limit) (EPA 2011a). The proportion of ND samples in the subject data set and whether multiple detection limits exist will affect the specific methods used to generate summary statistics and the UCL. EPA ProUCL 4.1 software has several options for handling left-censored data. Consult the technical guidance accompanying the software to determine which method is most appropriate for the specific data set and how to treat the censored data (EPA 2011a).
- If multiple surficial soil samples and/or multiple subsurface soil samples are available from the same borehole within the EU, the depth-weighted average or arithmetic average concentration of these samples may be used. If the samples are equally spaced, the depth-weighted average concentration will be the same as the arithmetic average concentration.
- An alternative to using discrete soil samples to calculate the UCL is to use incremental sampling methodologies (USACE 2009; Hawaii DOH, section 4 2008; Alaska DEC 2009). Incremental sampling is a sampling approach to obtain a pooled sample for analysis that has an analyte concentration representative of the EU. While it is similar to composite sampling, the incremental approach takes into account sample size to reduce variability and also allows for the calculation of a UCL while only requiring a few samples for laboratory analysis. It typically requires greater up-front planning with respect to sampling design, methodology, and defining of data quality objectives than traditional composite sampling.
- If vapor intrusion is a potentially complete pathway, collecting soil vapor data, in lieu of soil samples, for characterizing the potential risk should be considered. Consult Appendix G (Evaluation of the Vapor Intrusion Pathway) and section 4.5 of this appendix for sampling details.

Formatted: Highlight

### 3.2 Ground Water Concentrations

Follow the guidelines listed below to account for the temporal and spatial variation in ground water concentrations. These recommendations apply primarily to evaluation of ground water data for the purpose of estimating EPCs for risk evaluation. They are not

intended where other monitoring objectives, such as determining compliance with cleanup criteria, are the primary goal.

- For wells with a clear increasing or a decreasing trend, data from the most recent 12 months or the 4 most recent measurements should be averaged (use whichever covers the longer duration). Note that for wells with increasing trends, continued monitoring may be needed until the trend stabilizes or decreases.
- For wells with stable or fluctuating concentrations with no apparent trend, data from either the most recent 24 months or the 8 most recent measurements should be used to develop a 95% UCL.
- If site ground water analytical data are limited (number of wells or number of sampling events) and prevent adequate statistical analysis, using the maximum concentrations is preferred. Using the average concentration is discouraged, particularly if the plume stability status (increasing, decreasing, or stable) with respect to the release is unknown or the representativeness of the available data is in question.
- While developing the EPC for wells described by the first two bullets above, the treatment of left-censored data (concentrations below detection limits) deserves special consideration and may require specialized analysis techniques. Replacement techniques (such as using half the detection limit) are currently discouraged by the EPA (EPA 2011a). If the percentage of ND values is a significant percentage of the total number of data points (>25%), the representativeness of the data set for the EU in question should be evaluated.
- Wells with concentrations consistently below detection limits in the periphery of the EU should not be used.
- For wells that contain free product where it is not possible to obtain a representative dissolved phase sample, the use of the effective solubility of petroleum COIs should be considered as a conservative surrogate for their chemical concentration in estimating EPCs.

**Comment [m5]:** OK, but if we have 4 data points that are well below the risk based level (e.g. 1 ug/L at the 95% UCL based on 4 samples and the risk level is 50 ug/L), why would we need to collect more samples? We have 4 samples that account for seasonality and if there is no obvious trend, seems additional 4 samples is not necessary. I'd just like to see IDEQ accept 4 quarterly samples in cases where the measured values are well below the risk thresholds. If the mean and the 95% are below the thresholds, then taking additional samples provides no value (again there are conditions to this, e.g. you would have to determine travel times and make sure your plume has had time to get to the well, etc.

**Comment [MAB6]:** Previous comment - I'm ok with this approach. But what if I have 4 quarters of groundwater sample data and the maximum value is well below risk levels. Why can't I close the site with 4 quarters of samples? Seems like there should be greater flexibility here.

Dr. MM - we should add your suggestion if 95% UCL is below RULS = done

Two useful documents that provide guidance on the statistical evaluation of ground water monitoring data are the EPA's unified guidance (EPA 2009) and DEQ's *Statistical Guidance for Determining Background Ground Water Quality and Degradation* (DEQ 2009).

## 4 Calculation of Exposure Point Concentrations

An EPC is necessary for each complete exposure pathway at a site. Based on the pathways typically considered in the risk evaluation process, the EPCs listed below are typically needed for each media.

### 4.1 Surficial Soil (0–1 Foot below Ground Surface)

The risk evaluation process requires consideration of two pathways of exposure associated with the surficial soil: 1) the ingestion of chemicals in ground water due to leaching of residual chemicals present in the surficial soil and 2) the accidental ingestion

of soil, outdoor inhalation of vapors and particulates from surficial soil emissions, and dermal contact with surficial soil. These two pathways are referred to as the ground water protection and direct soil contact pathways, respectively. Thus, at most, two different surficial soil EPCs are required, though typically one EPC estimate can be used for both pathways.

#### 4.1.1 Exposure Point Surficial Soil Concentration for the Ground Water Protection Pathway

Figure 1 shows a schematic of the soil leaching to ground water pathway. The evaluation of this pathway for surficial soil assumes that the contamination does not extend greater than 1 foot below ground surface. If this is not the case, then samples taken in the surficial soil zone should be included with those from greater depth and evaluated together.

The conceptual model for this pathway also assumes that the leachate from the surficial (or subsurface) soil source travels vertically downwards to the water table without any lateral or transverse spreading. Thus, the horizontal dimensions of the surficial (or subsurface) soil source and the ground water source are identical. Estimating the source dimensions requires considerable professional judgment. Factors typically considered in making these estimates include historical knowledge of where a spill or source was located, visual clues such as soil discoloration, and laboratory data (taking care not to include samples with ND results).

Irrespective of the manner in which the source area is identified, it is important to indicate the dimensions of the source on a map. The exposure point surficial soil source concentration should be estimated using only the surficial soil data collected within the delineated source zone. The method used to derive the EPC should typically be either the UCL of the mean (when the quantity and characteristics of the data available allow a statistical analysis) or the values derived from an incremental sampling approach.

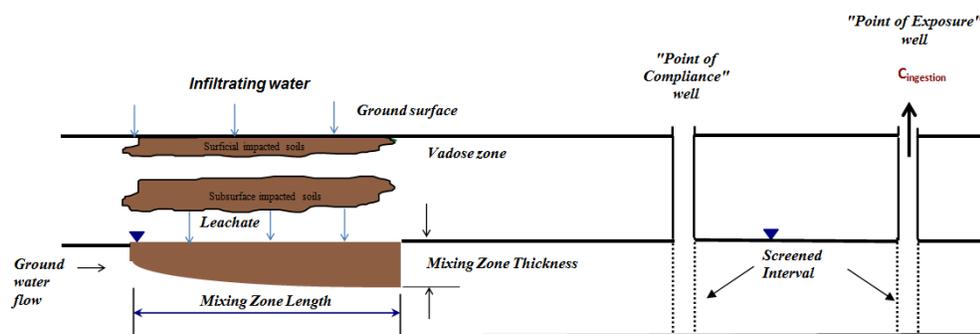


Figure 1. Schematic of soil leaching to ground water

### 4.1.2 Exposure Point Surficial Soil Concentrations for the Direct Contact Pathway

For this pathway, the exposure point surficial soil concentration has to be based on the receptor's EU (i.e., the area over which the receptor may be exposed to the surficial soil). The exact location of this area is often difficult to estimate since it must be representative of a period of time equal to the receptor's exposure duration (for example, up to 30 years for residential land use and about 7 years for nonresidential land use). In most cases, it is reasonable to assume that the receptor will access all portions of the EU in a random manner. Under current conditions, in the absence of specific information about the receptor's activities, the unpaved portion of the site may be considered as the receptor's approximate EU. Where volatile organic compounds (VOCs) are included in the list of potential petroleum COIs and/or the paved portion is in poor condition or consists of a material that does not limit VOC migration, this guide would not apply. For potential future exposures, if current condition cannot be assumed to continue, the assumption should be made that the pavement is removed, exposure to surficial soil is possible, and the entire site should be considered as the EU.

If the possibility exists that, for a future use residential scenario, contaminated subsurface soil existing under a current nonresidential scenario may be brought to the surface and result in direct contact residential exposures at the surface, the appropriate subsurface data should be included in the estimate of the EPC.

To estimate the EPC for this pathway, it would be necessary to estimate the receptor's area of exposure and determine the number of soil samples available within this EU. This information should be used to estimate the 95% UCL or an area-weighted average concentration using the procedures discussed in section 5. The use of an incremental sampling approach for characterizing EPCs for this route of exposure may be particularly well-suited and efficient.

## 4.2 Subsurface Soil (Greater Than 1 Foot below Ground Surface)

The risk evaluation process includes two pathways of exposure associated with subsurface soil: 1) the ingestion of chemicals in ground water or exposure to surface water impacted by discharge of contaminated ground water resulting from leaching of chemicals in subsurface soil and 2) indoor inhalation of vapor emissions. These two pathways are referred to as the ground water protection and vapor intrusion pathways, respectively. Thus, two different subsurface soil EPCs are required (one for each complete pathway). Additional EPCs may be required if the receptor's EU for current and future conditions is different.

**Comment [m7]:** I still think this one is a bit overly conservative and one that we typically have not included in risk assessments. Why would someone take subsurface soil (typically not suited for topsoil) and put it on the surface of a residential property?

#### **4.2.1 Exposure Point Subsurface Soil Concentration for Ground Water Protection Pathway**

The leachate from the subsurface soil source is assumed to travel vertically downwards without any lateral or horizontal spreading (Figure 1). Thus, the EPC for this pathway should be based on the subsurface soil concentrations measured within the source area.

As in the case of the surficial soil concentration protective of ground water (section 4.1.1), the exposure point subsurface soil source concentration would be the average concentration calculated using the data within the soil source area. If the source area is small (several tens of feet across), typically smaller numbers of soil samples are available. In this case, the 95% UCL should first be calculated if the sample numbers for applicable data are adequate. If the 95% UCL exceeds the maximum concentration, it may be appropriate to use the maximum concentration.

#### **4.2.2 Exposure Point Subsurface Soil Concentration for Vapor Intrusion Pathway**

The use of soil concentration data and development of exposure point soil concentrations for evaluation of vapor intrusion, while allowable, is not as desirable as the use of soil vapor data. The use of soil vapor data is discussed in more detail in Appendix G (Evaluation of the Vapor Intrusion Pathway) and in section 4.5 of this appendix.

The default methodology and model used to estimate the risks resulting from the indoor inhalation of vapors emanating from a contaminated subsurface soil source is the Johnson and Ettinger model (Johnson and Ettinger 1991). The Johnson and Ettinger model assumes that the chemicals volatilize from a subsurface soil source, travel vertically upwards via diffusion without any lateral or transverse spreading, and enter the building via advection through cracks in the foundation. Because this model does not account for biodegradation (an important attenuation process for petroleum hydrocarbon chemicals), the predictions are generally considered conservative for these chemicals. Other models that do incorporate biodegradation, such as the BioVapor model (API 2010) may also have applicability.

To be completely consistent with the Johnson and Ettinger conceptual model, the EPC for this pathway would be based on the soil concentrations measured in the soil directly below the enclosed space. In many cases, this is not possible. Furthermore, depending on site conditions (such as the location of pavement, preferential pathways, and site lithology), vapors from source areas adjacent to but not under an existing structure may contribute to indoor inhalation exposures. The goal should be to characterize the average soil concentration in the source area that may potentially contribute vapors to any existing or potential future structures. If the pathway is considered complete for current conditions, appropriate samples for EPC estimates should be selected to achieve this goal. Samples should be focused in the immediate vicinity of any existing structures as well as within 50 feet of the structure. If free product is suspected or known to exist in the area around the structure, sampling locations should be extended to 100 feet. If current and reasonably anticipated future land uses are the same, the EPC calculation is unchanged for future uses.

To evaluate EPCs for potential future vapor intrusion (e.g., in the event that an enclosed structure is constructed on top of contaminated soil), it is necessary to determine the nature of any future structure and estimate the size (footprint) of the structure and its location.

If the location and characteristics of future structures are known, the EPC should be conservatively estimated using samples from that vicinity, including the buffers mentioned above for existing structures. If the nature of future structures is not known, the assumption should be made that a structure could be placed anywhere on the property in question and potentially located directly over the source. The size of the structure would be assumed to be similar to that of the likely future land use, in most cases either residential or nonresidential. The default size of a residential structure assumed in this guidance is approximately 40 feet by 40 feet. For sites where the footprint of the current and likely future enclosed spaces are different, different exposure point subsurface soil concentrations (one for current conditions and one for future conditions) may be necessary. The 95% UCL or area-weighted average methods may be used, as appropriate. Where multiple boreholes with several depth interval samples are available, a depth-weighted average from individual boreholes can be developed.

### **4.3 Exposure Point Concentration for Protection of a Construction Worker**

The risk evaluation process includes the evaluation of one pathway of exposure for construction workers: accidental ingestion, dermal contact, and outdoor inhalation of vapors and particulates from soil.

For the construction worker, no distinction is made between the surficial and subsurface soil because subsurface soils may be exposed during construction. To estimate the EPC for the construction worker, it is necessary to identify the depth, areal extent, and number of samples taken within the zone of construction. The potential future depth of construction can be estimated by contacting local construction firms and identifying the typical depth of utilities on and adjacent to the site, contacting local utility companies, or using as-built plans for proposed facilities if they exist. If the areal extent of the construction area is not known, it may be conservatively estimated as the source area. If sample results are available for several depth intervals, these should be averaged using depth weighting. The depth-weighted averaged values from multiple boreholes could then be combined to calculate a 95% UCL or area-weighted average, as appropriate. The EPC would be the depth-weighted average concentration within this zone of construction.

### **4.4 Ground Water**

The risk evaluation process requires evaluating two routes of exposure associated with shallow ground water: 1) ingestion of ground water and 2) indoor inhalation of vapor emissions from ground water. Where multiple aquifers are present, the shallowest aquifer is typically the aquifer first considered for both pathways. Site-specific circumstances—such as the disappearance of the shallow aquifer or transport of contamination to the

deeper aquifer—may require evaluation of both aquifers. Characterization of petroleum COIs in both aquifers should still be performed. At a minimum, two different ground water EPCs, one for each complete pathway, are required.

#### 4.4.1 Exposure Point Compliance Well Concentration for Ground Water Protection Pathway

For the ingestion of ground water pathway, maximum contaminant levels (MCLs) or equivalent concentrations have to be met at the point of exposure location. Often, the point of exposure well location is hypothetical and data may not be available. Alternatively, if a point of exposure well is present, an upgradient sentry or compliance well is often used as an early warning monitoring location. In both of these cases, ground water transport models are used to calculate the predicted concentrations at the point of exposure based on source area concentrations, the allowable concentrations in the source area, or an alternate point of compliance location concentration that will result in acceptable concentration at the point of exposure. In any case, EPCs will need to be estimated for the source area or for the alternate point of compliance location. In addition, one or more compliance wells have to be identified, and target compliance well concentrations (typically higher than the exposure well concentration) have to be calculated at these wells.

To evaluate this pathway, the EPCs in the source area, point of compliance, or point of exposure locations should be calculated based on the measured concentrations as discussed below. In most cases, a rule of thumb is that measurements taken more frequently than quarterly would not be considered statistically independent samples, would not be accepted to meet the specified number of measurements, and should not be used for statistical analysis and hypothesis testing (DEQ 2009). Methods to evaluate temporal independence are discussed in EPA 2009 and DEQ 2009.

- For wells with no clear trend, the EPC should be estimated as the 95% UCL if the data permit. Where the calculated 95% UCL exceeds the maximum concentration or if the data are not suitable for statistical analysis, the maximum concentration should be used as the EPC. For compliance wells with stable, clearly decreasing, or clearly increasing trends, the EPC is estimated as the 95% UCL of the most recent 1 year of data or most recent 4 measurements, whichever represents the longer time duration. For wells with an increasing concentration trend, continued monitoring may be needed until the trend stabilizes. Quarterly data for at least 1 year is recommended. The data should be pooled for source area characterization where multiple wells are available. Wells clearly not part of the source area of contamination should not be included in the calculations.

Comment [m8]: Reference here the IDEQ gw stat manual about pooling of wells. Otherwise, this looks good.

#### 4.4.2 Exposure Point Ground Water Concentration for Protection of Indoor Inhalation Pathway

Ground water concentrations protective of indoor inhalation are commonly estimated using the Johnson and Ettinger model (Johnson and Ettinger 1991). This model assumes no lateral or transverse spreading or attenuation of the vapors as they migrate upward

from the water table through the capillary fringe, the unsaturated zone, and into the enclosed space. Thus, the EPCs for this pathway should be based on the ground water concentration measured within and adjacent to the footprint of the building. Refer to section 4.2.2 for discussion related to the future land use footprints and their relationship to the impacted area.

For the indoor inhalation of vapor emissions from ground water, multiple EPCs may be required if the plume has migrated below several current or potential future buildings. For example, if a plume has migrated or is likely to migrate below two different buildings (for example on-site and off-site buildings), separate on-site and off-site EPCs should be estimated.

If the plume has migrated below several buildings with similar receptors (residential or commercial), it may be sufficient to evaluate this pathway only for the building below which the concentrations are the highest and/or the depth to ground water is the lowest. If this building is protective of indoor inhalation exposures, it may not be necessary to evaluate other buildings.

The plume may not be in the proximity of current structures. If assumed future land use includes the possibility of building structures in the vicinity of the plume, a similar calculation of EPCs and risk should be made using appropriate assumptions about the location and type of future structures.

While the target ground water concentrations are based on the assumption of no lateral or transverse spreading of the vapors as they diffuse upwards to the building, site characteristics such as site lithology and preferential pathways may result in lateral migration towards a structure. For this reason, the EPCs should be conservatively based on data gathered adjacent to the structure. After identifying the locations of the building footprints and the appropriate ground water monitoring data within and adjacent to each footprint, the 95% UCL or area-weighted average concentration within each footprint may be estimated, as discussed in section 5.

#### **4.5. Soil Vapor**

Soil vapor is used exclusively to evaluate the risk posed via the vapor intrusion pathway. Many of the same considerations discussed for the development of EPCs using soil data in section 4.2.2 also apply to soil vapor data. However, one important difference is that, similar to ground water concentrations, the number of soil vapor sample locations is typically fewer than with soil data and the use of statistical methods is precluded. In most cases, because of the variability commonly observed with vapor measurements and the uncertainty of vapor flow paths from the subsurface into indoor spaces, it is preferable to use the maximum concentrations measured within the defined EU. Where multidepth sampling of soil vapor has demonstrated attenuation of concentrations and the presence of a sufficient thickness of oxygenated soil conditions, the use of lower concentrations may be acceptable. Sufficient sample numbers are more often available where source areas or the buildings under consideration are large. In these situations, the use of area-weighted averaging or other statistical methods may be appropriate.

## **5 Estimating Area-Weighted Exposure Point Concentrations**

Area-weighted EPCs can be estimated using the Thiessen polygon method (Fetters 1993; Linsley et al. 1975). If the available data are located on a uniform grid, the area-weighted average would be the same as the arithmetic average. If the dimensions of the source and the receptor's EU are relatively small (several tens of feet across) and very few (1 to 6) soil samples are available within the soil source, the arithmetic average concentration may be used as an approximation of the area-weighted average concentration.

### **5.1 Step 1: Identify the Exposure Unit**

The first and most critical step is to identify the size and location of the EU over which the area-weighted EPC has to be estimated. The location and size of this EU will often vary depending on the pathway being evaluated. Specific guidance on the location of the receptor's area of exposure has been discussed in sections 3 and 4. Area-weighted concentrations can only be estimated if multiple samples have been collected within the unit. If several samples are available just outside the EU, it may be reasonable to extend the size of the unit to include this data. If the values of these samples are ND, they should not be included. This exclusion is technically justified since at most sites the location of the EU is approximate at best.

As part of Step 1, the various EUs for which area-weighted concentrations are desired should be drawn on a site map. The location of data points (soil borings, monitoring wells, etc.) should also be clearly labeled on the map.

If the borings or monitoring wells within the EU are located in a regular grid, the calculation of an area-weighted average is unnecessary and the user should proceed with an EPC calculation using a different method, such as the 95% UCL.

### **5.2 Step 2: Subdivide the Exposure Unit**

The EU, identified in Step 1, is discretized into polygonal elements by connecting the sampling points within each EU (also identified in Step 1) and drawing perpendicular bisectors to these lines to form polygons. The area of each Thiessen polygon is then estimated.

### **5.3 Step 3: Estimate Exposure Point Concentrations for Each Thiessen Polygon**

The concentration measured at the sampling location within each polygon is considered representative of the area of each polygon. As discussed in section 3, if multiple data are available from a location (either multiple depths or dates), compute the arithmetic average concentration of each petroleum COI measured at that location. The arithmetic concentration is then considered representative of the polygon.

#### 5.4 Step 4: Estimate Area-Weighted Average Concentration for the Exposure Unit

The area-weighted average concentration for the EU is estimated using Equation 1:

$$C_{area} = \frac{\sum_{i=1}^{i=n} (A_i * C_{avg,i})}{A_{Total}} \quad \text{(Equation 1)}$$

Where,

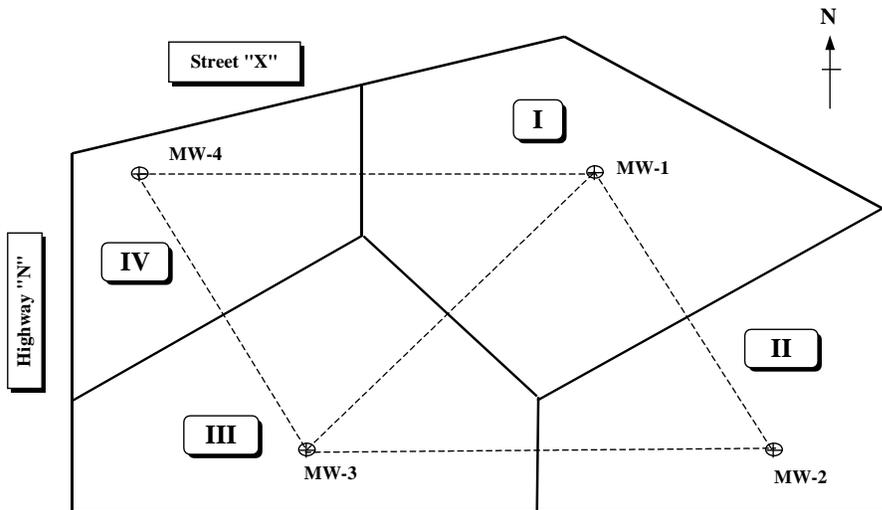
$C_{area}$  = area-weighted average concentration over the EU [mg/kg]

$A_i$  = area of each Thiessen polygon [m<sup>2</sup>]

$A_{Total}$  = total area of the polygons (i.e., area of the EU) [m<sup>2</sup>]

$C_{avg,i}$  = mean of soil or ground water concentrations measured within the polygonal element  $i$  [mg/kg]

An example application of the Thiessen polygon method is schematically shown in Figure 2.



Polygonal Element	Mean Soil Concentration $C_{avg,i}$ mg/kg	Area of the Element $A_i$ $m^2$	$A_i * C_{avg,i}$ $m^2 - mg/kg$	Area Weighted Average Concentration mg/kg
I	2	604	1208	
II	1.8	398	716.4	
III	1.2	578	693.6	
IV	1	234	234	
<b>TOTAL</b>		<b>1814</b>	<b>2852</b>	
Area Weighted Average Concentration = $C_{area} = \frac{\sum_{i=1}^{i=n} (A_i * C_{avg,i})}{A_{Total}}$				<b>1.57</b>

Figure 2. Thiessen polygon method

## 6 Recommendations

- For most pathways, 95% UCL techniques are recommended for development of EPC estimates of average concentrations. For cases where the number of samples is low (four or fewer) and/or the number of ND values is high, the use of the maximum concentration may be most appropriate. The use of the maximum may also be appropriate when the calculated 95% UCL exceeds the maximum

concentration measured at the site and the collected data are considered representative of site and EU conditions.

- The use of area-weighted average methods is not recommended for most pathways, but may be justified in developing EPCs for the surficial soil pathways. The inclusion of methods that evaluate and incorporate spatial uncertainty into the area-weighted average calculation increases the validity of the estimate derived (Burmester and Thompson 1997).

## References

- API (American Petroleum Institute). 2010. BioVapor Indoor Vapor Intrusion Model. <http://www.api.org/ehs/groundwater/vapor/bio-vapor-intrusion.cfm>
- Alaska DEC (Alaska Department of Environmental Conservation). 2009. *Draft Guidance on Multi-Increment Sampling*. Juneau, AK: Alaska DEC, Division of Spill Prevention and Response.
- Burmaster, D. E., and K. M. Thompson. 1997. *Estimating Exposure Point Concentrations for Surface Soils for Use in Deterministic and Probabilistic Risk Assessments*. Human and Ecological Risk Assessment 3(3):363–384.
- DEQ (U.S. Department of Environmental Quality). 2009. *Statistical Guidance for Determining Background Ground Water Quality and Degradation*. Boise, ID: DEQ. Version 2008-1. EPA (U.S. Environmental Protection Agency). 1992a. *Supplemental Guidance to RAGS: Calculating the Concentration Term*. Washington, DC: EPA, Office of Emergency and Remedial Response, Hazardous Site Evaluation Division. OSWER Directive 9285.7.08.
- EPA (U.S. Environmental Protection Agency). 1996. *Soil Screening Guidance: User's Guide*. Second edition. Washington, DC: EPA, Office of Solid Waste and Emergency Response. Publication 9355.4-23.
- EPA (U.S. Environmental Protection Agency). 2009. *Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities Unified Guidance*. Washington, DC: EPA, Office of Resource Conservation and Recovery, Program Implementation and Information Division.
- EPA (U.S. Environmental Protection Agency). 2011a. *ProUCL Version 4.1 Technical Guide (Draft)*. Washington, DC: EPA. EPA/600/R-07/041. Available at: <http://www.epa.gov/osp/hstl/tsc/softwaredocs.htm> .
- EPA (U.S. Environmental Protection Agency). 2011b. *ProUCL Version 4.1 Users Guide (Draft)*. United States Environmental Protection Agency. EPA/600/R-07/038. May 2011. Available at: <http://www.epa.gov/osp/hstl/tsc/softwaredocs.htm>.
- Fetters, C. W. 1993. *Contaminant Hydrogeology*. New York: MacMillan.
- Gilbert, R. O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold Company Inc.
- Hawaii DOH (Hawaii Department of Health). 2008. *Technical Guidance Manual for the Implementation of the Hawaii State Contingency Plan*. Interim Final. Honolulu, HI: Hawaii DOH. Section 4 available at <http://www.hawaiidoh.org/tgm-pdfs/HTGM%20Section%202004-02.pdf>.

- Johnson, P. C., and R. A. Ettinger. 1991. *Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings*. Environmental Science and Technology 25(8):1445–1452.
- Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus. 1975. *Hydrology for Engineers*. Second Edition. Columbus, OH: McGraw-Hill Publishing Company.
- USACE (U.S. Army Corps of Engineers). 2009. *Implementation of Incremental Sampling (IS) of Soil for the Military Munitions Response Program*. Huntsville, AL: USACE, Environmental and Munitions Center of Expertise. Interim Guidance 09-02. July 20 2009.

### Other Useful References

- EPA (U.S. Environmental Protection Agency). 1988. *Superfund Exposure Assessment Manual*. Washington, DC: EPA. OSWER Directive 9285.5-1. EPA/540/1-88/001.
- EPA (U.S. Environmental Protection Agency). 1992b. *Guidance for Data Usability in Risk Assessment, Part A*. Washington, DC: EPA, Office of Solid Waste and Emergency Response. Publication 9285.7-09A. See especially chapters 5 and 6.
- EPA (U.S. Environmental Protection Agency). 1997. *The Lognormal Distribution in Environmental Applications*. Washington, DC: EPA, Office of Solid Waste and Emergency Response. EPA/600/R-97/006.
- EPA (U.S. Environmental Protection Agency). 2001. *Risk Assessment Guidance for Superfund: Volume III—Part A, Process for Conducting Probabilistic Risk Assessment*. Washington, DC: EPA, Office of Emergency and Remedial Response. EPA 540-R-02-002. OSWER 9285.7-45.
- EPA (U.S. Environmental Protection Agency). 2002a. *Estimation of the Exposure Point Concentration Term Using a Gamma Distribution*. Washington, DC: EPA, Office of Solid Waste and Emergency Response. EPA/600/R-02/084.
- EPA (U.S. Environmental Protection Agency). 2002b. *Calculating Upper Confidence Limits for Exposure Point Concentrations at Hazardous Waste Sites*. Washington, DC: Office of Emergency and Remedial Response. OSWER 9285.6-10.
- EPA (U.S. Environmental Protection Agency). 2006a. *On the Computation of a 95% Upper Confidence Limit on the Unknown Population Mean Based Upon Data Sets with Below Detection Limit Observations*. Washington, DC: EPA, Office of Research and Development. EPA/600/R-06/022.
- EPA (U.S. Environmental Protection Agency). 2006b. *Data Quality Assessment: Statistical Methods for Practitioners, EPA QA-G-9S*. Washington, DC: EPA, Office of Environmental Information. EPA/240/B-06/003. Available at <http://www.epa.gov/quality/qs-docs/g9s-final.pdf>.
- Remington, R. 2003. *Robust Confidence Interval Estimation on the Lognormal Mean*. M.S. Thesis. Moscow, ID: University of Idaho.

*This page intentionally left blank for correct double-sided printing.*

**Appendix J: Sample Table of Contents for a Risk Evaluation Report**

*This page intentionally left blank for correct double-sided printing.*

**TABLE OF CONTENTS**

---

**TABLE OF CONTENTS**

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

1.0 INTRODUCTION

1.1 SCOPE

1.2 OBJECTIVES

2.0 REVIEW AND ANALYSIS OF AVAILABLE DATA

2.1 INTRODUCTION

2.2 SITE DESCRIPTION AND LAND USE

2.2.1 Location and Vicinity

2.2.2 Topography

2.2.3 Current Land Use

2.2.4 Future Land Use

2.3 CHRONOLOGY OF EVENTS

2.4 SITE GEOLOGY AND SOIL STRATIGRAPHY

2.4.1 Regional Geology

2.4.2 Stratigraphy

2.4.3 Ground Water Flow Direction and Magnitude (horizontal and vertical)

2.5 WATER USE

2.5.1 Current Water Use

2.5.2 Future Water Use

2.6 RELEASE SCENARIO AND SOURCE

2.6.1 Chemicals of Concern

2.6.2 Distribution of Chemicals

- 2.6.2.1 Chemicals in Soil
- 2.6.2.2 Chemicals in Ground Water
- 2.6.2.3 Chemicals in Surface Water
- 2.6.2.4 Chemicals in Soil Vapors

3.0 SCREENING LEVEL EVALUATION

- 3.1 COMPARISON WITH ~~IDL~~IRUSL
- 3.2 RECOMMENDATIONS

4.0 EXPOSURE ASSESSMENT

- 4.1 INTRODUCTION
  - 4.1.1 Source
  - 4.1.2 Release Mechanism
  - 4.1.3 Transport Media
  - 4.1.4 Receptors
  - 4.1.5 Route of Exposure
- 4.2 SITE DISCRETIZATION INTO EXPOSURE UNITS
- 4.3 SITE CONCEPTUAL EXPOSURE MODELS FOR EACH EXPOSURE UNIT
  - 4.3.1 Site Conceptual Exposure Model for Current Conditions
  - 4.3.2 Site Conceptual Exposure Model for Future Conditions
- 4.4 GROUND WATER PROTECTION

5.0 INPUT PARAMETERS FOR RISK EVALUATION-1, ESTIMATING RISK, AND DEVELOPING REMEDIAL ACTION 1 TARGET LEVELS

- 5.1 JUSTIFICATION OF SITE-SPECIFIC FATE AND TRANSPORT PARAMETERS
- 5.2 REPRESENTATIVE CONCENTRATIONS FOR EACH RECEPTOR, ROUTE OF EXPOSURE, AND EXPOSURE UNIT
- 5.3 COMPARISON OF CALCULATED RISK WITH TARGET RISK CRITERIA FOR EACH EXPOSURE UNIT
- 5.4 CALCULATION OF REMEDIAL ACTION 1 TARGET LEVELS
- 5.5 RECOMMENDATIONS FOR EACH EXPOSURE UNIT

- 6.0 INPUT PARAMETERS FOR RISK EVALUATION-2, ESTIMATING RISK, AND DEVELOPING REMEDIAL ACTION 2 TARGET LEVELS
  - 6.1 TARGET RISK LEVEL
    - 6.1.1 Treatment of Carcinogenic Chemicals
    - 6.1.2 Treatment of Non-Carcinogenic Chemicals
  - 6.2 QUANTITATIVE TOXICITY PARAMETERS
  - 6.3 PHYSICAL AND CHEMICAL PROPERTIES
  - 6.4 CHEMICALS WITH MISSING DATA
  - 6.5 MODELS AND EQUATIONS
  - 6.6 REPRESENTATIVE CONCENTRATIONS
  - 6.7 EXPOSURE FACTORS
  - 6.8 JUSTIFICATION OF SITE-SPECIFIC FATE AND TRANSPORT PARAMETERS
  - 6.9 COMPARISON OF CALCULATED RISK WITH TARGET RISK CRITERIA FOR EACH EXPOSURE UNIT
  - 6.10 CALCULATION OF REMEDIAL ACTION 2 TARGET LEVELS
  - 6.11 RECOMMENDATIONS FOR EACH EXPOSURE UNIT
- 7.0 CONCLUSIONS AND RECOMMENDATIONS
- 8.0 REFERENCES

Comment [MAB1]: Delete 2?

Comment [MAB2]: Delete 2

*This page intentionally left blank for correct double-sided printing.*

## **Appendix K: Practical Quantitation Limits**

*This page intentionally left blank for correct double-sided printing.*

## Introduction

During the risk evaluation process when collecting media-specific chemical concentration data and establishing remediation standards, situations may arise where practical quantitation limits (PQLs) for specific chemicals and samples may exceed screening levels or site-specific, risk-based concentrations. Section 500 of IDAPA 58.01.24, Application of Risk Based Corrective Action at Petroleum Release Sites, delineates the following factors that may be used to allow the use of PQLs as remediation standards:

- Analytical method
- Method detection limit
- Sampling procedures
- Estimated risk levels
- Other

This appendix provides guidance on how to apply these factors when making this determination.

## Practical Quantitation Limits and Method Detection Limits

A PQL is defined in part in 58.01.24.010 as “The lowest concentration of a chemical that can be reliably quantified among laboratories within specified limits of precision and accuracy for a specific laboratory analytical method during routine laboratory operating conditions.” The method detection limit (MDL) is defined as “The minimum concentration of a substance that can be reported with 99% confidence is greater than zero.”

Formatted: Highlight

PQL values are derived in a number of ways, and there is no consensus as to the process used to develop them. In some cases, they are derived as a fixed multiplier applied to the MDL value or the standard deviation of samples used to develop the MDL. The multiplier commonly ranges from 3 to 5 and may be as great as 10. In other cases, PQLs may be derived by analysis of data from actual laboratory performance studies. In these cases, PQL values are a function of analytical methods, a given laboratory’s equipment, operating protocols, operating conditions, quality assurance/quality control procedures, and sampling and media considerations. Values are sometimes reported by laboratories at levels between the MDL and the PQL and are commonly qualified as estimated quantities. The closer the estimated value is to the PQL, the more confidence in the estimated value.

For the petroleum chemicals of interest (COI) listed in the rule, the common analytical methods employed at petroleum release sites are established by the U.S. Environmental Protection Agency (EPA) in SW-846 (EPA 2011). Table 1 lists methods commonly employed in the analysis of the petroleum COI along with typically achieved detection and quantitation limits.

These values were obtained from sample laboratory reports for site investigations done for the Idaho Department of Environmental Quality (DEQ) at a number of sites where petroleum COI were suspected. In their method descriptions, EPA lists examples of lower limits of quantitation for individual analytes but indicates that they are instrument-dependent and influenced by sample preparation/introduction technique (EPA 2006) or highly matrix-dependent and are provided for guidance only (EPA 2007).

**Comment [MAB1]:** We will need to discuss and adjust this section. Our goal is to develop a scientifically valid and legal approach to developing a "Standard" PQL. The process should provide a path to modify the PQL as technology improves. In the interim, a PQL goal (similar to EPA's to MCLg used in drinking water standards) may be an appropriate approach

For a given media, sampling considerations may have an impact on achievable detection limits. For example, when sampling soil vapor or ambient air with certain methods, the achievable quantitation limit can be a function of the amount of vapor or air sampled. Quantitation limits are commonly reduced as the amount of air sampled increases.

Specialized analytical techniques can sometimes provide lower MDL and PQL values. Table 1 illustrates this with a comparison of values between the use of standard method 8270 for semivolatile compounds versus employing 8270 using selective ion monitoring (SIM). PQL values are 6 times lower for soils and 20 times lower for water samples.

**Comment [MAB2]:** Analytical techniques should fall within the scope of normal laboratory practice

Depending on the petroleum product released, levels of contamination, chemicals present, and media in question (soil, water, and vapor), interferences to analytical detection and quantitation may be present. This may require procedures such as sample dilution in order to quantify petroleum COI concentrations in a sample but which also results in elevated detection and quantitation limits.

## Remediation Standard

A remediation standard is defined in IDAPA 58.01.24 as a "media specific concentration which, when attained, is considered to provide adequate protection of human health and the environment."

Remediation standards are established at petroleum release sites where corrective action has been determined to be required. The need for corrective action is commonly determined after completion of a risk evaluation. Remediation standards are commonly established as part of a risk evaluation or an approved corrective action plan (CAP).

The magnitude of a remediation standard that is established for a given chemical and the potential that it may be exceeded by a PQL is dependent on a number of factors, including, but not limited to, the following:

- Assumptions regarding current and future site land use, both on and off site
- What petroleum products were released and the relative distribution of chemicals detected
- The magnitude and distribution of contamination (which media are impacted)
- The routes of exposure determined to pose the greatest threats

The two risk evaluation scenarios where elevated PQL values may require the reevaluation of initially selected remediation standards are as follows:

### 1) Screening Level Evaluation

The screening level evaluation described in IDAPA 58.01.24 employs the simplest and most straightforward use of remediation standards in the form of the residential use screening levels. The screening levels are conservative, calculated, risk-based concentrations determined to be protective of unrestricted use exposures.

Because laboratory analytical technology is continually changing, these media-specific chemical concentrations are established without consideration of the ability of standard laboratory methods to detect and quantify these values. For the petroleum COI in Table 1, the compounds benzo (a) anthracene and benzo (b) fluoranthene in water and ethylene dibromide in soil pose the greatest potential challenges with respect to PQL values meeting screening level concentrations.

In the screening level evaluation, the user must compare maximum media-specific concentrations measured during site assessment activities to the screening levels. If the measured concentrations do not exceed the screening levels, the site may be eligible for site closure. If the measured concentrations do exceed screening levels, the user may select screening levels as the remediation standards upon which corrective action is based and develop a CAP. The user may also choose to conduct additional investigation/evaluation and perform a site-specific risk evaluation. Samples may also have results reported as undetected at a concentration that is less than the PQL but higher than the screening level. In this case, a potentially unacceptable risk would be indicated.

**Comment [MAB3]:** The comparison of maximum concentrations to calculated Screening Levels is appropriate provide the "Standard" PQL is achievable via regular laboratory practices. It should not be necessary to expand an evaluation, an alternative PQL must be established if the Screening Level is unachievable via regular laboratory practices

### 2) Site-Specific Risk Evaluation

During the site-specific risk evaluation process, media-specific chemical concentration data are collected and used, along with assumptions regarding exposure pathways and receptors, to calculate risk to expected receptors. If the calculated risk is unacceptable, media-specific, risk-based chemical concentrations are established. These risk-based concentrations become the remediation standards for site corrective action. Samples are then taken during and after corrective action to demonstrate the standards have been attained.

PQLs for selected analytes in a given media sample may exceed one or more of the calculated risk-based remediation standards, making the demonstration that the standard has been attained problematic. It is also problematic when samples with results below a PQL are included in the calculation of exposure point concentrations and risk.

Remediation standards are oftentimes the lowest at sites where:

- screening levels have been selected as the standards,
- unrestricted use is the desired corrective action land use goal,
- contamination has migrated offsite in ground water,
- on-site vapor intrusion risk is determined to exist, or
- diesel fuel contamination (and polynuclear aromatic hydrocarbon chemicals) is present in surface soil or in close proximity to surface water.

Accordingly, PQL-related issues often arise at such sites.

**Table 1. Method detection limit (MDL) and practical quantitation limit (PQL) soil, water, and vapor concentrations for petroleum chemicals of interest using selected analytical methods**

CHEMICALS	SOIL			WATER			VAPOR		
	Method	MDL (mg/kg)	PQL (mg/kg)	Method	MDL (mg/L)	PQL (mg/L)	Method	MDL (µg/m <sup>3</sup> )	PQL (µg/m <sup>3</sup> )
Acenaphthene	8270(SIM)	0.0087 (0.0016)	0.036 (0.006)	8270(SIM)	0.0004 (0.000013)	0.001 (0.00005)	NA		
Anthracene	8270(SIM)	0.0074 (0.0008)	0.036 (0.006)	8270(SIM)	0.00036 (0.000012)	0.001 (0.00005)	NA		
Benzo(a)anthracene	8270(SIM)	0.0093 (0.0011)	0.036 (0.006)	8270(SIM)	0.0004 (0.000023)	0.001 (0.00005)	NA		
Benzo(a)pyrene	8270(SIM)	0.0098 (0.0008)	0.036 (0.006)	8270(SIM)	0.00053 (0.000013)	0.001 (0.00005)	NA		
Benzo(b)fluoranthene	8270(SIM)	0.0098 (0.0011)	0.036 (0.006)	8270(SIM)	0.00046 (0.000024)	0.001 (0.00005)	NA		
Benzo(k)fluoranthene	8270(SIM)	0.0089 (0.0005)	0.036 (0.006)	8270(SIM)	0.00036 (0.000020)	0.001 (0.00005)	NA		
Chrysene	8270(SIM)	0.013 (0.0006)	0.036 (0.006)	8270(SIM)	0.00028 (0.000018)	0.001 (0.00005)	NA		
Fluoranthene	8270(SIM)	0.011 (0.0008)	0.036 (0.006)	8270(SIM)	0.0004 (0.000020)	0.001 (0.00005)	NA		
Fluorene	8270(SIM)	0.0078 (0.0018)	0.036 (0.006)	8270(SIM)	0.00042 (0.000012)	0.001 (0.00005)	NA		
Pyrene	8270(SIM)	0.010 (0.0006)	0.036 (0.006)	8270(SIM)	0.00035 (0.000022)	0.001 (0.00005)	NA		
1,2-Dichloroethane	8260	0.00053	0.001	8260	0.00027	0.001	TO-17	--	0.4
Ethylene Dibromide	8011	0.000007	0.00001	8011	0.0000057	0.00001	TO-15 SIM	--	0.8
Benzene	8260	0.00033	0.001	8260	0.00029	0.001	TO-17	--	0.32
Ethylbenzene	8260	0.00023	0.001	8260	0.00022	0.001	TO-17	--	0.43
Toluene	8260	0.0012	0.005	8260	0.00027	0.005	TO-17	--	0.38
Total Xylenes	8260	0.00046	0.003	8260	0.00086	0.003	TO-17	--	0.43
MTBE	8260	0.00028	0.001	8260	0.00019	0.001	TO-15 SIM	--	0.5
Naphthalene	8260	0.0004	0.005	8260	0.00017	0.005	TO-17	--	0.05

Comment [MAB4]: We will want to discuss this table and develop alternatives if PQLs are above Screening Levels

## Process for the Consideration of PQLs as Remediation Standards

When a REM user proposes the use of PQLs as remediation standards, the user must develop and provide to DEQ as part of a proposed CAP a proposal of PQLs as the remediation standards. The proposal should include the results of any risk evaluation, the remediation standards developed from that process, and the proposed PQL. The proposal should be completed so as to answer the questions below. The proposal should identify and discuss the site-specific issues, with supporting information, that justify the use of the proposed PQL(s) as a remediation standard(s).

### Risk Evaluation

- What are the chemicals, media, and pathway or route of exposure for which the issue exists?
- Is the PQL issue related to a screening evaluation and screening levels or a site-specific evaluation and risk-based concentrations?
  - ~~If a screening level evaluation, would performing a site specific evaluation address the PQL issue?~~
  - If a site specific evaluation, what is the impact on the estimated risk of assuming the specific petroleum COI at the proposed PQL? Is the risk still acceptable? If the risk was calculated for a residential receptor, would the risk be acceptable for nonresidential receptors? Does the chemical(s) with PQL issues contribute a significant portion of the cumulative risk?
- ~~Would the implementation of activity and use limitations through an environmental covenant mitigate the risk presented by the chemical(s) at the PQL?~~
- If risk based-concentrations (remedial action target levels) are calculated for multiple chemicals, can the risk be allocated in a different manner such that the allowable concentrations for chemical(s) without PQL issues can be reduced to meet the cumulative risk criteria while maintaining the chemicals of issue at their respective PQLs?

**Comment [MAB5]:** Screening level evaluations should not require additional evaluation due to PQL issues, provided that the sample is undiluted

**Comment [MAB6]:** A screening level evaluation should not result in a EC requirement based on PQLs issues

### Analytical Methods

- What are the analytical methods being employed that are the basis of the PQL?
- Are there other accepted analytical methods available that can provide lower quantitation limits?
- Are there special analytical techniques (such as SIM) that may be employed to achieve lower detection and quantitation limits?
- Are there other laboratories available that can achieve lower quantitation limits?
- Are there quality assurance/quality control issues that impact the stated PQL? Supporting lab quality assurance information should be provided.

**Comment [MAB7]:** Analyses should be achievable using regular laboratory practices

## Method Detection Limit

- What is the stated MDL, and what is the magnitude of the difference between it and the PQL?
- Is the MDL at or below the risk-based remediation standard?

**Comment [MAB8]:** MDLs are generally inappropriate to use in Screening Level evaluations

## Sampling

- What sampling procedures are used for the media and chemical of interest?
- Are there alternative sampling procedures (such as increasing sample air volumes for soil vapor samples) that may result in lower detection and quantitation limits?
- Are there matrix interference issues with the samples being used in the proposal that prevent adequate quantitation limits from being attained? What is the supporting laboratory evidence that matrix interference issues exist? Are there specialized sample preparation methods that might reduce these interferences?
- Has resampling taken place to confirm the PQL issue?

DEQ will review the proposal for use of a specific PQL as a remediation standard as part of the overall CAP and approve or deny the request along with specifying any conditions of approval or reasons for denial.

**Comment [MAB9]:** A specific approach to how the IDEQ will make its determination is required

## References

- EPA (U.S. Environmental Protection Agency). 2006. Method 8260C. Volatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC/MS), Revision 3, August 2006 *in* *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*. United States Environmental Protection Agency. SW-846.
- EPA (U.S. Environmental Protection Agency). 2007. Method 8270D. Semivolatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC/MS). ), Revision 4, February 2007 *in* *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*. United States Environmental Protection Agency. SW-846.
- EPA (U.S. Environmental Protection Agency). 2011. *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*. United States Environmental Protection Agency. SW-846. Update IV of the Third Edition. Available at: <http://www.epa.gov/epawaste/hazard/testmethods/index.htm>

## Appendix L: Quality Assurance Project Plan Template

Comment [MAB1]: No comments at this time

*This page intentionally left blank for correct double-sided printing.*

---

## 1. Title and Approval Page

<hr/> <p>(Project Name)</p> <hr/> <p>(Responsible Agency)</p> <hr/> <p>(Date)</p>	
<i>Project Manager</i> Signature	
	Name/Date
<i>Project QA Officer</i> Signature	
	Name/Date
<i>Program Manager</i> Signature	
	Name/Date
<i>Quality Director</i> Signature	
	Name/Date

## 2. Table of Contents

List sections with page numbers, figures, tables, references, and appendices (attach pages).

### 3. Distribution List

Names and telephone numbers of those receiving copies of this QAPP. Attach additional page, if necessary.

- i. \_\_\_\_\_
- ii. \_\_\_\_\_
- iii. \_\_\_\_\_
- iv. \_\_\_\_\_
- v. \_\_\_\_\_
- vi. \_\_\_\_\_
- vii. \_\_\_\_\_
- viii. \_\_\_\_\_

ix.

---

x.

---

---

#### 4. Project/Task Organization

List key project personnel and their corresponding responsibilities.

Name	Project Title/Responsibility
	Advisory Panel (contact)
	Project Manager
	QA Officer
	Field/Sampling Leader
	Laboratory Manager/Leader

#### 5. Problem Definition/Background

##### A. Problem Statement

---

---

---

---

---

##### B. Intended Usage of Data

---

---

---

---

---

#### 6. Project/Task Description

##### A. General Overview of Project

---

---

---

---

---

B. Project Timetable

<b>Activity</b>	<b>Projected Start Date</b>	<b>Anticipated Date of Completion</b>

7. Measurement Quality Objectives

A. Data Precision, Accuracy, Measurement Range

<b>Matrix</b>	<b>Parameter</b>	<b>Measurement Range</b>	<b>Accuracy</b>	<b>Precision</b>

B. Data Representativeness

---

---

---

---

---

C. Data Comparability

---

---

---

---

D. Data Completeness

<b>Parameter</b>	<b>No. Valid Samples Anticipated</b>	<b>No. Valid Samples Collected &amp; Analyzed</b>	<b>Percent Complete</b>

8. Training Requirements and Certification

A. Training Logistical Arrangements

<b>Type of Volunteer Training</b>	<b>Frequency of Training/Certification</b>

B. Description of Training and Trainer Qualifications

---

---

---

---

---

9. Documentation and Records

---

---

---

---

---

10. Sampling Process Design

A. Rationale for Selection of Sampling Sites

---

---

---

---

---

B. Sample Design Logistics

	<b>Type of Sample/ Parameter</b>	<b>Number of Samples</b>	<b>Sampling Frequency</b>	<b>Sampling Period</b>
Biological				
Physical				
Chemical				

11. Sampling Method Requirements

Parameter	Sampling Equipment	Sampling Method

12. Sample Handling and Custody Procedures

---

---

---

---

---

---

13. Analytical Methods Requirements

---

---

---

---

---

14. Quality Control Requirements

A. Field QC Checks

---

---

---

---

---

B. Laboratory QC Checks

---

---

---

---

---

C. Data Analysis QC Checks

---

---

---

---

---

15. Instrument/Equipment Testing, Inspection, and Maintenance Requirements

<b>Equipment Type</b>	<b>Inspection Frequency</b>	<b>Type of Inspection</b>

16. Instrument Calibration and Frequency

Equipment Type	Calibration Frequency	Standard or Calibration Instrument Used

17. Inspection/Acceptance Requirements

---

---

---

---

---

18. Data Acquisition Requirements

---

---

---

---

---

19. Data Management

---

---

---

---

---

20. Assessment and Response Actions

---

---

---

---

21. Reports

---

---

---

---

---

22. Data Review, Validation, and Verification

---

---

---

---

---

23. Validation and Verification Methods

---

---

---

---

---

24. Reconciliation with DQO's

---

---

---

---

---

*This page intentionally left blank for correct double-sided printing.*